Journal of Open Innovation: Technology, Market, and Complexity

MDPI

Article

Open Innovation in Times of Crisis: An Overview of the Healthcare Sector in Response to the COVID-19 Pandemic

Zheng Liu [1,2,*], Yongjiang Shi [3] and Bo Yang [4]

[1] Cardiff School of Management, Cardiff Metropolitan University, Cardiff CF5 2YB, UK
[2] Centre for Innovation and Development, Nanjing University of Science and Technology, Nanjing 210094, China
[3] Department of Engineering, University of Cambridge, Cambridge CB3 0FS, UK; ys@eng.cam.ac.uk
[4] School of Social Sciences, Swansea University, Swansea SA1 8EN, UK; bo.yang@swansea.ac.uk
* Correspondence: zliu@cardiffmet.ac.uk

Abstract: The COVID-19 pandemic has caused huge and disruptive technological changes in the healthcare sector, transforming the way businesses and societies function. To respond to the global health crisis, there have been numerous innovation projects in the healthcare sector, including the fast design and manufacturing of personal protective equipment (PPE) and medical devices, and testing, treatment, and vaccine technologies. Many of these innovative activities happen beyond organizational boundaries with collaboration and open innovation. In this paper, we review the current literature on open innovation strategy during the pandemic and adopt the co-evolution view of business ecosystems to address the context of change. Based on a detailed exploration of the COVID-19-related technologies in the UK and global healthcare sectors, we identify the key emerging themes of open innovation in crisis. Further discussions are conducted in relation to each theme. Our results and analysis can help provide policy recommendations for the healthcare sector, businesses, and society to recover from the crisis.

Keywords: open innovation; ecosystem; digitalization; COVID-19

Citation: Liu, Z.; Shi, Y.; Yang, B. Open Innovation in Times of Crisis: An Overview of the Healthcare Sector in Response to the COVID-19 Pandemic. *J. Open Innov. Technol. Mark. Complex.* **2022**, *8*, 21. https://doi.org/10.3390/joitmc8010021

Received: 18 November 2021
Accepted: 12 January 2022
Published: 14 January 2022

1. Introduction and Background

Since Spring 2020, the COVID-19 pandemic has caused huge disruptions to the healthcare sector, the impacts of which are felt widely in businesses and society. The worldwide public service emergency and ensuing shutdowns of economic activity have put technological innovation at the center of debate. It has pushed business to react rapidly to challenges, such as real-time decision making and business continuity, in innovative ways [1]. To respond to this global health crisis, there have been innovative incentives in the healthcare sector to accelerate the design and production of personal protective equipment (PPE) based on 3D printing technologies and online crowdsourcing platforms. Manufacturing companies have converted part of their production line to make hand sanitizers. Medical companies have considered the re-adjustment of drugs and vaccine technologies which had been already approved for other medical use. Many of these innovative activities happen beyond organizational boundaries in an open, collaborative way. The mobilization of knowledge across organizations and industries demonstrates the feature of open innovation [2], which is defined as "*the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation, respectively. [This paradigm] assumes that firms can and should use external ideas as well as internal ideas, and internal and external paths to market, as they look to advance their technology*" [3] (p. 1). In the open innovation paradigm, organizations exchange ideas and knowledge between internal and external sources to promote innovation in the forms of new products, services, processes, and business models.

The pandemic has also dramatically changed the way organizations operate. Meanwhile, issues of social innovation and user innovation extend the context of open innovation and ecosystems by providing new products, services, or solutions which can solve social problems [4]. Additionally, with the recent technology advancement of digitalization, big data, 3D printing technology, and Internet of Things (IoT), Artificial Intelligence (AI), Virtual Reality (VR), and Augmented Reality (AR), digital and platform innovation based on the Internet becomes an emerging stream of innovation to transform business and social relationships with openness, affordances, and generativity [5].

