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Repair as a circular strategy for increasing resource availability and health system resilience during a crisis

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HIGHLIGHTS

- Automakers, SENAI (National Industrial Apprenticeship Service) and other companies in Brazil were volunteers to repair broken ventilators for covid patient intubation.
- 2.514 ventilators, around 3% of the ventilators in Brazil at the time were repaired by volunteers.
- There is evidence ventilator repair impacted positively the supply chain resilience aspects.
- Despite the benefits of the temporary alliance for repairing ventilators there is a need for perennial repair policies engaging all stakeholders across the healthcare ecosystem to promote the "right to repair".

ABSTRACT

Background. Healthcare is a complex socio-technical system where nations regularly struggle with the misalignment between public needs and available resources. The advent of COVID-19 further exacerbated shortcomings, as evidenced by the global panic to find ventilators and beyond. However, the pandemic catalysed a successful Brazilian public-private voluntary partnership that united key industry players, industrial

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training centres and several volunteers, who, in the absence of a supportive government, could repair ventilators in record time, giving the health system means to succeed.

Objectives. Characterise how a voluntary public-private partnership came into existence and codify recommendations on how it effectively used repair as a circular strategy to increase ventilator availability and bolster health system resilience.

Methods. Case study using multiple data sources collected over 10 months, including national data, semi-structured interviews, daily reports, and internal communications. Sampling, research instruments, and subsequent qualitative data analysis and theory development grounded in repair strategy, resilience, and supply chain literature.

Results. A successful public-private voluntary partnership delivered 2,514 repaired ventilators, approximately 3% of the total ventilators in use in Brazil and impacting around 24,700 lives. Furthermore, effectively functioned as a first-responder bringing to hospitals approximately 500 repaired units as early as April 2020, surpassing the government's procurement and doing so just-in-time for Brazil's COVID 1st wave. More than 70 institutions and 700 professionals helped hospitals in 25 out of 27 Brazilian states. This case documents how the initiative persevered through adversity, including inadequate policies representing a widespread difficulty in enforcing the "right to repair".

Public interest summary. In Brazil, automakers, the National Industrial Training Service and other organisations formed a voluntary and temporary alliance to repair broken ventilators that had accumulated in hospitals. This initiative took place at the beginning of the COVID-19 pandemic and returned 2,514 ventilators to hospitals, supporting patient care and partially alleviating the shortage of ventilators. This repair depended on the training of technical staff who had never worked with health equipment before. In addition to training, there was a need to share information and manuals, calibrate repaired equipment, procure spare parts, organise logistics and find funding, among other activities, meaning that it was a wide scale operation involving several organisations - both within and outside the health system. This research demonstrates the role of ventilator repair in making a health system more resilient in the event of a health emergency, and the urgent need to develop strategies to make repair an everyday commitment.

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INTRODUCTION

Health Systems are primarily focused on restoring and maintaining health [1] while having to continuously manage scarce resources and potential disruptions that may undermine their sustainability and objectives. The complex interplay of cause and effect among sustainability aspects and health systems' components ranges from linking one-quarter of all diseases to environmental impacts [2], to considering climate change the most significant health threat of the 21st century [3].

Despite being fundamental to all levels of health systems resilience [4], [5], medical supplies are a building block (figure 1) often ignored in the health system resilience literature [6]. Nevertheless, those medical supplies also represent an intersection between sustainability aspects and health systems resilience, for they are: i) a core element to care delivery [7]; ii) necessary to maintain health systems during emergencies; iii) a source of waste and therefore a potential negative impact to the environment and surrounding communities' health quality [8]–[10]; iv) and part of health system resilience and evaluation tools [5], [11], [12]. However, even when considering potential health system resilience frameworks, empirical research has yet to fully embrace the importance and complexity of medical supplies [6].

Most of the empirical evidence on health system resilience operationalisation revolves around the "service delivery" building block (figure 1) [6]. Some frameworks for health systems resilience include a detailed role of medical device management in composing the resilience measurement [5], [12]. For Kruk (2017), if a health system needs to increase its resilience, then it should be "aware", "diverse", "self-regulating", "adaptative", and "integrated". Each of these characteristics represents a set of indicators, and medical device appear explicitly in the first aim of the "aware" bundle, namely to "know health system capacity", which monitors supplies and anticipates possible disruptions. A more general framework reflects how the system preserves its functions and continues to deliver health services ("absorptive capacity"); how stakeholders adapt to maintain satisfactory levels of healthcare services ("adaptative capacity"); and how actors transform their functions and the structure of their relations ("transformative capacity") [6], [13].

While the end-of-life stage of medical device remains a challenge, there is a movement for bringing sustainability upstream and adopting strategies that maximise the value obtained from medical products and the materials embedded in them, e.g., by designing products that withstand multiple uses and have clear maintenance and repair alternatives, thereby avoiding premature obsolescence [14]. The circular economy is a field that studies how to replace the current end-of-life practices with broader circular strategies that maintain and prolong materials and products in the system [15]. Emerging research suggests a strong relationship between the concepts of sustainability, circular economy and resilience [16]. Understandably, others have noted the circular economy's potential role in tackling material scarcity [17] and optimising medical device availability [14], [18], [19].

