Exaptive innovation in constraint-based environments: lessons from COVID-19 crisis

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Received 20 July 2021
Revised 5 November 2021
23 December 2021
Accepted 10 January 2022

Abstract

Purpose – This paper explores how exaptive innovation process might be considered a useful innovation model in constraint-based environments. Through an in-depth case study, it illustrates clearly the antecedents of exaptation processes, which are particularly relevant in rapidly changing environments requiring new solutions under time and resource constraints.

Design/methodology/approach – The authors adopt a single case study approach that is particularly suitable in case of an inductive research design, which is required because of the novelty of the topic. The research is inspired by the use of the snorkeling mask EASYBREATH, commercialized by the giant Decathlon, as a medical device, a respirator to treat patients affected by coronavirus in Italy. The authors organized the evidence according to a novel taxonomy grounded in the literature.

Findings – The case study stimulates reflections on the existence of some antecedents to the exaptive innovation process in constraint-based environments: (1) the availability of specific actors in the innovation process; (2) the creation of platforms of interaction between people with different competences, nurtured by collective bottom-up financing systems; (3) the role of the community of makers, in particular, and of the 4th industrial revolution, in general, for creating enabling technologies; (4) multidisciplinary individual background of key actors in the innovation process is crucial to ensure the exaptive path to be in place.

Research limitations/implications – This work has some limitations, due to the choice of limiting the analysis to a single case, nevertheless, it offers a first glance on a new technological trajectory available in constraint-based environments.

Originality/value – The case study results underline the importance of new digital collaboration platforms as knowledge multipliers, and illuminate on the potential of the fourth manufacturing revolution, which, through new technologies, creates opportunities for distributed forms of innovation that cross long distances.

Keywords Exaptation, KIBS, Innovation, EASYBREATH, 3D-printing (3DP), Crisis

Paper type Research paper

1. Introduction

The term crisis applies to events that belong to the “un-ness” category: unexpected, undesirable, unimaginable and often unmanageable situations (Hewitt, 1983). A crisis occurs when a community of people – an organization, a town, or a nation – perceives an urgent threat to core values or life-sustaining functions, which must be dealt with under conditions of uncertainty (Rosenthal *et al.*, 2001). There are two defining conditions of crises. First, the widespread sense of *urgency*. This is what differentiates crises from serious threats, such as climate change (Boin and Hart, 2007). Crises are here and now and must be solved right on time. Second, a high degree of *uncertainty,* which pertains both to the nature and the potential consequences of the crisis.

European Journal of Innovation Management
Vol. 25 No. 6, 2022
pp. 549-566
Emerald Publishing Limited
1460-1060
DOI 10.1108/EJIM-07-2021-0348

At this moment, the world finds itself in the middle of a severe crisis, fighting against an ill-understood enemy, which is challenging every aspect of our normal daily lives. The reality of this unexpected global health emergency caused by the COVID-19 virus is reshaping everything we know about social and economic systems. Even if we are still overwhelmed with the impending widespread perception of threat and uncertainty, the world crisis, in both Chinese and Greek, indicates a critical point, a fork in the road of development: the word "crisis" implies threat but also opportunity. It is this second path that we want to cover in this paper. We want to look at the pandemic crisis as an opportunity for development. First, an opportunity to learn how crises may stimulate collective creativity in finding prompt solutions to emergent and contingent problems. Second, by deriving policy indications on how to enhance social resilience in situations of crisis and unforeseen events. Scholars have started considering future scenarios characterized by turbulence and instability; in these contexts, resilience and antifragility have become key properties of business ecosystems able to recovery after being hit by crises and natural disasters (Ramezani and Camarinha-Matos, 2020).

Even if, as already well pictured by Schumpeter in his metaphor of creative destruction, the concept of crisis is inherent in that of innovation, innovation scholars have shown little appreciation for studying the relationship between innovation and crisis. The majority of them followed the general agreement that crises are either cyclical or counter-cyclical in respect to the fluctuation in the demand. An exception is represented by Filippetti and Archibugi (2011) who attempted to explain the resilience to the 2009 financial crisis with the variety of national innovation systems approach.

In our view, crises shape a peculiar context of innovation, which is characterized by both time and resource constraints. We claim that exaptation (Gould and Vrba, 1982) is particularly suited for giving rise to constraint-based innovations (see Agarwal *et al.*, 2017 for an overview) in contexts of crisis, when it is crucial to find quick solutions without relying on the usual time-consuming research and development path, driven by long-term objectives and developing plans (Dierickx and Cool, 1989). The concept of exaptation has been recently adopted in evolutionary economics to characterize the co-option of an existing artifact to a new and emergent function. Exaptation is a term originated in biology, for indicating the process through which characters, evolved for other usages (or for no function at all), are later "co-opted" for their current role (Gould and Vrba, 1982). The typical example in evolutionary biology is feathers, which were probably selected for thermal insulation in baby dinosaurs, and were later co-opted first for camouflage, then for sexual display and finally for flight (Stettenheim, 1976). In few words, exaptation is an innovation related to the creation of a new artifact derived from alternative uses of existing technologies (for complete reviews, see Andriani and Cattani, 2016; Bonifati and Villani, 2013; Garud *et al.*, 2016; La Porta *et al.*, 2020).