Meanwhile, to build business resilience during this emergency, organizations should think beyond the traditional boundaries of the supply chain [6]. This phenomenon is linked to the concept of a business ecosystem, an economic community supported by a foundation of interacting organizations and individuals, where participants co-evolve their capabilities and roles and tend to align themselves with the directions set by one or more central companies [7]. With the COVID-19 disruptions and challenging situations in a global economy featured with volatility, uncertainty, complexity, and ambiguity (VUCA), such a business ecosystem can provide a context for new supply chain transformation, highlighting co-evolution, dynamics, and interactions [8,9]. The view of ecosystems can potentially be applied to open innovation with a further extension of the innovation boundaries.

The impact of COVID-19 on businesses, society, and academic research has received much attention since March 2020. In the healthcare sector, there have been studies highlighting fast and frugal innovation [10] and reverse innovation and crowdsourcing [11] with empirical evidence, while others explore innovation across broader sectors. Despite this, a limited amount of evidence is found and, in fact, how open innovation strategy can be performed in times of crisis is still a new topic [2].

Considering the above background, the key research question of this paper is "How can open innovation strategy help the healthcare sector to achieve flexibility and resilience in response to the COVID-19 crisis?" It provides an overview of the open innovation process that is pivotal in understanding the technological disruption amid the healthcare crisis. It aims to contribute to the theory of open innovation by exploring its new meanings, approaches, and connection to the business ecosystem paradigm during crisis. Also, as recent years have seen a rapid pace of globalization of financial markets and technological innovations, this implies that a severe shock, such as COVID-19 spreading throughout the globe, has raised significant challenges for the urgent research need for regulatory policies and effective governance that serve in critical and recovery times.

2. Literature Review

2.1. Open Innovation

In the traditional closed innovation model, large firms tend to conduct Research and Development (R&D) internally, getting to market first and protecting intellectual property (IP) from competitors [12]. In contrast, the concept of open innovation, i.e., generating knowledge and profiting from it through internal and external exchange and breaking organizational boundaries, has attracted wide academic research and business practices. There are three broad types of open innovation. Inbound (outside-in) open innovation activities normally include IP in-licensing, idea and start-up competition, and crowdsourcing, whereas spin-offs and corporate business incubation are examples of outbound (inside-out) activities [13]. Coupled open innovation exhibits the features of both inbound and outbound open innovation, as seen in several strategies, such as co-development, complementary partners through alliances, and joint ventures [13].

Extant studies have shown that open innovation can lead to organization performance improvement in terms of more profitability [14], better R&D performance [15], customer satisfaction [16], and product innovativeness [17]. While informal open innovation strategies include crowdsourcing, formal collaboration, and integrated approaches can take the form of joint ventures, consortia, and cross-industry alliances [18]. As an established paradigm in innovation management, the two main strands of research on open innovation focus on broadening its definitions, and a move towards a collaborative and integrative approach [19].

More recently, several studies have extended the scope of open innovation at micro and macro levels [20]. At the micro level, an ambidextrous open innovation model should concern the nature of the output in terms of products and services [21]. At the macro level, there are interactions among open innovation systems formed with small- and medium-sized enterprises' (SMEs') knowledge sharing, closed innovation system led by large firms, and social innovation system with society engagement [22]. In the long term, there is a need to integrate micro- and macro-open innovation dynamics to achieve sustainability-oriented innovation [20].

Open innovation plays a moderating role during the financial crisis [23]. Openness is the common feature of innovation in medical science through ways of sharing medical research in a machine-readable form (outside-in), sharing designs of masks and hand sanitizer (outside-in), opening up ventilator design and IP (inside-out), and converting manufacturing processes to produce scarce supplies (inside-out) [2]. User innovation and ideas come from non-conventional sources and can also contribute to the solution during a crisis [2]. It is found that crowdsourcing has helped to tackle the pandemic through engaging with healthcare providers, industries, governments, academics, and the civil community in an open and collaborative approach [24]. Through online problem solving and using an innovative sourcing model, crowdsourcing provides is low cost, rapid, and has potential to accelerate research [25]. Other studies explore the impact of COVID-19 on technologies and value chain with evidence of innovative processes aiming for business resilience [1] and how innovation policies can promote open innovation [19,26]

Nevertheless, in general, innovation in times of crisis is an under-studied topic in the stream of innovation management literature [2].