The COVID-19 pandemic brought with it severe disruption of medical devices supplies which in turn shifted perspectives toward circular strategies and system resilience in healthcare [20]. Even though the health systems resilience debate intensified during the Ebola outbreak in 2014 [21], it gained worldwide attention during the COVID-19 pandemic [22]–[24], which tested every aspect of health systems across the globe[25]. During the COVID-19 crisis management, medical devices proved to be a critical factor for resilience in global health systems that faced shortages of medicines, personal protective equipment (PPE), oxygen and ventilators [26]. As a result, circular strategies such as reuse and repair gained importance due to the necessity of making the most with limited resources [20]. Furthermore, He et al. 2023 propose a "right to repair" framework for medical devices, addressing the environmental impact benefits through reduction of CO_2 emissions, increased equipment lifespan, waste elimination and reduced demand for new equipment [27].

In the case of developing nations, repair strategies assumed vital importance in handling the unusually competitive medical device landscape that exacerbated previously existing economic constraints [26], [28]. The Brazilian health system was no different in experiencing deep and consecutive shocks due to the lack of all sorts of medical supplies, as was the case with ventilators that are worthy of further in-depth discussion [29]. Indeed, there is a bias in the academic literature around health system resilience theory as evidenced in the lack of empirical studies drawn from South America [6]. A unique opportunity exists to bolster resilience theory development with the inherent realities of developing countries, investigating if and when these were successfully addressed and whether innovations are applicable to other countries.

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This paper focuses on the circular strategy of repairing ventilators for the Brazilian health system and studies a multi-stakeholder voluntary initiative to increase ventilator availability during the first year of the COVID-19 pandemic. The aim of this paper is to discuss how the adoption of a repair circular strategy ensured the availability of ventilator supplies and enhanced the health system's resilience. We present the impact of the repair circular strategy on the supply chain resilience and offer recommendations for advancing ventilator policies towards a sustainable supply chain.

PRE-PANDEMIC BRAZILIAN VENTILATOR SCENARIO AND INITIAL RESPONSE OVERVIEW

The pre-pandemic configuration of the Brazilian health system revealed a strong dependence on external markets for acquiring ventilators, with the leading suppliers in China and the United States. In response to this scenario, several institutions addressed the expansion of Brazilian ventilator supplies. Efforts to address the ventilator shortage went in three directions: new design and production, acquisition and repair.

The design and production strategy attempted to increase the stocks of ventilators and their parts. This strategy stimulated the discussion of patents and open design. Some examples of this strategy were: the VITAL ventilator model developed by NASA and produced by a collaboration between Russer (Brazilian medical equipment manufacturer) and SENAI CIMATEC (health technology innovation centre) [30]; the ICU ventilator "Luft-3" from LEISTUNG (Brazilian ventilator producer) that began to be manufactured also by WEG (Brazilian electric equipment manufacturer) [31]; the "Inspire" a low cost ventilator developed by the Poli-USP Engineering School at the University of São Paulo and manufactured by the Navy Technological Center in São Paulo [32]. All of those examples are similar to the Product Development Partnerships (PDP) that promoted access to critical medicines in the prior decades [33], the ventilator production ramp up also relied on the close collaboration between multiple stakeholders in the government, private sector, universities and technology centres. However, despite its value, the strategy cannot mitigate health emergency issues in the short term.

The acquisition strategy can achieve faster results and depend on procurement processes and collaboration with national and international ventilator producers. While internationally the market displayed rising prices and competition and in April 2020, at least 80 countries imposed restrictions on the export of medical supplies (Shalal 2020). Also, the limited Brazilian national production faced unprecedented demands. As a result, a multiple sector stakeholders alliance facilitated the expansion of the ventilator production, in order to respond to government contracts to procure 14.100 ventilators in 2020 [34]. For example, Magnamed, a Brazilian ventilator producer, was responsible for 6.500 ventilators (R$322.5 million order) to be delivered within six months [35]. The company was able to expand its production capacity from 200 to 400 ventilators per month with the voluntary support from other Brazilian industries from other sectors: Positivo, Suzano, Klabin, Flex and Embraer [35]. Meanwhile, in parallel to these positive collaborations, the continued high demand for ventilators gave rise to corruption cases showing scams, fraud and inflated costs that in many cases delayed or prevented the ventilator acquisition [36].

Diverging from the acquisition strategy, which relied on a structured process and dedicated resources, repair faced severe constraints and varied significantly among sectors and regions. While ventilators would last longer in for-profit institutions, public institutions had broken equipment in store. This insufficient repair strategy resulted from the lack of political interest, insufficient repair service providers, absence of data on broken ventilators and leaving the repair as a hospital-level decision. Attending to this demand another multi sectoral partnership, called "+ Ventilator", emerged to promote repair innovation and support the fight against the COVID-19 pandemic burden in the health system.

