Brazilian Frugal Ventilators to Tackle COVID-19

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Abstract

The COVID-19 pandemic caused immediate overburden to healthcare systems and initiated a race in search for means to prevent and treat the disease. Among the disruptions caused by the COVID-19 are the lack of equipment and technologies to attend all patients, especially in resource-constrained contexts of emerging and developing countries. Fast and frugal innovations were developed, especially for attending regions where the healthcare system was in critical condition. This paper analyses the case of the ventilator called INSPIRE, designed to tackle COVID-19 in Brazil. It was built utilizing the frugal innovations perspective and the narrative of one of the participant institutions (Federal Institute of Sao Paulo – IFSP). The following dimensions of frugal innovations: affordability, adaptability, accessibility, value proposition and sustainability. To conclude, a comparison is made with other initiatives across the country which revealed that although the development teams had not previous knowledge about frugal innovation, the projects helped creating a collaborative network of different institutions aiming to reach the same goal. Now that these networks are in place and advancing to develop other innovative products, there is a need to establish a framework for developing frugal innovations.

Keywords
COVID-19, Pulmonary Ventilator, Frugal innovation

1. Introduction
The COVID-19 pandemic along with its exponential outbreak brought, as primary consequence, a great pressure to the public and private healthcare systems, overloading the first care units and Intensive Care Units (ICUs) in many

hospitals. The most needed item was the pulmonary ventilator (Moreira 2020). According to the Brazilian Ministry of Health, 10 ICUs are needed per 100,000 inhabitants and one ventilator for every two beds in all ICUs (Resolucao 7 2010). Based on this Resolution, approximately 22,000 ventilators in total were needed according to the number of ICUs at the beginning of the pandemic (Palamin and Marson 2020). Although having over 61,000 pulmonary ventilators available before the pandemic (Braun 2020), that number was not enough to meet the demand because of the non-uniform distribution along the Brazilian territory (Figure 1). Besides that, at the peak of the pandemic, there were 1,750,540 active cases. It is estimated that 1 in every 30 cases of COVID-19 needed to be intubated, based on numbers from Ministerio da Saude (2022). That translates to more than 58,000 patients needing pulmonary ventilation. Due to the vast dimension of the Brazilian territory, in most of the situations, patients had a limited access to the treatment site. Anticipating this demand, the team lead by the Polytechnic School of University of Sao Paulo, along with the Federal Institute of Sao Paulo and the Brazilian Navy, developed, manufactured, and donated 1,000 pulmonary INSPIRE ventilators (Figure 2) to 200 hospitals across the country. These hospitals, operated under the United Healthcare System (SUS in its acronym in Portuguese), is the Brazilian universal healthcare and offers free assistance to the population.

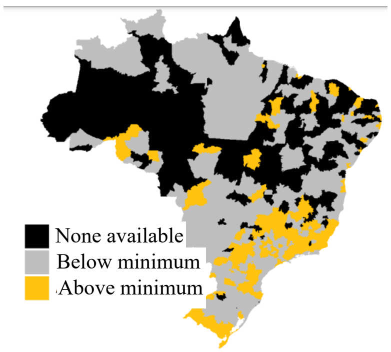


Figure 1: ICUs per region – reference: 10 per 100,000 inhabitants
Source: Rache et al 2002

Figure 2: Inspire pulmonary ventilator Inspire version 1.0 model C (October 2021)
Source: https://www.poli.usp.br/inspire

1.1 Objectives

The objective is to present a specific frugal innovation case study, the INSPIRE pulmonary ventilator, developed by the University of Sao Paulo (USP), the Federal Institute of Sao Paulo (IFSP) and the Brazilian Navy. This paper is divided in two sections: 1 – detailed analysis of the INSPIRE ventilator under the frugal innovation perspective and value proposition; 2 - comparison with other initiatives for solving the lack of ventilators around the country.

2. Literature Review

The COVID-19 pandemic that has been afflicting the world since December 31st, 2019, was first diagnosed in Wuhan - China. It was identified as caused by a new type of virus, poorly known, with a high rate of contagion that caught the attention of the World Health Organization (WHO) in the following month. In a few weeks, the organization issued guidelines to monitoring and testing suspected cases (Barreto 2020).