2.2. Ecosystem and Systems of Innovation

While implementing an open innovation strategy is primarily led by a focal, large firm or SMEs collectively, innovation systems and ecosystems have expanded the scale of open innovation to national and regional levels with multiple innovative actors.

At the regional level, the Triple Helix model provides the dynamic connection involving a network of relationships [27]. The system consists of an evolutionary process in which each helix of universities, industries, and governments keeps its distinctive characteristics while simultaneously assuming the role of the others in a non-static, non-linear way [27]. A further developed model regards media and culture-based civil society as a new innovative actor, which forms the Quadruple Helix with a combination of top-down university, industry, and government policy-driven innovation and bottom-up society initiatives [28]. While there is now a large body of literature on Triple Helix models based on the condition that innovation systems can be planned in a stable circumstance, relatively little exists on how the Triple Helix can function during a crisis, especially in response to the unexpected global disruption caused the COVID-19 pandemic.

The concept of ecosystem is often formed from the perspective of focal innovation or a focal firm with the structure-based view and co-evolution-based view, respectively [8]. The boundary of an ecosystem is wider than region- or nation-based systems of innovation, such as the Triple Helix system. The structure-based view often refers to the innovation ecosystem, which is defined as "*the complex relationships that are formed between actors or entities whose functional goal is to enable technology development and innovation*" [29] (p. 2). Inside the ecosystem, knowledge creation, development, transfer, and exchange are operated among economic agents and non-economic parties, such as technology, institutions, sociological interactions, and culture [30]. The focal firm approaches the alignment of partners and secures its roles, while providing a governance structure to deal with non-generic complementarities [31]. The structure-based view addresses the ecosystem as a structure of multilateral interdependences [31,32], yet it does not cover the starting point to evoke the ecosystem logic [8].

In contrast, a coevolution-based view can be traced back to the concept that "ecosystem is an economic community supported by a foundation of interacting organizations and individuals—the organisms of the business world" [33] (p. 26). Ecosystem can facilitate evolutionary dynamics [33,34]. Thus, the ecosystem is a complex adaptive system which reacts to external disruptions and absorb opportunities [8]. In addition, a holistic model indicates that business ecosystems can start with a resource pool in social networks, then through innovation systems it can transform the fragmented resource into an integrated industrial system, and eventually through the iteration process it is re-embedded back to the resource pool [35]. However, there is still a need to validate the model with empirical evidence.

The ecosystem theory provides a perspective to understand evolution and changes faced by high external uncertainty in the VUCA framework, such as the COVID-19 pandemic. Nevertheless, there is currently a limited number of studies on how an ecosystem can facilitate new products, processes, and business model innovations in times of crisis. Its emphasis on collaboration and dynamic evaluation can potentially be linked to open innovation strategy, which opens an avenue for contributions to the literature.

3. Research Methodology

Extant literature has provided the theoretical foundation for open innovation strategy at firm, inter-firm, and regional levels. However, they are mainly based on the facts that the input of innovation, such as technology's ability to be planned, and the output, such as products and services having commercial potential or predicting demand through the sales and marketing strategy. There is a need to answer the research question "How can open innovation strategy help the healthcare sector to achieve flexibility and resilience in response to the COVID-19 crisis?". In this paper, we simply define open innovation as innovation strategies and activities happening beyond the boundary of one organization. Our research method is shown in Figure 1, which combines a structured literature review, secondary document review. and thematic analysis.