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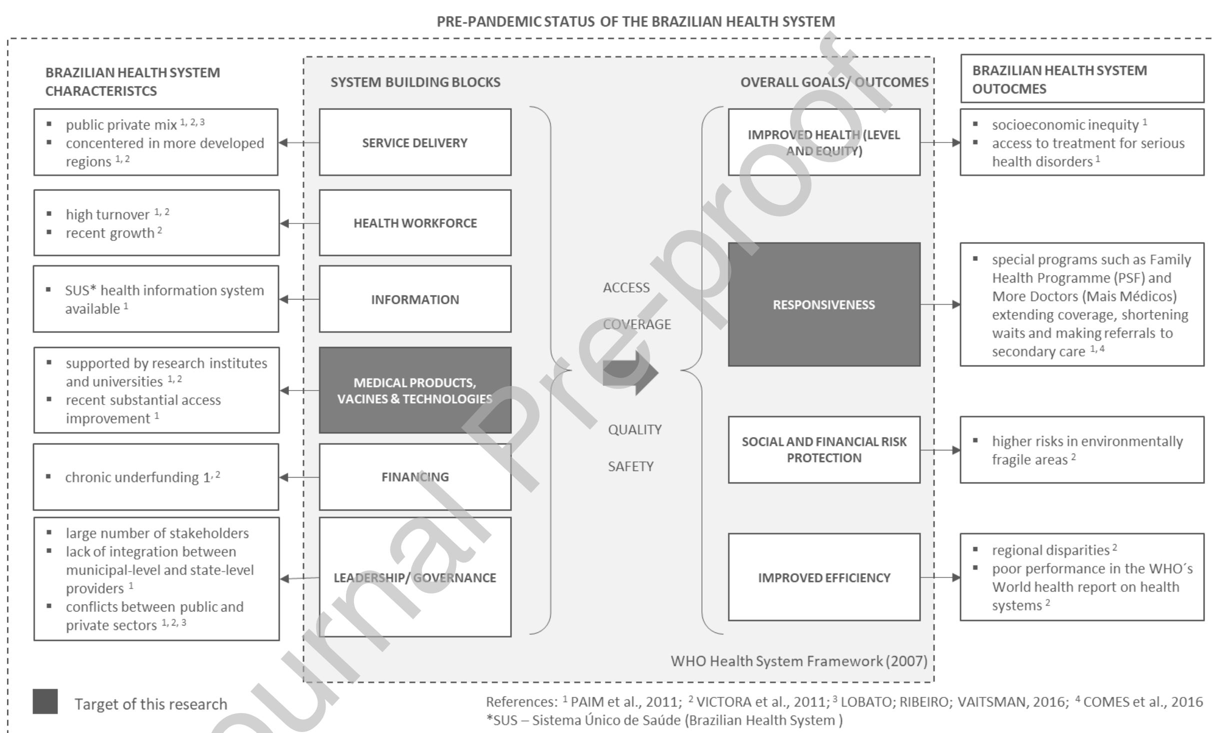

Figure 1 *- Pre-pandemic status of the Brazilian health system and research focus. SUS – Sistema Único de Saúde (Brazilian health system), WHO – World Health Organization*

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METHODS

Similar to other qualitative studies in the health innovation management field [37], we used a case study research approach [38] to analyse how the broad adoption of repair strategies [27] in medical devices may impact the resilience of the healthcare system's supply chain [39]. Following Eisenhardt's recommendations (1989, 2021), we adopted a theoretical sampling approach in contrast to a random sampling method, implying that we chose a particular case in which we could observe the phenomenon of interest. The case selected was the Brazilian disruptive ventilator repair initiative, named *+Ventilator Repair initiative*. This was a voluntary network solely created to maintain and repair unused mechanical ventilators in private and public hospitals during the COVID-19 Pandemic. Several characteristics made this dedicated project an excellent opportunity to study the repair circular strategy in the Brazilian health system: its national coverage, the significant stakeholders mobilised in the public and private sectors, and the impressive results achieved at the beginning of the pandemic.

We conducted semi-structured interviews with senior personnel from multiple firms. The firms were selected based on two criteria: their role in the initiative and their capacity to provide insightful information about the phenomenon of interest. Insofar as their role, firms were leaders in their respective areas across the supply chain: technical assistance (repair and maintenance), training, logistics (identification and transport of ventilators), regulators and accreditors, and financial provision. Lastly, interviewees were senior leaders from the Automakers Association, the Health Ministry, the Clinical Engineers Association, and the front line managers from the University Hospitals Association.

The interview protocol's objectives were twofold: (1) to recognise and map the elements, services and actors of the initiative, along with its strengths and weaknesses, and (2) to investigate the supply chain resilience aspects (i.e., agility, flexibility, visibility, structure and knowledge, collaboration, reduction of uncertainties and integration of operational capacities [39]). Interviews were recorded, transcribed verbatim, and analysed using a qualitative data analysis program (i.e., MAXQDA Software).