By March 2020, there were queues of patients waiting for hospitalization, new cases growing every day and, simultaneously, the economy stopped due to the need for social isolation to contain the virus (Paiva 2020).
In such context, government and private institutions began to look for solutions to overcome the lack of resources using low cost and widely available components. When we think about innovation, it leads us to something complex and that uses technologies that are both expensive and difficult to access (Metah 2020). However, to make products and services more accessible and focused on the basic needs of the population, innovations to attend the needs of resource-constrained localities tend to intensify at a time like this (Metah 2020). Thus, those innovations, in particular frugal innovations, are considered as the preferred way to deal with the effects of the pandemic due to its low impact on resources and environment (Herstatt and Tiwari 2020).

Frugal innovation is characterized by offering solutions with greater accessibility, lower cost, focused on core functionalities, and ensuring a performance above the market average (Weyrauch and Herstatt 2016). Thus, frugal innovation grants greater accessibility to products and services. However, the idea of accessibility needs to be defined in a more holistic way, considering not only financial aspects, but also social aspects, the infrastructure and sustainability. It is noticeable the tendency that the post-pandemic world starts to worry about the development of products and services more comprehensively (Herstatt and Tiwari 2020).

The concept of frugal innovation can be described as a series of principles used to deal with resource-constraint situations and it is seeing as business opportunities (Santos, Borini and Oliveira 2020). In general, such perspective is associated with emerging economies, with a large share of consumers at the base of the pyramid (low-income), who generally have a series of unattended needs.

Some authors, however, see frugality not only as a type of innovation, but as an approach or a mindset (Koerich and Cancellier 2019). It is a way of thinking that started focusing on India and China, since those countries have markets with extremely specific needs. Defined as "moderate use of resources", it involves a process of redesigning products, services, or systems with the objective of cutting significant cost without sacrificing the value in their target market (Santos, Borini and Oliveira 2020).

Sometimes, there is a sort of a negative connotation in frugal innovation about it being a simplistic process that involves a lower degree of formal innovation and a lot of originality (Koerich and Cancellier 2019). The Indian term "Jugaad", which means "the art of overcoming severe restrictions by improvising an effective solution using limited resources" (Radjou and Prabhu 2015), is considered the precedent of the term "frugal". From this perspective, frugal innovation means using creativity and improvisation in the process of creating something new or more efficient by using less resources (Santos, Borini and Oliveira 2020). Other definitions, such as from Koerich and Cancellier (2019), states that frugal innovation is the capacity of doing more with less, in other words, creating more commercial and social value with less resources.

Zeschky argues that there are three types of innovations: cost, good-enough and frugal innovations. Figure 3 depicts the relationship between the three types. Cost innovations are the simplest one, based only on operational cost reduction. Good-enough innovations add the removal of non-essential product features. Frugal innovations are achieved only after passing through the cost and good-enough stages, where in addition to the points already mentioned, it applies technological innovations, bringing down costs with excellent levels of quality and usability (Zeschky 2014).

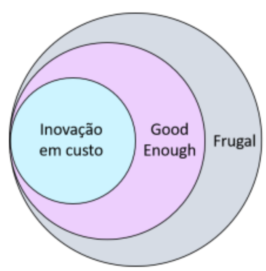


Figure 3: Relationship between the three types of innovation
Source: Gregorio (2021) based on Zeschky (2014)

Bhatti et al. (2018), define frugal innovation as "means and ends to do more with less for many" and defines three core characteristics: affordability (low cost), adaptability (out-perform, as good, or good enough under the context) and accessibility (scalable). These dimensions are illustrated in Figure 4.

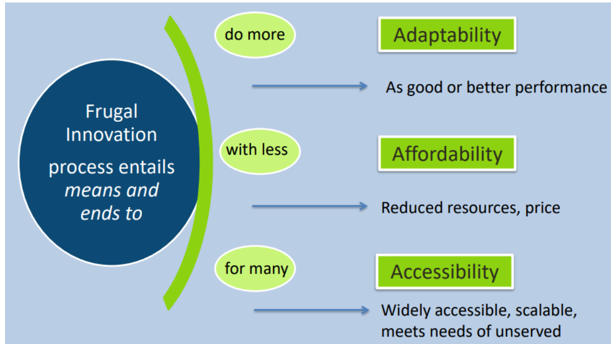


Figure 4: Frugal innovation dimensions
Source: Bhatti et al (2018)

The latter definition by Bhatti et al was used in this work to compare different frugal innovation approaches.