Some researchers may be more familiar with the concept of bricolage (Garud and Karnøe, 2003; Senyard *et al.*, 2014), which is focused on the recombination of existing resources for innovation and overcomes the liability of newness and smallness of start-ups and SMEs. Santos *et al.* (2020) recently looked at bricolage as a firm capability to develop frugal innovation (Zeschky *et al.*, 2011, 2014) in emergent market economies. But frugal innovation must be low-cost by definition (Cadeddu *et al.*, 2019; Radjou *et al.*, 2012; Rao, 2013; Weyrauch and Herstatt, 2017; Vesci *et al.*, 2021), but it might be difficult, in time of crisis, to find solutions that are simultaneously cheap and fast. We are more inclined to embrace the perspective of Garud *et al.* (2016, p. 160) who well explained that "bricolage is a mechanism for exaptation", because, while bricolage responds to emergent issues with a quick fix that is ephemeral, exaptation is an evolutionary process that entails necessarily a long-term perspective. In our view, exaptation in time of crisis is as a constraint-based innovation, which nevertheless activates networks of resources that have the potential of surviving after crisis. Within an evolutionary approach to technology development, the time plasticity of exaptation evoked by Garud *et al.* (2016) leads us to sustain the hypothesis that, even if exaptation searches for solutions to existent (and somewhat ephemeral problems), these temporary solutions might give rise to permanent innovation structures. It is under these lenses that we propose to illustrate, with a narrative approach, the reaction to the scarcity of breathing device in hospital during the pandemic crisis in Italy.

Our research has been initially driven by the curiosity that a fact raised: the use of the snorkeling mask EASYBREATH [1], commercialized by the giant Decathlon, as a medical device, a respirator to treat patients affected by coronavirus in Italy. Ventilation, which is needed to help patients breathe when they can no longer do so on their own, is crucial to saving lives during the pandemic, as the disease attacks the lungs. The dimension of the pandemic created a shortage of these biomedical devices, encouraging a pool of Italian engineers to find a solution through the creation of retrofitted masks. The use of EASYBREATH as a medical device is a case of exaptive innovation in a constraint-based environment, which exploits as resource a potential, but not explored, function of an artifact. EASYBREATH was selected because of its analogy with the shape of the helmets traditionally used in the biomedical context to ease breathing. In order to provide patients ventilators that were unavailable in the market, EASYBREATH was adapted to the new function, paving the way for a new and emergent innovation trajectory. In light of the premises suggested by the case of EASYBREATH, we put forward the following research questions: Does exaptation fuel innovation in a constraint-based environment? And more, which are the antecedents of an exaptive innovation process in a constraint-based environment? In order to respond to these research questions, we rely on a case study methodology, with the objective of building theory from a case study (Eisenhardt, 1989).

From a theoretical point of view, this paper aims to contribute to the literature on exaptation, and in particular on exaptive forms of innovation in a constraint-based environment. More specifically, it sheds further light on the resources and competencies mobilized in turning crisis into an opportunity to innovate and enhance the resilience of firms, supply chains and communities.

In particular, the case study stimulates reflections on the existence of some antecedents of the exaptive innovation process in time of crisis: (1) the availability of specific actors in the innovation process (i.e. the knowledge-intensive business Services [KIBS]); (2) the creation of platforms of interaction between people with distant competences (i.e. crowdsourcing platforms), nurtured by collective bottom-up financing systems (i.e. crowdfunding platforms); (3) the role of the community of makers and of the 4th industrial revolution for creating enabling technologies; (4) multidisciplinary individual background of key actors in the innovation process is crucial to ensure the exaptive path to be in place.

The paper proceeds as follows. Section 2 introduces the concept of exaptation and how it was developed in relation to innovation research; Section 3 illustrates the methodology; Section 4 presents the case study; Section 5 offers a discussion; Section 6 provides some conclusive remarks.

2. Innovation through exaptation

The term exaptation was originally coined by Gould and Verba (1982). They introduce this term to name characters that are co-opted for a new use from a previous function or no apparent function at all. In the first case, from a previous function, characters were shaped by natural selection. Differently, in the second case, from no apparent function, natural selection did not play any role in shaping the co-opted characters. A popular example of exaptation is the feathers of birds, which were selected for a thermo regulating function and later co-opted to the flying function. In the second case, the relevance of exaptation is associated with phenomena like genetic drifts, which implies the accumulation of genetic code that does not play any apparent function. In both cases, irrespective, exaptation implies a discontinuity in biological lineage of species.