Additionally, we used three documentary sources to corroborate interviewee accounts, access quantitative data, and obtain new information. We had full access to all the initiative's daily reports. In total, 148 daily reports provided quantitative information, such as the number of ventilators received by each volunteer institution and the number of ventilators repaired and delivered back to hospitals. The Brazilian governmental health database, CNES-DATASUS[1] was accessed to obtain supplementary data, including the official number of ventilators and their status in public and private hospitals and facilities and the epidemiological parameters during the pandemic. Lastly, official reports and media reports supplemented the research with data of ventilator purchase deals and processes.

+Ventilator Repair Initiative Motivation and Operation

The voluntary initiative happened from March 2020 until December 2020 and began through efforts from the National Service for Industry Training (SENAI) and automotive industries, later joined by volunteers in other segments.

SENAI, with other members of the Brazilian innovation ecosystem, while targeting the expansion of the ventilator availability (mainly by new design), identified a gap in the ventilator records of the CNES-DATASUS, showing 5,62% of all ventilators were not in use at the beginning of the pandemic (figure 3). To contribute to closing this gap of ventilators not in use, the volunteers assigned their call centres to contact hospitals and identify the demand for repairing ventilators. In effect, the initiative was started and lead by SENAI, supported by the Health Ministry, Economy Ministry, Defense Ministry, Brazilian Agency for Industrial Development and the Brazilian Association of Clinical Engineering, and had the intense participation of private institutions, in particular from the automakers industry[2].

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[1] CNES - DATASUS: data base for information from all public and private health care facilities in Brazil under the authority of the Informatics department of the Brazilian Health Ministry.

[2] ArcelorMittal, BMW Group, Fiat Chrysler Automóveis, Globo Comunicação e Participações, Ford, Fundação Oswaldo Cruz, General Motors, Honda, Hyundai Motor, Instituto Votorantim, Jaguar Land

All public hospitals and healthcare facilities were contacted directly by the Automakers call centres. The Health Ministry prepared a letter to hospitals affirming the initiative's legitimacy to overcome recurrent suspicions from health facilities personnel. To formalise the free-of-charge repair request, hospitals needed to fill out an online form specifying the ventilator model and known technical issue . Initiative leaders consolidate all requests on a daily basis and then allocated them to specific repair centres and arranged for logistics.

The volunteers were organised to act in specific roles according to their capacities: technical assistance (repair and maintenance), training, logistics (identification and transport of ventilators), regulators and accreditors, and financial provision. Worth noting that the initiative's governmental stakeholders were not members of the elected government, but rather technical officials in permanent positions. This nuance is of further relevance when considering that the elected government, who was frequently accused of hindering medical supply acquisitions, neglected to fund or voice support toward the ventilator repair initiative. Hence, in a way, making this public-private volunteer partnership even more remarkable and worthy of study. The operationalisation of the initiative involved converting industrial workshops into temporary repair centres (Figure 2), and creating knowledge transfer procedures to train their staff in the specificities of ventilator repair and COVID-19 sanitary protocols. This training was led by a SENAI centre specialised in medical equipment and was supported by the Clinical Engineers Association. The training sessions happened online and were recorded to be accessible to other partners joining the initiative later on and also served as training material to other Latin American countries.

Access to parts and manuals often posed a more significant challenge than the repair itself. The University Hospitals Association, the Clinical Engineers Association, some hospitals and the authorised repair service providers supplied several ventilator manuals. However, in extreme cases, a lawsuit was necessary to access the passwords and information indispensable for the ventilator repair. Judges granted fast access to this data in 100% of the cases.

The returning procedure established that ventilators could only go back to the original institution it came from due to restrictive property management regulations. Institutions would get ventilators back in every case, either repaired or with the statement they could not be repaired. Receiving back the equipment usually took only a few days but in some cases the need for parts or information would delay the process. To speed up the process and repair a greater number of ventilators, the volunteers pressured the regulation agency and were authorised to perform the "cannibalisation" of beyond repair ventilators, which became a source of used parts.

Figure 2 – *Ventilator repair operation*

+Ventilator Repair Initiative Outcomes

In July 2020, the initiative had 51 institutions repairing ventilators in 21 out of 27 Brazilian states. During the ten months of the voluntary initiative, those temporary repair centres received a total of 4.047 units from hospitals in 25 of 27 Brazilian states. As a result of the combined efforts of over 700 professionals

Rover, Mercedes-Benz, Moto Honda, Petrobras, Renault, Scania, Itaú, Toyota, Troller, Usiminas, Vale, Volkswagen e Volvo.

and 70 institutions working for ten months, from March 2020 until December 2020, the initiative repaired 2.514 ventilators (62% of the ventilators received).