3. Methods

A qualitative methodology was used for the case studies since the information gathered about the ventilators are not standardized and most of them comes from different sources for each case, such as: official websites, news agencies, scientific databases, and interviews. The information was categorized and analyzed according to the context.

The analysis of the pulmonary ventilators was conducted using Bhatti et al (2018) definition of frugal innovation. Added to that, the value proposition of each initiative in terms of economic, social, and environmental dimensions has been evaluated.

For the interviews, the authors sent a standard questionnaire to the management staff of the development teams but not all responded. In those cases, the authors had to rely on other sources of information such as official websites and news agencies articles.

4. Data Collection

4.1. The INSPIRE ventilator

Among the various projects developed, the one with the greatest repercussion, and which will be analyzed in depth, is the INSPIRE, a mechanical respirator developed by a team of engineers at the Polytechnic School of University of Sao Paulo. A summary of the project was described by Ota (2021), who was member of the training staff along with Professor Raul Gonzalez (project coordinator).

Among its many advantages, compared to conventional ventilators, are the low cost of production, as it was made mostly with locally sourced components, minimizing the dependency on imported material parts (Jornal da USP 2020).

Starting its development in March 2020, a month later the project had already been approved in its final stages of tests, tried out in four patients at the Heart Institute (Incor Hospital, Sao Paulo, Brazil). It was funded by donations, which reached a total amount of R$ 7 million (seven million Brazilian Reais, about 1,3 million US dollars), coming from companies and more than 800 individuals within the USP Vida program and Amigos da Poli Association (Jornal da USP 2020).

The production started after the Federal Health Surveillance Agency (ANVISA) granted its certification in October 2020 and ended in December 2021 with 1,000 units built. The 1,000th unity is currently displayed at the University of Sao Paulo – Figure 5.

Figure 5: INSPIRE unit 1,000, displayed at the University of Sao Paulo. Source: the authors

4.2 Other ventilators initiatives in Brazil

4.2.1 – AMBU (Artificial Manual Breathing Unit)-based respirators

Vent19 – by the Polytechnic School of the University of Sao Paulo, was one of several initiatives to develop artificial respirators started by using Open-source development platform like ARDUINO, windshield wiper motor and an AMBU (Tsuzuki et al. 2020) - Figure 6.

(a) – early version (b) finished prototype

Figure 6: Poli Mecatronica – Vent19 Ventilator
Source: https://www.poli.usp.br/noticias/25867-grupo-da-poli-desenvolve-ventilador-mecanico-de-emergencia-para-enfrentar-coronavirus.html. Accessed on May 30, 2022.

Technology Park of Sorocaba - Other initiative also using ARDUINO and AMBU was sponsored by the Technology Park of Sorocaba in partnership with the Federal Institute of Sao Paulo – Sorocaba Campus and the startup Pi Project - Figure 7.

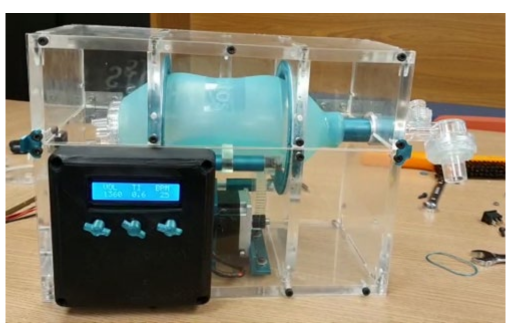


Figure 7: Ventilator built at the Technology Park of Sorocaba
Source: https://parquetecsorocaba.com.br/blog/startup-do-parque-tecnologico-desenvolve-respiradores-para-tratamento-do-coronavirus Accessed on May 30, 2022.