In the managerial literature, the term exaptation was originally introduced by the historian economist Mokyr (1990), to describe the existence of discontinuity in the evolution of technological lineages and to explain the rise of new and emergent punctuated equilibria. However, Mokyr never attempted to develop a comprehensive theory of technological exaptation. Two contributions signed a change of pace in the conceptualization of exaptation in the managerial literature. Dew *et al.* (2004) offered a comprehensive classification of technological exaptation and showed how exaptation is associated with true Knightian uncertainty, the rise of new markets and the role of entrepreneurship. Cattani (2006) conceptualized the term pre-adaptation, referring to knowledge accumulated by a company without anticipation of its future use. In his view, this might be considered as a precondition for exaptive processes to occur, which can take place in a phase in which the opportunity to reuse an existing artifact/know-how into a new and distant domain is perceived and consciously exploited and leveraged. These contributions gave rise to a fertile debate on the opportunity and relevance of the use of the term exaptation. There is now a generalized consensus on the validity of the concept for explaining technological change alongside an evolutionary view (Nelson and Winter, 1982), which acknowledges the possibility to produce radical innovation through the co-option of already existing artifacts and indeed know-how to a new function (Dew *et al.*, 2004). The concept of exaptation provides a theoretical basis that can help to address the evolution of technology (Adner and Levinthal, 2002; Andriani and Cohen, 2013; Beunza, 2007; Cattani, 2005, 2006, 2008; Dew, 2007; Dew *et al.*, 2008; Dew *et al.*, 2004; Grandori, 2007; Lane *et al.*, 2007; Levinthal, 1998; Mastrogiorgio and Gilsing, 2016; Mokyr, 1997, 2000; Ganzaroli and Pilotti, 2010; Villani *et al.*, 2007).

It can be observed that many technologies were not purposefully invented for the actual use, but they derived from a functional shift (see also Johnson, 2010). Microwave ovens started life as radar magnetrons; Edison's phonograph was born as a recording device for dictation; Internet was a military communication exchange network. These are only few examples of exaptations.

The adoption of a Gould's perspective to evolutionary trajectories of technology implicitly means considering that not all changes are deliberate, due to ad hoc investments; some of them are emergent, context-dependent and favored by serendipitous patterns. Garud *et al.* (2018) introduced the notion of distributed serendipity, which includes the possibility that others than inventors could find new uses for scientific discovery. In this work, following Sedita (2012) and Sedita and Ozeki (2021), we define exaptation as serendipitous innovation, derived from functional shift [2]. The intrinsic nature of exaptation suggests its adoption as an innovation model in times of crisis, where lack of resources and prompt response to urgent problems is needed. Nevertheless, no previous research illustrated exaptation as a possible innovation model in constraint-based environments. Therefore, our approach is novel and can be considered the first attempt to explore the preconditions of exaptive innovation process in constraint-based environments.

3. Methodology

The current study is of an exploratory nature; therefore, it was conducted using a qualitative approach, which is oriented toward investigating if exaptation can be seen as a useful innovation process in time of crisis, under time and resource constraints, and to build propositions in relation to the identification of specific factors which play a relevant role in the exaptation process. In particular, the case study research method was preferred in this inductive research, mainly because of the novelty of the topic (Eisenhardt, 1989; Ellram, 1996; Strauss and Corbin, 1998; Whetten and Cameron, 1998; Yin, 2009). Merriam (1994) and Stake

(2000) assert that the case study approach provides scholars and researchers with the opportunity to generate a deep understanding of an emergent and understudied phenomenon.

In the last 2 years several institutes, industries, universities, designs, came forward to print 3D medical components to fight the pandemic worldwide. In Sri Lanka, thanks to Dr. Lakmal Fernando, a doctor at the intensive care unit of Sri Jayawardenepura General Hospital, scuba diving masks were converted into personal protective equipment adding a viral and bacterial filter. A Barcelona-based print farm, BCN3D, produced more than 4,200 reusable face shields in just one month and reached more than 50 hospitals and health centers across Spain (BCN3D, 2021). Airwolf3D, after working with medical professionals to evaluate various protective equipment contributed toward pandemic by printing face shield, valves and other medical components (Airwolf3D, 2021). Universities such as the University of Washington, Case Western Reserve University, University of Tennessee, Swansea University, University of Hull, Czech Technical University, Brno University of Technology, Michigan State University and Penn State University are doing all they can to contribute to the national effort against the outbreak (Advincula *et al.*, 2020). Industries have used 3D printing to support efforts to respond to COVID-19 producing personal protective equipment, face shields, patient sampling swabs (i.e. Formlabs, Carbon, Stratasys, Johnson and Johnson, HP Inc., Markforged), 3D metal components (i.e.Desktop Metal), ventilator parts using selective laser sintering (SLS) of medical grade nylon (i.e. 3D Systems). Finally, many notable designs were also found from repository files such as NIH 3D Print Exchange, Grab CAD, Thingiverse and projects from Creality, Prusa, Isinnova and Materialise.

Given the relevance and urgency to find rapid solutions to the lack of medical devices in hospitals worldwide, we decided to analyze in great details a single case study, in order to profile the network of actors involved in the exaptation process that was at the very heart of the search for alternative ways to respond to the critical shortage of official and usual health care supply.