The percentage of ventilators not in use in January 2020 decreased by 0,66% in January 2021 (Figure 3). The same figure reveals the increase in one year in ventilator stock and how their proportion grew in relation to the Brazilian population, jumping from 3 per 10.000 people to 4 per 10.000. Also, according to the bubble map, the ventilators are more concentrated in the southeast region. The records of existing ventilators in the Brazilian health system show that while the northern region, which faced severe health system collapses due to the lack of medical devices, went from 1,9 ventilators/10.000 people to 2,6 ventilators/10.000 people, the southeaster region went from 3,6 ventilators/10.000 people to 4,7 ventilators/10.000 people, showing the ventilators were not evenly distributed in the Brazilian territory.

This remarkable number of repaired ventilators represents around 3% of the total of ventilators in use in Brazil and has impacted at least 24.700 lives. The importance of those repaired ventilators originates from the fact that they were delivered back to hospitals early in the pandemic and supported patient treatment longer than ventilators bought later. This early response is demonstrated in figure 4 by the most significant number of ventilators repaired in April, May, and June when the COVID-19 cases began to increase compared with the following months. In April, the number of repaired respirators was even superior to the ventilators procured by the government. Also, the number of ventilators suitable for repair is close to that of possibly impaired ventilators registered as existing but not in use, according to governmental databases.

The ventilators were mainly delivered to the state of São Paulo and the southeaster region, followed by the midwestern and northeaster regions. The northern region had the smallest number of ventilators repaired due to the smaller ventilator supply. Additionally, the map shows more ventilators were repaired for states that concentrated the most considerable number of COVID-19 cases.

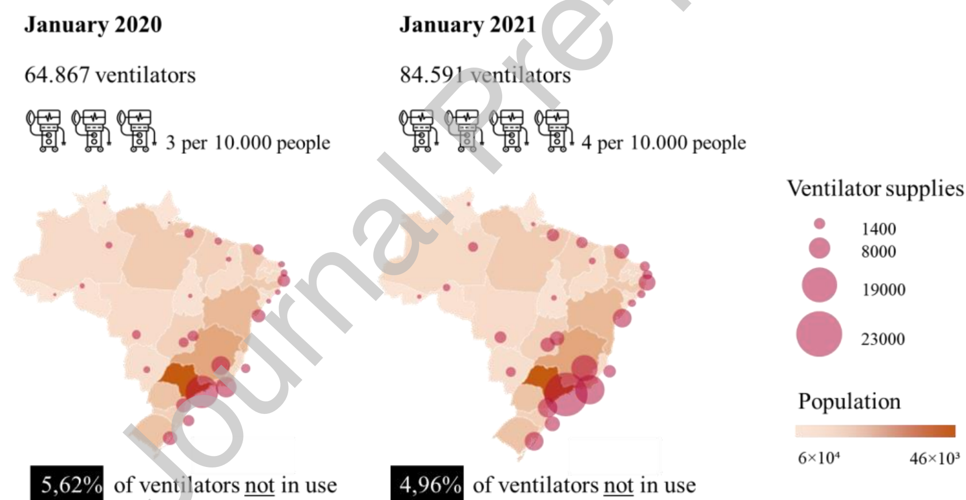

Figure 3. *Ventilator supplies in 2020 and 2021 (based on DATASUS data)*

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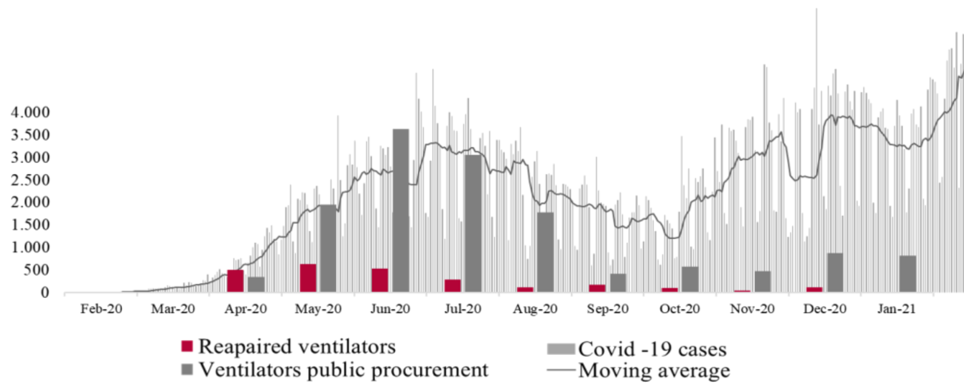

Figure 4 . Timeline of ventilators and COVID-19 case

RESULTS

Repair circular strategy impact on supply chain resilience

This research leveraged seven elements of supply chain resilience [39] to assess how the adoption of a circular strategy for repairing ventilators had an impact, if any, on health system resilience. Table 1 describes key findings as to how the repairing ventilators voluntary initiative manifested each element.

There was ample evidence related to "agility and responsiveness" thereby corroborating its significance toward supply chain resilience. Speed was of primary concern at multiple levels beginning with the mobilisation of central volunteers and the start of operations within a mere week. Such agility made possible the availability of repaired ventilators at the critical time when COVID-19 cases surged and the government had yet to supply new ventilators. Several measures secured the broken ventilators' repair speed at the operational level. Those operational solutions included, among others, real-time problem solving with repair experts, mining components across supply networks, and reusing parts sourced from unrepairable ventilators to maintain the pace during the shortages.