4.2.2 – Flow-Control Valve Ventilator

FATEC Tatui – FATEC is the technical college in the city of Tatui, Sao Paulo. Industrial Automation students developed a ventilator in less than 4 months using hydraulic valves – Figure 8.

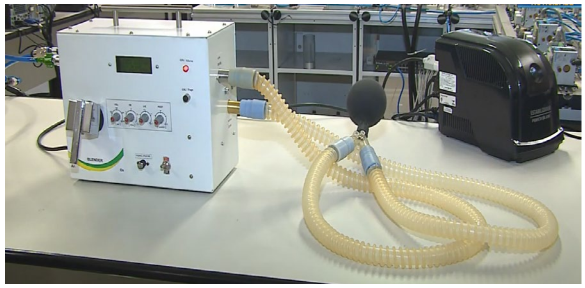


Figure 8: FATEC Tatui Emergency Ventilator
Source: https://tvsorocaba.com.br/ventiladores-pulmonares-desenvolvidos-em-tatui/ Accessed on May 30, 2022.

4.2.3 – ANVISA registered ventilators

OxyMag by the company Magnamed: supported by the Ministry of Science, Technology and Innovation, this ventilator was manufactured in Sorocaba during the pandemic, in May/2020. A total of 7,000 units were produced and it is available commercially – Figure 9.

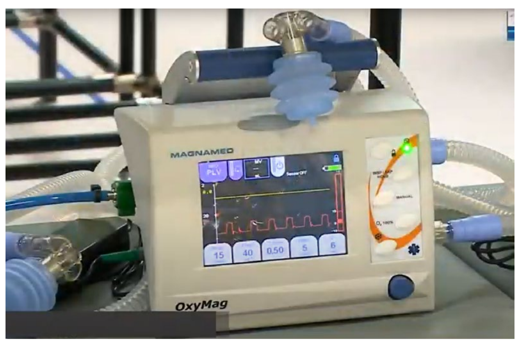


Figure 9: OxyMag
Source: https://tvsorocaba.com.br/ministro-da-ciencia-e-tecnologia-visita-fabrica-que-produz-respiradores-pra-todo-o-pais/ Accessed on May 30, 2022.

SENAI - Remanufacturing of ventilators by the National Service of Industrial Learning (SENAI) of the National Industry Confederation (CNI). A voluntary network program funded by Petrobras, the oil and gas company, and executed by SENAI and CNI, technical school and industry association. 500 ventilators were remanufactured – Figure 10.

Figure 10: SENAI remanufacturing program
Source: https://clickpetroleoegas.com.br/petrobras-doa-1-milhao-de-reais-e-ajuda-senai-na-recuperacao-de-ventiladores-pulmonares/ Accessed on May 30, 2022

Hortron by the Hortron company, which specializes in medical equipment. The total development cycle was extremely fast, 70 to 80 days from the start until getting the ANVISA registration – Figure 11.

Figure 11: Hortron ventilator

Source: https://hortron.com.br/pt/produtos?catid=5&productid=26 Accessed on May 30, 2022.

Frank5010, an emergency ventilator for COVID-19 developed by volunteer engineers at the University of Caxias do Sul, under the coordination of the Science, Technology, and Innovation Park – Figure 12.

Figure 12: Frank 5010 ventilator
Source: https://www.frank5010.com.br/ Accessed on May 30, 2022.

5. Results and Discussion

5.1 Frugal innovation - INSPIRE

5.1.1 – Affordability

During the development of the system requirements, in March 2020, there was a shortage of imported components, mainly valves, sensors and actuators of pressure and flow. Therefore, the main requirement was to either remove or replace the usual component by alternative or repurposed ones. This helped to solve the supply issue and to lower the final cost of the product. Also, the use of 3D printed, and laser cut parts helped to reduce logistics and material costs. The final material cost was around 1,000 USD (Jornal de Boas Noticias 2020) as opposed to 15,000 USD sale price of a commercial ventilator[1].

5.1.2 – Adaptability

The INSPIRE is an AMBU-based ventilator that does not require compressed air for normal operation, only an oxygen cylinder. This characteristic makes it suitable for emergency use and transportation of patients inside or outside a hospital. Another important feature of this ventilator is the user-friendly human interface that makes it easier to setup parameters and train the operators.