The present study is based on primary data, collected through in-depth interviews to key players, and secondary data coming from multiple sources (companies' website, newspapers articles and social media). Data collection started in March 2020; last interviews were conducted by one of the authors in mid-October 2021. The research offers a narrative of the exaptive innovation process related to the adaptation of the EASYBREATH snorkeling mask for being used as a medical device for patients affected by COVID-19 in Italy. The case of Italy is of considerable importance, Italy is among the 20 countries most affected by the pandemic in the world with respect to the number of inhabitants, and it was the first country that, after recognizing the seriousness of the health situation at the end of January, on March 9, 2020, imposed a national quarantine. Italy, therefore, was the country that pioneered measures to counteract the health emergency by COVID-19 and inspired other European countries, including France, Germany and the United Kingdom, to take action.

4. The case of the EASYBREATH snorkel mask

As already stated in the introduction, the focus of our analysis is the EASYBREATH snorkel mask, which was exapted to be used as a ventilator. A central role in the process was covered by the collaboration between Dr. Favero, a retired doctor, previously head of the department of reanimation and anesthesia of a small hospital located in Gardone Valtrompia (Brescia), and Isinnova, which is a KIBS company located in Brescia (Lombardy region), composed of a heterogeneous team of engineers, designers and communication experts that collects ideas from all types and sectors and transforms them into concrete objects (14 people). Isinnova assists companies and individuals who have an innovative idea and wish to transform it into a finished product. It also develops internal projects and provides numerous other business consulting and research and development services.

The story starts with a call from the director of the local newspaper of Brescia, who had just hung off the phone from another call with the head of a small local hospital of Chiari, in the province of Brescia, requesting permission to publish a news informing the public that the hospital had run out of Venturi valves for their respiratory helmets and open a call for the supply of Venturi valves for their ventilator systems. However, before publishing the news, the director decided to make a few phone calls to local companies specialized in rapid prototyping and 3D printing services. Isinnova was the third in her list. Cristian Fracassi, an engineer CEO and founder of Isinnova, was working on his desk when he received the phone call, and a few minutes later he was on his way to fetch the valves to be reverse engineered. As Eng. Fracassi told us, “We did not have a clue that what we had to reverse engineer was a Venturi valve with almost no error tolerance. Even a millimeter could make the difference for patients’ life”. After some preliminary measurement, he realized a first 3D-printed model with FDM (filament) technology to be validated. Isinnova named the new valve Charlotte.

Meanwhile, nearby, another story was unfolding. Dr. Renato Favero, contrary to many of his former colleagues, promptly realized that soon there will be also a shortage of ventilation masks. Dr. Favero has a peculiar background. He holds high-school diploma in electronics and worked for many years in a small hospital. Therefore, as he told us, “I have learned to do my job in economic hardship”. Lacking the budget to keep his instruments updated and having the competencies to understand how those work, Dr. Favero developed the competence and the attitude to hack his machines.

Therefore, when confronted with the shortage of ventilation masks, Dr. Favero, as usual, started to think how he could hack objects available in large supply to the function of the ventilator mask. He came up with the idea of exapting the Decathlon EASYBREATH Mask to the function of the ventilation mask. Dr. Favero, when asked how he came up with the idea of adapting the Decathlon mask to the ventilation function, cited two reasons that helped him to make the connection. First, the recent development of non-invasive ventilation (NIV) systems; as Dr. Favero suggested, he had been exposed to several ventilation masks derived from those used by airplane pilots or divers. Second, his experience with portable hyperbaric chambers for the pulmonary edema in high mountain.

Making the connection, Dr. Favero immediately realized that two adjustments were needed to adapt the Decathlon mask to the new function. The first was to invert the underlying principle making the mask work. The Decathlon mask was originally designed for keeping water outside of the mask. Therefore, it was designed to depressurize and create the vacuum within the mask. Ventilation systems work on the opposite principle. The goal is to keep a certain level of pressure within the mask to avoid alveoli from fully deflate. According to Dr. Favero, this first adaptation was easy to be handled. It was sufficient to invert the direction of the valve in the mask. As Dr. Favero stated, “even children can handle this activity if appropriately instructed to do it”. The second adaptation was, at least for Dr. Favero, more difficult to accomplish. It was necessary to design and produce a connector to plug the Decathlon mask to the ventilation system.

It is at this point that the two stories come together and the opportunity to exapt the Decathlon mask to the medical ventilation function is fully seized. The success of Isinnova in reverse engineering and 3D-printing Charlotte had already received much attention in national and international media. Eng. Fracassi recalled having done a number of interviews after the first version of Charlotte was been 3D-printed and tested. All this public coverage and exposure helped Dr. Favero to find a way to devise the second adaptation. His wife, reading the news on the local newspaper, suggested to him to call Eng. Fracassi to design and 3D-print the connector.