Reusing parts not only provided a means to deliver ventilators faster but also enabled an alternative to sourcing components and parts, thereby offering **"flexibility/redundancy**". In this context, hospitals allowed volunteers to disassemble unrepairable ventilators to use parts elsewhere. Numerous operational adaptations were necessary. For example, adapting installations and methods or even redistributing the demand of overloaded repair centres. Ultimately, the ventilator repair was a system adaptation that created redundancy, considering the conventional and volunteer repair services were operating in parallel. In this scenario, the repair services were insufficient to meet the demand, so the volunteer creation of a separate stream to quickly process the accumulated stock of broken ventilators was fundamental.

To implement the initiative, volunteers needed to guarantee **"visibility"** of the demand for repair. While the national health database only showed a gap between ventilator total and ventilators in use, it was still unclear how many defective ventilators there were, what their condition was and if they would even be repairable. Hence, volunteers actively searched for broken ventilators using call centres to contact health facilities and ask about their damaged equipment. Another tool, an online form, required health workers to fill in details of their ventilators, to initiate the repair process, starting with collection logistics. Additionally, daily reports sent to all initiative members would make the repair progress visible thereby improving their local planning ability and confidence in addressing the surge.

The daily reports registered the number of ventilators received, in repair, and delivered back to health facilities by each volunteer. These data were only part of the information shared in the virtual platforms supporting the initiative's "**structure and knowledge"**. The physical structure was the idle shopfloor and equipment from volunteer institutions repurposed to repair ventilators. However, achieving this goal required new knowledge of ventilators' peculiarities and sanitary protocols, such as contamination prevention, and what was needed from the physical structure. The solution to this knowledge gap was to prepare protocols covering the processes of collection, distribution, and decontamination. The Clinical Engineers Association and the SENAI provided online training sessions on the repair procedure to

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address the knowledge gap. Therefore, all the information sharing depended on an internet-based informational structure to optimise stakeholder interaction. Notably, the virtual platforms would register demand, offer access to ventilator manuals and protocols, host training sessions, and provide instant communication channels.

Online communication between volunteers increased the degree of **"collaboration"**. Such interaction aimed to tackle emergent issues and bring together people with the right skills to solve them. This collaboration and the constant sharing of technical information on online platforms helped overcome ventilator technology diversity and complex technical issues in the repair process. Nevertheless, unique situations would arise, such as the challenge of explaining to highway patrol that a truck full of ventilators was travelling across cities without any purchase documentation. In this last case, it was necessary to contact authorities in the Economic Ministry to release the truck's cargo.

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Table 1. Resilience aspects and their correlation with the ventilator repair initiative. Resilience aspects and description from Ponomarov and Holcomb 2009

Resilience Aspect	Description	Evidence from the voluntary initiative for repairing ventilators
Agility, responsiveness	Agile supply networks have a faster response to changing circumstances.	- the initiative was a fast response to the COVID-19 pandemic and started in the same month as the first death registered in Brazil (March 2020); - volunteers took one week to set up the basic repairing operations; - the ventilator repair was faster than ventilator procurement; - the speed in acquiring parts and performing repairs was seen as a matter of "life and death", for there were not enough ventilators in the health system; - at critical moments, it was faster to reuse parts from unrepairable equipment than to wait for new parts purchased internationally.
Flexibility/ redundancy	Flexible supply chains change and adapt quickly.	- when some repair centre would face an overload, other repair centres would absorb the excess demand; - the reuse of parts from unrepairable ventilators was an alternative to purchasing, constituting two methods for obtaining the necessary parts; - using car manufacturing installations and other facilities with professionals, tools, and machinery from non-health backgrounds was a systemic adaptation and became an alternative to the conventional repair mechanisms; - due to the pandemic safety concerns, volunteers created hygiene protocols.
Visibility	Demand visibility across the supply chain minimises risks.	- the demand found was a stock of broken ventilators accumulated in the public health facilities in the Brazilian health system; - the initiative had to actively contact health facilities and find out if they had broken ventilators and register the repair requests; - all volunteers could visualise the repair requests for local and national scales; - a daily report would depict the complete repair input and output results, including all repair centres.
Structure and knowledge	Knowledge on the supply chain physical and informational structure.	- the physical infrastructure relied on the temporary allocation of the volunteer's facilities and equipment - the virtual structure was extensive and relied on multiple means for storing data, reporting results, obtaining requests, training, and allowing communication between the volunteers - preparing protocols and systematising knowledge demanded great efforts from the initiative
Collaboration	Partnership behaviour, managing risks collectively.	- the initiative was grounded in intensive online collaboration; - stakeholders collaborated, sharing multiple expertise; - volunteers shared emergent challenges in group discussions and collaborated to develop alternatives.
Reduction of uncertainty, complexity, reengineering	A set of business processes that reduce uncertainties to increase supply chain resilience.	- negotiations with governmental stakeholders waved technical responsibility certificate fee for the ventilator calibration process - authorities discharged volunteers from legal responsibility for the ventilators - official statements backing the absence of invoice for repairing ventilators - repair and decontamination protocols were a simplification of the information held by experts or included in product manuals
Integration, operational capabilities, transparency	End-to-end integration of orders, inventory, transportation, and distribution.	- the mix of operational and strategic, public, and private stakeholders formed the entire ventilator repair solution from the hospital to a workshop and back to the hospital; - leading stakeholder representatives would integrate several fronts and consolidate information.