The infrastructure for manufacturing the INSPIRE is very simple, just a workbench, test and calibration equipment and oxygen cylinders and it can be setup in a very small area. The actual manufacturing site, at CTMSP (Brazilian

[1] The correct currency is USD, not BRL as publicized by the media.

Navy's Technological Center), occupies less than 100 square meters, and 10 operators were able to build 10 units per day.

The ventilator can be built with off the shelf components, custom 3D and laser cut parts and specifically designed components locally supplied. Figure 14 shows the block diagram and the unique parts of INSPIRE ventilator and the technical specs in Table 1. Unique parts are highlighted in red, which are:

1. O2 Sensor
2. Solenoid Valve
3. Motor Driver
4. Computing Processing Unity - CPU Board
5. Peep Valve
6. Unidirectional Valve
7. Pressure Sensor

The two pressure sensors, **items 1 and 7** that measure the O2 input and the patient's lung pressure, are off-the-shelf electronic parts, widely available. These components were repurposed to be used in medical application.

Item 2, the Solenoid Valve is based on a commercial item, repurposed to work in higher pressures. Modifications to the internal mechanism made it more robust and reliable to work in a pulmonary ventilator.

Item 3, the stepper motor driver, had its heat sink redesigned to be mounted inside the ventilator.

The CPU Board, **item 4**, was designed and manufactured by the Technology Integrated Systems Laboratory (LSI-TEC) at the University of Sao Paulo, responsible for the INSPIRE project. It embeds a Labrador© board, which is a 32-bit quad core ARM processor, running a Linux distribution open-source software, called Debian. It has Wi-Fi, Bluetooth and LoRa connectivity that turns the INSPIRE ventilator into a IoT device. The board allows the ventilator parameters and data to be monitored via a mobile phone or a computer connected on the internet.

Item 5, the Positive End Expiration Pressure (PEEP) Valve has its actuator derived from an automotive part, repurposed to control the patient's PEEP by setting the valve's spring pressure.

Item 6, the Unidirectional Valve, has a special designed component, called diverter, mounted over the valve, to collect the expiration air from the patient and direct it to the Heat and Moisture Exchanger (HME) filter and then to the PEEP Valve – Figure 13.

Figure 13: Diverter mounted over the unidirectional valve
Source: Inspire User's Manual

Table 1: INSPIRE technical specifications
Source: INSPIRE User's Manual

Operating Modes	PCV (pressure-controlled ventilation), PSV (pressure support ventilation), VCV (volume control ventilation) and PCV assisted mode
Maximum pressure	55 cmH2O
Maximum delta pressure	50 cmH2O
Maximum PEEP pressure	20 cmH2O
Maximum volume	1,200 ml
Maximum breathing rate	40 BPM
FiO2 (fraction of inspired oxygen)	21% to 100%
Inspiration time	600 to 1,200 ms

Trigger sensitivity (assisted mode)	1 to 10 cmH2O
Minimum ventilation time with battery only	2 hours