Eng. Fracassi told us the story of their first meeting: “Dr. Favero entered the door of our meeting room with a bag containing a Decathlon EASYBREATH mask, which was borrowed from a friend. He put the mask on the table, and he said that it could be converted into a C-PAP mask. He lectured on how the human breathing system and the ventilation system work. Then, he left the meeting room, leaving us with the mask on the meeting table and a lot of work to do." Then, the product was disassembled, studied, and modifications were evaluated, including the possibility to use the Charlotte valve. Isinnova created a prototype, which was tested on a member of the Isinnova staff directly at the Chiari Hospital, and was proven to work properly. The hospital itself was enthusiastic about the idea and decided to test the device on a patient that need it, subject to acceptance of the use of a noncertified biomedical device by means of a signed declaration. The test was successful. However, Eng. Fracassi soon realized that no one held the 3D-printing capacity to satisfy the demand for valves. The only option was to set up a globally distributed system, leveraging on the collective capacity of the 3D-printing community worldwide. Thus, he picked up the phone and explained his idea to Dr. Favero who immediately agreed to patent the idea and distribute the design of the mask and of the valves free of charge on the web. A patent application was immediately filed and the CAD files of the mask were uploaded on the Isinnova website. Then, a press conference was called to engage the 3D-printing community to start printing valves for local hospitals, which were in demand. As Eng. Fracassi suggested, the international exposure received by Isinnova for reverse engineering and 3D-printing the first version of Charlotte valve helped to give international visibility to the press conference and engage the global community in 3D-printing the valves worldwide. By doing so, healthcare facilities in difficulty could buy the Decathlon [3] mask and make arrangements with 3D-printers who could make the piece and supply it. The overall initiative was totally nonprofit.

Meanwhile, the Erasmus Hospital in Brussels was testing snorkeling masks as respirators for patients, drawing on the initiative developed in Italy. Indeed, it began working with a local medical device company to develop the masks, known as EASYBREATH, and which cover the entire face. This example gives an idea of the scalability of the exaptation process.

In a similar vein, Isinnova also promoted a crowdfunding campaign through the platform GoFundMe, for launching the project "3D EMERGENCY – ISI 3D - 4The Future", which aimed at shipping 3D-printers and materials for on-site production in developing countries (mainly Africa), where the uncertified masks could not pass the border. The idea was to create a platform to put all the project participants in contact: 3D-printers in areas where the devices are needed, already experienced makers who gave support, doctors or other people who provided their contribution. This project, initially planned for developing countries that needed breathing devices, can be seen as a first attempt to bring together 3D-printing and the community of printers, with the aim of creating useful objects, tools and, at the same time, spread a culture of innovation and, above all, help those who need it, also beyond the COVID-19 crisis. Emergency situations can rise anywhere, in developed and developing countries, and for a variety of reasons. The seminal idea of Isinnova is to be prepared and to create permanent solutions to a variety of temporary problems, perfectly aligning with the rationale behind the exaptation process, as described in the introduction.

The large demand for 3D-printing triggered another process of exaptation. That is, the co-option of an extrusion plant producing strings for musical instruments to the production of filament for the 3D-printing. This happens in Aquila Corde Armoniche, which is a small factory producing strings for musical instruments in Caldogno, in the Vicenza province (Veneto region), founded by Mimmo Peruffo. Almost overnight, the company became the only one in Italy able to produce the thread that was used by 3D printers to make the valves for diving masks, converted into respirators. "Long before the pandemic," Peruffo explained, "I had done this little "madness" of taking an extrusion plant, about 15 m long, which is used to produce the wire. It's a small machine that, however, I discovered later, had hardly anyone". Then as the emergency broke out, he read an article stating that Isinnova found the system to convert diving masks into respirators, and that a 3D printer was used to make an essential component which was a valve, for which the wire he produces was needed.

His factory at that time was closed due to the COVID-19; thus, he decided to contact a hospital in Brescia to offer his help. "I wanted to give them my thread, but they did not need it because they used another system", he said [4]. Then, the opportunity came. "I read that there was a company in Naples that produced these valves, I contacted them, and they thanked me in every way. Then my nephew, who has a small company that uses the 3D-printer, had heard that these wires were needed, and he told me that there was an Italian WhatsApp group, dedicated to the COVID-19 emergency, requesting that I produce it". During the pandemic peak, Mimmo responded promptly to the requests, from hospitals in Rome (42 kilos), Bergamo (75 kilos), and Monza (25 kilos). "The WhatsApp group coordinator told me, we cannot find the wire in Italy anymore, we have to order it from China and they will not send it to us anymore. In this moment, you are the only one in the whole country who produces it", Peruffo stated.

However, this is not the end of the story. The adapted Decathlon mask presents two major advantages compared to conventional C-PAP. First, it is more comfortable. According to Eng. Fracassi, this results from two facts. First, ventilation pipes are inserted from above rather than from the front. This allows for greater mobility and clearer sight. Second, ears are positioned outside of the helmet resulting in less noise and better hearing (even if, according to Dr. Favero, there were already C-PAPs allowing for free ears). The second advantage is that it is cheaper than conventional C-PAP. For these two reasons, as Eng. Fracassi told us, a company is presently (in 2021) working on industrializing and marketing the mask. Therefore, an impromptus solution rising from a situation of crisis and resource constraints may turn into pathbreaking innovation in the development of ventilation systems.