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Later, the risk of having a ventilator cargo apprehended due to the lack of documentation led to a **"reduction of the complexities and uncertainties"** via an official statement discharging the obligation of emitting purchase documentation. Indeed, mounting legislative barriers triggered the simplification of the legal frameworks. Among the adaptations, those designed to protect volunteers and reduce costs stand out. For instance, to absolve responsibility for ventilators, permit non-medical companies to repair, and waive the fee for ventilator calibration certificates.

A ventilator is a relatively high technology equipment where repair raises complicated legal and financial issues that were only successfully addressed by this initiative as a result of a diverse group of stakeholders **"integrating the[ir] operational capabilities"**, including among others, funding, parts, calibration, regulations, and other support activities.

Recommendations for advancing ventilator policies towards a sustainable supply chain

Our analysis uncovered the importance of repair strategy as a viable and effective response to health system disruption in developing countries. The lack of effective policies to guarantee the preventive maintenance and repair of ventilators resulted in the accumulation of damaged equipment in hospitals across the country. Absent policy may directly adversely impact health system resilience and its capacity to respond to emergencies. Our results support the argument that systemic initiatives for repairing ventilators can enhance health system resilience.

The initiative's volunteer characteristics demonstrate the potential for institutions beyond the healthcare sector to play key roles in fighting a sanitary crisis. Another particular trait of the assistance provided is that volunteer institutions did not simply combat the pandemic by donating money or equipment but also contributed with labour and human capital expertise that each organisation already possessed.

Indeed health related stakeholders directly benefited from the greater ventilator availability made possible by this initiative. However, one can argue that most stakeholders did also, including those beyond healthcare. For instance, gaining experience and footing in a new sector; reducing the pandemic's duration and negative economic impact to their core business; and attaining acknowledgment and appreciation from existing and potential future customers within and beyond the health sector. Thus, policies involving cross-sectoral partnerships represent a viable and largely unexploited strategy for resource scarcity and progress towards sustainability goals.

However, despite the success in repairing ventilators, there are still severe barriers to a perennial and comprehensive medical equipment repair program in the Brazilian health system. Even though resilience was associated with the repair initiative, its presence could be incidental, for it remained a temporary movement with benefits restricted to the duration and scale of the partnership. Furthermore, after the voluntary initiative was demobilised, no other large-scale repair and maintenance program took its place, and the newly damaged ventilators could only rely on the individual hospital's management capacity, competing with higher priorities. Therefore, it remains urgent to understand what hinders or supports repair strategies in health systems. For this reason, based on the evidence from the case presented, we introduce a framework of barriers and enablers to repairing ventilators in Brazil that can provide considerable insights for longer term and sustainable policy-making (Figure 5).

In our case, stakeholders fall into four categories, including the three categories for circular initiatives in health systems [18]. First, the cluster "Regulators, accreditors, professional and financial organisations" is responsible for supporting the initiative and providing legal and financial means to continue operating. Second, the cluster "Manufacturers and retailers" represents those companies responsible for producing ventilators and their parts, which are indispensable for repair. Third, the cluster "Consumers" represents those that demanded ventilator repair, namely hospitals and society in general. Fourth, the research team added "Volunteers for repair and logistics", representing the group of institutions performing the repair operations and transporting ventilators from hospitals to repair centres and then back to hospitals. Notably, those volunteers did not profit in any circumstances from the repair services and spent their own resources to run the operations in most cases.

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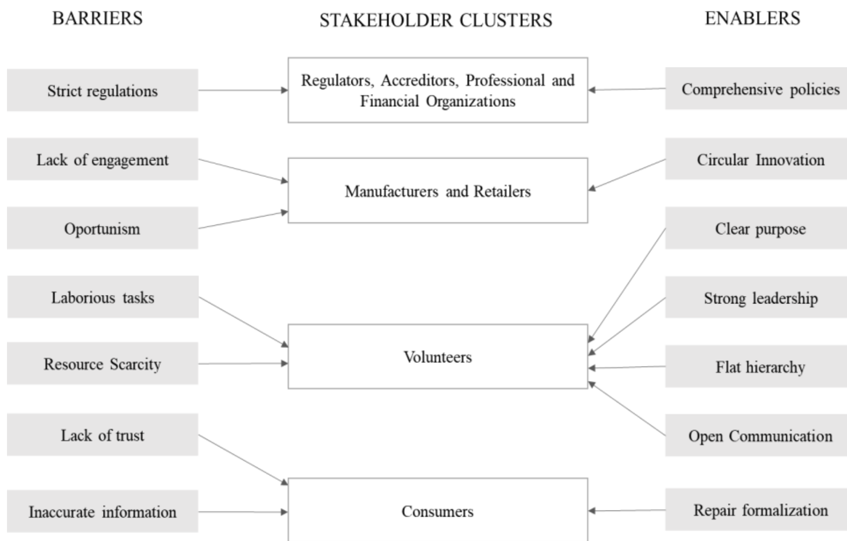