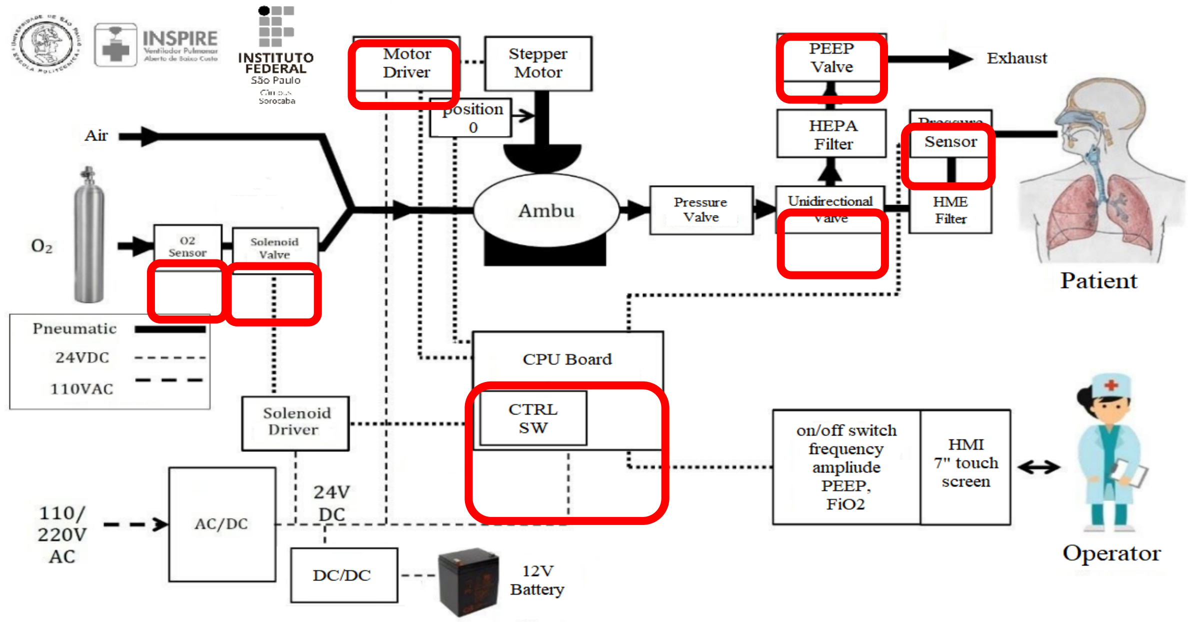
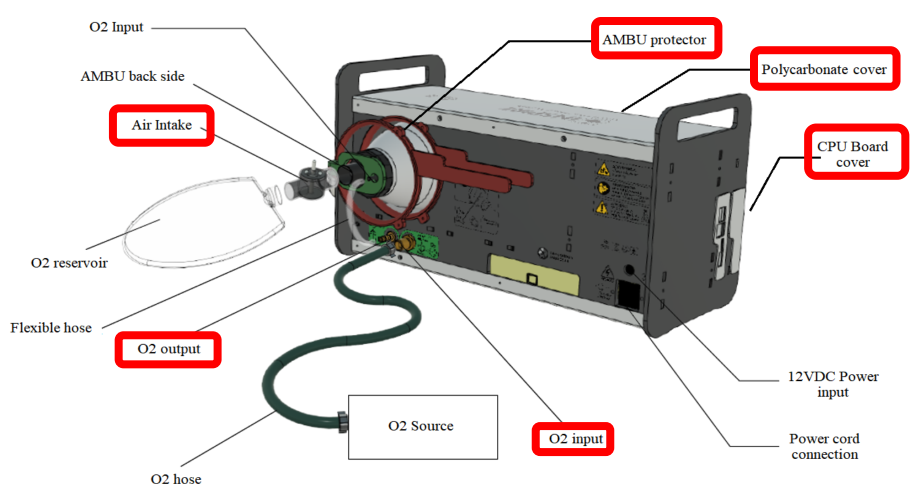


Figure 14: INSPIRE Ventilator block diagram – Unique parts are highlighted in red
Source: INSPIRE User's Manual

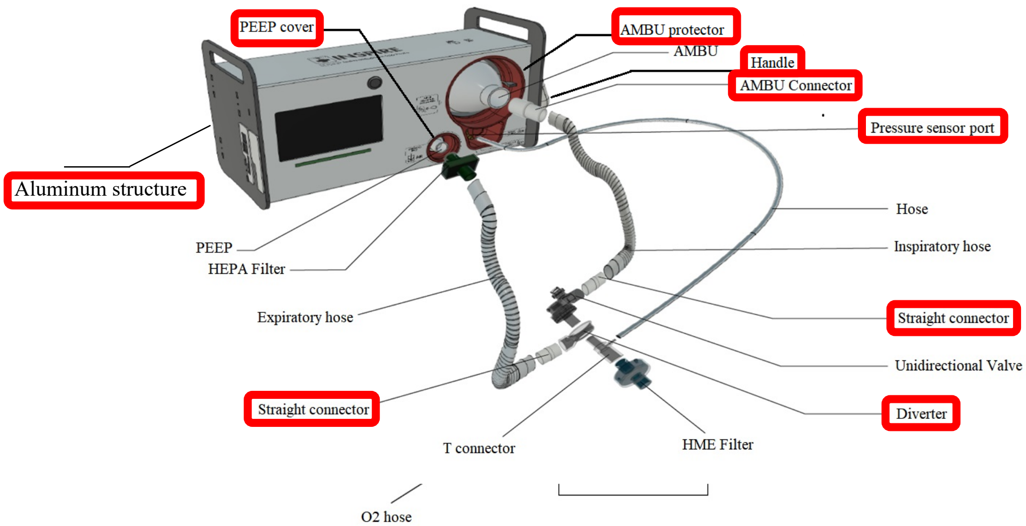
Figures 15a and 15b show the front and back view of the ventilator. In these pictures the special designed parts are highlighted. The parts are:

Figure 15a:
1. Bronze O2 output connector.
2. Air intake blocking disc.
3. Back side AMBU Protector.
4. Polycarbonate Cover.
5. CPU Board Cover.
6. Bronze O2 input connector.

Figure 15b:
7. PEEP Cover.
8. Front side AMBU Protector.
9. Handle.
10. AMBU Connector.
11. Bronze Pressure Sensor Port.
12. Straight Connector.
13. Diverter.
14. Straight connector.
15. Aluminum structure.



(a) – Back side of INSPIRE Ventilator



(b) – Front side of INSPIRE Ventilator
Figure 15: Special designed parts made by 3D, laser cut and lathe machines
Source: Inspire Development Documentation

Items **1, 6** and **11** were designed and made by a partner institution, SENAI. Those are bronze connectors to the O2 input and output.

Item **2** is a blocking disc used only with Moriya AMBU (the blocking disk is needed because the input valve is external to the AMBU). This is an acrylic disc that needs to be mounted inside the input valve which is shown in Figure 16. This item, along with item **4** are laser cut and made exclusively for INSPIRE.

Items **3, 5, 7, 8** and **9** are 3D printed parts made exclusively for INSPIRE.

Items **10, 12, 13** and **14** are machined by SENAI.

Item **15** is water pressure cut from a local supplier of aluminum sheets.

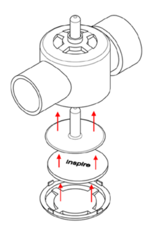


Figure 16: how to assemble the blocking disc into the input valve
Source: INSPIRE Users's manual.

5.1.3 – Accessibility

The 1,000 units built had a very important role during the critical periods of the pandemic: first, second and third waves, in March/2020, January/2021 and January/2022 respectively, in Brazil. Figure 17 shows the production and training graphs with monthly and accumulated numbers.

The State of Sao Paulo (Secretary of Development) designated the 200 hospitals across the country that received the donations, and the Brazilian Navy provided the logistics to deliver the ventilator to their destinations.

Training was provided on-site and online by three instructors. It consisted of a 2-hour session where the student had the chance to assemble the components, configure and test the equipment (Ota 2021).

Here are some feedbacks from the hospitals staff:

- Very low consumption of oxygen: 15 liters/min compared to 60 liters/min of conventional ventilator.
- Only ventilator that can be used either in ICU or transport.
- Easy to operate. Two hospitals (Quirinopolis-GO and Sorocaba-SP) received a conventional ventilator, but the staff preferred to use the INSPIRE instead, because it is easier to setup and the instruction are in Portuguese.
- Very reliable. No failures reported during ventilation.
- Small size and does not require compressed air, suitable for emergency and transport.
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Some more audio feedbacks are transcribed below:
"… I speak on behalf of Hospital Santa Lydia Foundation. We have 8 hospitals, for 4 of them have only the INSPIRE ventilator. It is the only equipment available. So, I wanted you to know... all of you, who are part of this project, how much you helped Ribeirao Preto, how many people you have helped… From the day we started, 89 patients have already used this ventilator. Do you have any idea how much you are helping us? So, I'm very happy that you gave Hospital Santa Lydia Foundation an opportunity to participate in this project with you, helping to save lives!" (Physiotherapist at Santa Lydia Hospital Foundation).