As it emerged from the case study, multiple actors were involved in the exaptation process, moreover, we observe an exaptation cascade (Andriani and Cohen, 2013), where one exaptation gives rise to another one, finding multiple uses for the same materials/devices/machines. A single mutation (i.e. the diving mask converted to respirator), unlocks cascading exaptations (i.e. the ukulele wire co-opted to wire for the 3D-printing of the valves). Figure 1 illustrates the exaptation process presented above.

5. Discussion

This section is dedicated to stress peculiar features of an exaptive innovation process that was triggered by the COVID-19 crisis. It is not a complete overview of all the implication of this case, but a reasoned illustration of what the authors consider as relevant issues that can

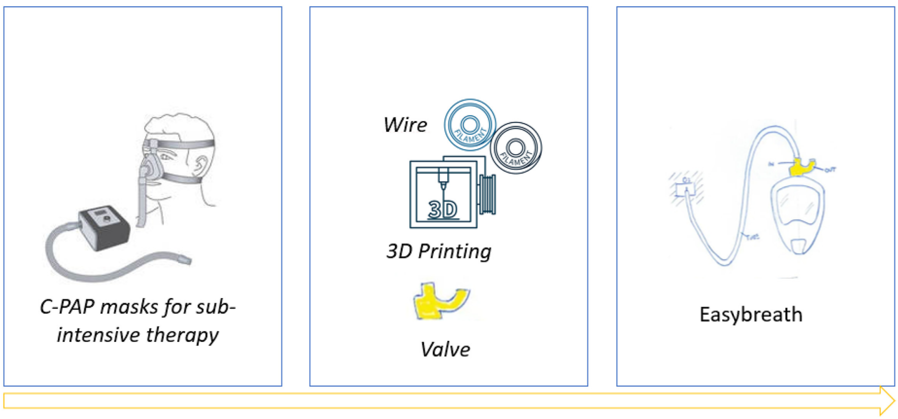

Figure 1.
The exaptation process

contribute to the present understanding of exaptive innovation models in constraint-based environments and connected enabling factors.

The case study informs of the relevance of KIBS as meta-organizers (Belussi *et al.*, 2007), able to work as serendipity arrangements (using the wording of Garud *et al.*, 2018), and creating the right connections to activate fruitful knowledge recombination between experts operating in different realms, especially at the local level. KIBS are enterprises whose primary value-added activities consist in the absorption, creation and transfer of knowledge for developing customized services (Bettencourt *et al.*, 2002; Miles, 2005). Providing services in fields such as R&D, ICT, engineering, design, marketing and professional services, they develop innovations on their own and support the innovation processes of their clients, operating as knowledge brokers (Grandinetti, 2018; Shearmur and Doloreux, 2019). Braga and Marques (2016) conducted a bibliometric analysis of literature on KIBS, analyzing 140 scientific articles with publication dates between 1994 and 2014, retrieved from ISI Web of Sciences. Their review highlights the important and often understudied role of KIBS as innovation partners for manufacturing firms, with whom they collaborate for co-producing innovative products and services (Muller and Doloreux, 2009). KIBS function as catalysts that bridge codified scientific and technical knowledge with tacit and know-how knowledge (Den Hertog, 2010; Fernandes and Ferreira, 2013), which represents an enabler for exaptation processes to take place. By connecting experts from different disciplines, KIBS create the opportunity to explore the adjacent possibilities (Kauffman, 2000), which can be associated with the concept of related variety, very popular amongst the community of scholars in the geography of innovation (Frenken *et al.*, 2007). Therefore, we can put forward our Proposition 1.

Proposition 1. KIBS are propitious for enabling localized multidisciplinary knowledge recombinations that lead to exaptations in constraint-based environments.

The case study also informs on the role of crowdsourcing and crowdfunding platforms as mechanisms to capture global knowledge input and to rapidly sustain innovative initiatives through the engagement of the crowd. In the last decades, firms increasingly resorted to crowdsourcing platforms by making open calls to unknown crowds to find different solutions (Jeppesen and Lakhani, 2010; Lüttgens *et al.*, 2014). Crowdsourced resources cover human intelligence (e.g. MTurk), ideas (e.g. Ideastorm), problem solution (e.g. Innocentive), financial resources (e.g. Kickstarter) and product deliveries (e.g. PiggyBee) (Zhu *et al.*, 2017). The use of the crowdsourcing platforms is pushed by the quick development of information and communication technologies (Zhu *et al.*, 2017, 2018; Hutter *et al.*, 2011). Social media applications allow multidirectional communication between different people (Ooms *et al.*, 2015). In this context, companies use online idea competitions to find good ideas on intermediated open innovation platforms (Bigliardi *et al.*, 2021; Corvello and Iazzolino, 2013; Frey *et al.*, 2011; Greco *et al.*, 2015) or in innovation communities hosted by the company (Jensen *et al.*, 2014; Piller and Walcher, 2006) by involving an external crowd, such as users, customers, suppliers and research partners (Blohm *et al.*, 2011; Mortara *et al.*, 2013). Crowdsourcing platforms can be also viewed as crucial elements for social innovation to take place (Randhawa *et al.*, 2019; Kohler and Chesbrough, 2019). The possibility to rely on an extended base of skills and competences, beyond geographical boundaries, is extremely important when looking for fast and novel remedies to current problems, such as in the case of a crisis.