Figure 5*- Barriers and enablers to repairing ventilators in Brazil*

Health regulators and other organisations needed to change their attitude towards ventilator repair, which could even be considered illegal, before updating regulations. These updates in regulations advanced the consolidation of the "right to repair" [40] and represented an autonomy gain for the public health system over the ventilator supply chain, in other words, more control over the national stock and the strategies that maintain it operational. As a result, after the changes brought by the pandemic, the Brazilian health system has a legal structure and accumulated technical knowledge on ventilator repair to host comprehensive repair policies and continuous equipment care programs.

Meanwhile, some manufacturers and retailers perceived the repair initiative as a threat to their business, and proceeded to report non-medical companies' repairing activities to the authorities, thereby hampering access to manuals and passwords, and raising the prices for ventilator parts. In an extreme case, one company filed a lawsuit against the initiative questioning the legitimacy of their handling of medical products. For manufacturers and retailers, a possibility would be to design ventilators according to circular innovation that incorporate extended equipment life.

Volunteers needed to perform laborious tasks such as contacting hospitals to ascertain the demand and faced a scarcity of ventilator parts and calibrating professionals. However, some factors enabled volunteer participation: a clear purpose, strong leadership, and a flat hierarchy that fostered communication and ownership.

On the Consumer side, the lack of trust made some hospitals doubt their ventilators would be returned, while the number of defective ventilators was often inconsistent with data available on the health system's databases. Those same hospitals would greatly benefit from a unified and formalised repair program such as the one carried out by the Public Universities Hospital's Association, transcending the pandemic emergency, and moving into continuous equipment care.

FINAL CONSIDERATIONS

First and foremost, the results emphasise the value of medical devices as an indispensable part of the health system during a public health emergency. Our evidence shows how repair affects the health system resilience that depended on regional disparities. Those disparities, in turn, affected the access to ventilators and repair services, consequently impacting local health system resilience. Countering those systemic deficiencies, the + Ventilator initiative gathered leading public and private stakeholders to boost ventilator repair in Brazil.

The initiative studied is an excellent example of a successful public-private partnership that expanded ventilator supplies, optimised resources, and updated legal requirements. In addition, all volunteers saw indirect benefits for their businesses from the increased autonomy gain of the Brazilian health system, which would mitigate the economic impact of the pandemic. Ultimately, the repair also pushed the health system's sustainability agenda beyond waste management and towards a circular economy to extract the most value from the system's available resources.

Contrary to the positive results of the initiative, repairing so many ventilators was only possible because of the accumulation of damaged ventilators in health facilities in the first place. Such a scenario implies that pre-pandemic repair

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and maintenance policies were insufficient to ensure full access to ventilators once part of the stock became inoperable. Thus, the insufficiency of medical equipment repair policies deserves a more thorough examination of the long-term impacts of these public-private partnerships on the availability and quality of medical equipment and whether the partnerships led to improvements in the overall repair and maintenance of medical equipment in Brazil. Another future research path is exploring how other countries' policies can inform the design and implementation of more effective public policies on repairing medical equipment, building on the lessons from this case study to building more resilient healthcare systems.

The repair of ventilators and various other medical devices is inevitably critical to patient care, where equipment failure can have serious consequences, including patient harm or even death. Accordingly, the availability of repair services is essential to ensure the continued functionality and safety of medical devices. However, manufacturers may assert their responsibility to ensure the safety and effectiveness of medical devices by restricting access to repair information and parts. Conversely, manufacturers and authorised repair service providers had to relinquish control over ventilator repair in extreme pandemic circumstances for health systems. Therefore, there is an urge to rethink the "right to repair" in the health sector, its ethical implications and the broad view of stakeholders in the healthcare ecosystem.

All in all, COVID-19 laid to bare many of the known and unknown shortcomings of health systems around the globe. However, the pandemic was also a catalyst for a highly successful Brazilian public-private voluntary partnership that brought together key automotive industry players, industrial training centres and several other volunteers, who even in the absence of a fully supportive government, were able to repair ventilators in record time and give the country's health system means to succeed. Undoubtedly the initiative's automakers will have benefited from their vast experience in lean manufacturing principles, as evident in the sheer speed that the + Ventilator initiative came into existence, and how they valued transparency and simple tools to deliver effective and efficient solutions. Finally, one could argue that repair strategies should be part of any developing country healthcare agenda not just for the sake of planning and responding to health emergencies, but also fostering cross-industry collaboration and exploring opportunities for growth and economic development with resilience and sustainability in mind.

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