"I'm sending you this message to let you know about the ventilator and how important it is for us! Our therapist is doing NIV (Non-Invasive Ventilation) on patients, and they reach 100% saturation. It's being very good! Thank God you donated these respirators to us and it's being of a great value! Thank you very much!" (Physiotherapist, city of Pirangi)

Two hundred hospitals around the country received the INSPIRE ventilator without any charge. One hundred and thirty online and on-site 2-hour training were delivered to the hospitals.

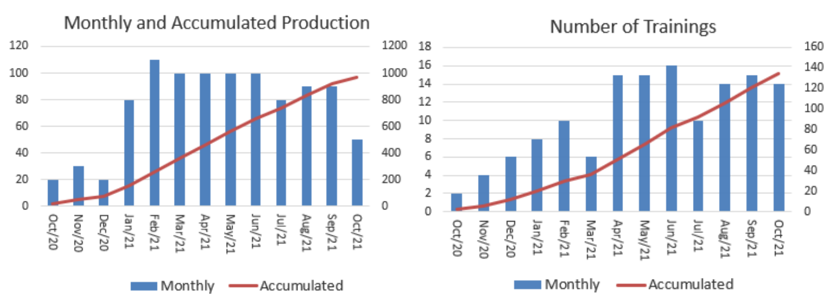

Figure 17: Production and Training numbers of INSPIRE production from October 2020 through October 2021
Source: INSPIRE Manufacturing Operation

5.1.4 – Value proposition

Economic: the cause of COVID-19 crisis in Manaus (capital of Amazonas State), in January 2021, was both the lack of ventilators and oxygen. Forty INSPIRE Ventilators were delivered to hospitals in Manaus without any cost. From that crisis the team learned another great advantage of INSPIRE: it consumes much less oxygen than a commercial ventilator. The average is 15 liters/min whereas the commercial equipment consumes 60 liters/min.

Social: the most relevant social impact is that the project helped to save lives. But also helped to create and strengthen volunteer networks and cooperation agreements among the participant institutions, such as the one signed between USP and IFSP on April 9, 2021.

Environmental: As mentioned earlier, the oxygen consumption is a very important environmental aspect of the INSPIRE ventilator. Another aspect is that as some of the units in the field are approaching the end of life, the hospitals are shipping the used ventilators back to the LSITEC laboratory at USP. There is a program under development in which the returned units will be recycled and either remanufactured and sent back to hospitals or disassembled and the parts sent to recycling facilities.

5.2 – Frugal innovation – other initiatives

All ventilators' initiatives started with the emergency caused by the pandemic, and they all suffered from the lack of important components such as valves, sensors and actuators of pressure and flow.
In common, they used a network of volunteers, open-source hardware and software tools and produced results in a very short period of time.

The adaptations vary from windshield wiper motor to power the AMBU to mixer valves used in bathroom sink faucet and showers. However, those simplest versions of ventilator were not able to receive ANVISA registration.

5.2.1 – Affordability

The ventilators with ANVISA registration listed in section 4 were all commercial, so the authors did not have access to the sales prices.

5.2.2 – Adaptability

Hortron developed their own FiO2 (fraction of inspired oxygen) sensor and proportional valves to deal with the component's shortage.

5.2.3 – Accessibility

According to the news report, Oxymed ran a single batch of 7,000 units in 2020; SENAI a total of 500 units (at the time when the news was released); Hortron increased sales in 30% and about Frank 5010 we found no information.
Based on Hortron's interview, the ventilator demand by the end of 2020 was low.

5.2.4 – Value proposition

Economic: the surplus of ventilators from those initiatives will certainly cause ventilators prices to drop.
Social: the volunteer network was the most common practice for the ventilators development and shown in most of the news report.
Environmental: unfortunately, we gather no information regarding the environmental aspect of their business.

6. Conclusion

Frugal innovation during the pandemic happened without planning and without methodology. The interviewees had not previous knowledge about the theme. The COVID-19 emergency helped creating a collaborative network of different institutions aiming to reach the same goal. Although these developments were, in concept, frugal innovations, now that these networks are in place and advancing new forms of collaboration and developing more innovative products, there is a need to establish a framework for developing frugal innovations under societal pressure. This will foster the development of adaptable, affordable, accessible solutions using less resources, building a more inclusive, secure, and sustainable future.

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