Crowdfunding is a technique designed to raise external financing from a large constituency rather than from a small group of specialist investors (e.g. banks, business angels, venture capitalists), see Gleasure and Feller (2016) for a review. In this model, each individual provides a small amount of the total funding requested. Participation in crowdfunding initiatives is mainly linked to intrinsic more than extrinsic motivation (Zheng *et al.*, 2011), and this is particularly relevant when it comes to sustain innovations oriented to "save the world" from a pandemic. The uncertainty inherently associated with the innovation process, which could otherwise hinder the financing, is mitigated by the small amount of money required and the real possibility to benefit from the innovation (Belleflamme *et al.*, 2013).

The joint action of crowdsourcing and crowdfunding platforms, which leverage the power of the crowd, is an essential component of a toolkit for reacting to crisis in a prompt and innovative way. Together, they sustain distributed forms of knowledge exploration and exploitation, which are crucial mechanisms at the basis of exaptive processes of innovation.

Proposition 2. Crowdsourcing and crowdfunding platforms are propitious for enabling global virtuous mechanisms of idea generation and collective actions of financing exaptations in constraint-based environments.

The term 3DP (three-dimensional printing) refers to a range of additive manufacturing processes, which create products by building up layers of plastic, metal or other material, directly from digital design files (Holmström and Partanen, 2014; Petrovic *et al.*, 2011). 3DP is touted as a core element of a new industrial revolution, in which digitization, information and connectivity transform product innovation. Faced with uncertainties in both demand and technology, product innovators are advised to turn to 3DP to become flexible and agile (D'Aveni, 2015; Weller *et al.*, 2015) and join the much vaunted Industry 4.0 (Rüßmann *et al.*, 2015; Lasi *et al.*, 2014). Candi and Beltagui (2019) show how 3DP is increasingly used in many industries, and it can be effectively used in the innovation process. 3DP facilitates distributed manufacturing, since resources can be shared through digital transfer of designs for production closer to their point of use (D'Aveni, 2015). This offers clear benefits when demand is unpredictable and geographically distributed. The idea of using 3DP for fueling innovation processes exactly where needed, with the possibility to customize rapidly the output, offers a clear value when it comes to react to an unexpected demand for a specific supply, and to rapidly diffuse the solutions across locations. The makers' movement represents the ideal labor force to be used in order to deliver fast and customized solutions worldwide (Hausberg and Spaeth, 2018). Beltagui *et al.* (2020) deepen this aspect by connecting the concept of exaptation with that of innovation ecosystem. Makers are crucial components of an innovation ecosystem oriented to stimulate exaptation-driven innovations.

Proposition 3. Communities of makers sustain distributed exaptation processes for innovation in constraint-based environments.

Our case study also informs of some specific features of key actors able to trigger the exaptation process. If we look at the profile of Dr. Favero, we can notice that he is a very eclectic person, with a multidisciplinary background, and also a clear ability to work under budget constraints. According to Mastrogiorgio and Gilsing (2016), technological exaptation requires inventors with analogical ability that is the capacity of linking knowledge from different domains. They describe this ability as a function of the inventors' prior knowledge stock in these domains. Dr. Favero embodies this analogical ability, which helps him navigate through his stock of knowledge coming from different domains. This characteristic of the exaptation agent also aligns with theory of creative and lateral thinking (De Bono, 1971), with the profile of the Pasteur scientist (Stokes, 1997; Baba *et al.*, 2009), and with theories of exploration of the adjacent possible (Kauffman, 2000). A parallel case can be found in Sedita and Ozeki (2021), where the exaptation of the kimono culture through digitalization was possible thanks to the ability of a computer graphic designer, raised in a family of kimono craftsmen. Therefore, we can put forward our Proposition 4.

Proposition. 4 Exaptation is driven by prepared minds. In other words, multidisciplinary individual background of actors involved in the exaptation process is crucial for making things happen.

Exaptation is a form of context-driven or user-led innovation. It shows how radical innovation is not always outcomes of significant and largely discontinuous advancement in the technology (Li *et al.*, 2018). On the contrary, radical creativity and innovation may be triggered off by insignificant technological advancement breaching across technological boundaries. It is the omen of a possible analogy between two evolutionary domains of use, but which were grown separately, which triggers the creative flow and the exchange of knowledge between different contexts and builds the condition for the springing out of radically new evolutionary niches.

6. Conclusive remarks

This work aimed at providing hints for further reflection on innovation in constraint-based environments. In particular, we focus on an innovation process led by the re-use of existing resources through exaptation during a pandemic crisis. Through an in depth case study, it illustrates clearly the antecedents of exaptation processes in constraint-based environments, which are usually rapidly changing environments requiring new solutions under time and resource constrains.

As suggested by Beunza (2007) exaptation processes are often driven by serendipity, which is nevertheless not simply related to pure chance, but is fueled by specific contextual factors, which can be connected to what Callon (1998) labeled as a "socio-technical network", composed of people, artifacts, models, relations and connections. In time of crisis, this fluid system of relationships is emergent in nature and responds to specific solicitations that shape the way ties are built.

This new perspective on innovation highlights the importance, at the local level, of specific actors, such as KIBS, which work as knowledge brokers and exaptation process enablers. According to Huber *et al.* (2020), the use of external assets can help SMEs overcome resource and capability constraints (Eftekhari and Bogers, 2015; Henttonen and Lehtimäki, 2017), manage the liability of smallness (Colombo *et al.*, 2012), increase revenue growth (Chesbrough and Crowther, 2006) and innovation performance (Apa *et al.*, 2021). Despite this, research by Lee *et al.* (2015) has suggested that open data use, as part of open innovation and open-source mechanisms, has so far been unsuccessful in meeting its full potential, with organizations failing to commercialize open data into new digital products and/or services. Accordingly, the case study underlines the importance of new digital collaboration platforms as knowledge multipliers, and it illuminates on the potential of the fourth manufacturing revolution, which, through new technologies, creates opportunities for distributed forms of innovation that span across distances (Urbinati *et al.*, 2018). Our findings align with what already discussed by Brennan and Dooley (2005), who developed a framework for networked creativity, according to which organizations need to shape the right infrastructure to embrace a culture of sustainable and systemic innovation, oriented to increase the quantity and quality of ideas and solutions available as potential innovations.

However, this perspective imposes the need for reconsidering the role of intellectual property rights in stimulating collective innovation (Von Hippel and Von Krog, 2006). This institution is founded on the idea that innovation is the result of a substantial technological effort concentrated on a few large research centers, which hold the capacity and critical mass of resources and competencies required to produce breakthrough innovation (Lessig, 2008). Therefore, granting intellectual property rights should allow (large) companies to profit from the capital invested in this important endeavor.

Exaptation tells us a different story. Breakthrough and radical innovations may emerge from a large and distributed network of serendipitous and non-adaptive connections (Garud *et al.*, 2018).

They are serendipitous because largely unplanned but driven by the capacity to find a different explanation for something that is not expected. Also, they are nonadaptive because not driven by a function (Andriani and Carignani, 2014), but by the possibility of hacking an existing function already embodied in a technology to solve a contingent problem, at a given point in time. In this framework, intellectual property rights are more a blockage point than an incentive (Von Hippel and Von Krog, 2006; De Noni *et al.*, 2013). They limit *ex ante* the free circulation and sharing of knowledge across largely distributed network of makers/hackers. If something can be learned from this pandemic crisis, it is that large productivity gain can be achieved through the continuous and rapid prototyping of solutions and sharing of the feedback data. Even web giants like Google and Facebook decided to provide "free access" to their big data spurring alternative uses of their data, on which they could potentially build new areas of business [5].

Last, but not least, exaptation is driven by prepared minds. Multidisciplinary and interdomain skills are fundamental prerequisites to activate exaptation processes. Therefore, we expect to find a fertile ground for exaptation whenever an exaptation ecosystem is in place, where favoring multidisciplinary training and education stimulates individual creativity.

This work has some limitations, due to the choice of restricting the analysis to a single case; nevertheless, it offers a first glance on a new technological trajectory available in constraint-based environments. This research, in fact, offers an in-depth view on how exaptation might be a complementary innovation model whenever fast and constraint-based solutions are required in a context of high uncertainty. What we observed as working well in the case of the COVID-19 crisis could be replicated in other situations characterized by high instability in the social and economic system coupled with high need of novel solutions.

Notes

1. EASYBREATH is a registered trademark of Decathlon.
2. We embrace here the etiological definition of function, aligning with Andriani and Carignani (2014). Exaptation implies technological continuity but functional discontinuity. It is therefore important to solve the ambiguity derived from adopting an ill-defined concept of function.
3. Decathlon supplied the majority of masks for free.
4. Transcript of the interview with Mimmo Peruffo available here: https://www.adnkronos.com/coronavirus-storia-di-mimmo-le-mie-corde-di-chitarra-ora-servono-a-respiratori-di-tutta-italia_65zCITCy7MjBYzC6zHHxSD#
5. See, for instance, Facebook Data for Good (https://dataforgood.fb.com/) for an account of the emerging uses of Facebook data driven by the COVID-19 crisis.

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