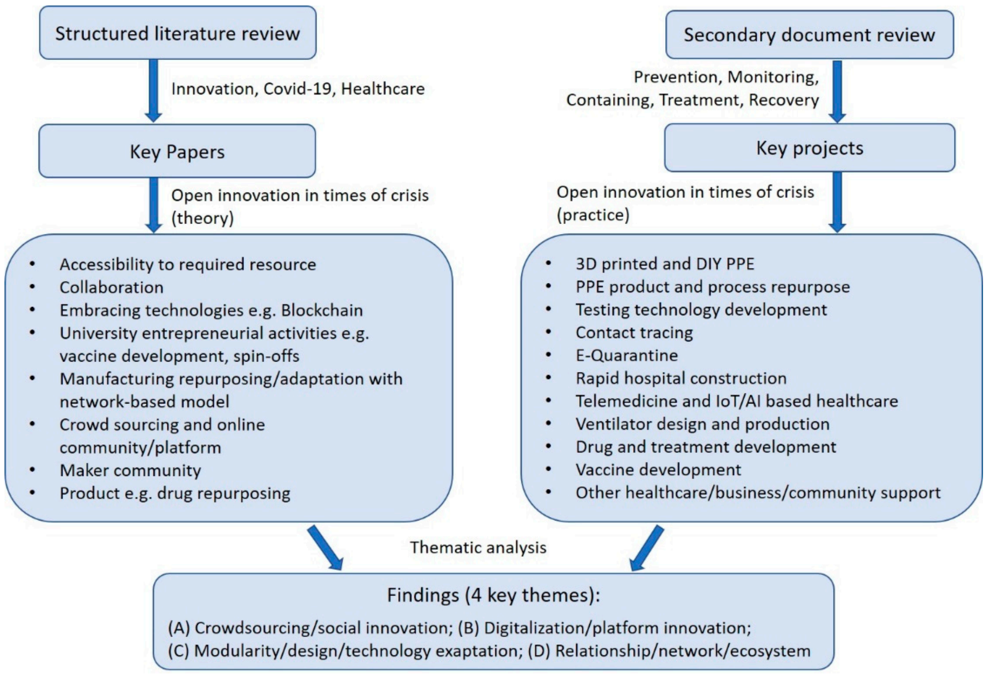

Figure 1. Research design.

First, the structured literature review is conducted with the aim of identifying key concepts and connections between open innovation and the COVID-19 crisis. By using 'innovation', 'COVID-19' and 'healthcare' as the key words appearing in the abstract or author-supplied abstract to search publications in the database of Business Source Premier and EBSCO, we found 24 papers published since 2020 as peer-reviewed journal papers. Then the papers are further screened down according to whether the study concerns open innovation, meaning innovative activities happening beyond one organization. Nine core papers are examined in detail with the key findings summarized in Table 1.

Table 1. Findings of healthcare open innovation in response to COVID-19 from the literature review.

Paper	Key Findings
Suresh et al. [36]	The paper analyzes the factors influencing the healthcare system during COVID-19 using a TISM approach. Accessibility and availability of the required resources, training and development, and collaboration and resilience are the key driving factors.
Mallikarjuna et al. [37]	This paper supports deep neural network (DNN) analysis in healthcare and the COVID-19 pandemic and gives the smart contract procedure to identify the feature extracted data (FED) from the existing data. At the same time, the innovation will be useful to analyze future diseases.
Abidi et al. [38]	The challenges and constraints imposed by the COVID-19 pandemic have demonstrated the importance of coordinating the efforts of all parties, including those of entrepreneurial universities in order to develop vaccines and generate healthcare solutions, which could be patented and commercialized afterwards.
Chiarini et al. [39]	During the COVID-19 pandemic, many manufacturing companies quickly adopted a network-based production approach to provide a rapid response to healthcare organizations needing PPEs. This paper addresses the topic of social manufacturing, with the aim of understanding the key features of such a new manufacturing, network-based model, its enabling factors, and the reasons why a company should join and/or establish it.
Vermicelli et al. [24]	Crowdsourcing and harnessing the power of crowds and online communities can help tackle the COVID-19 pandemic
Abbassi et al. [40]	The paper explores how a crisis can spontaneously create these collaborations between the maker's community, the users (public healthcare professionals), and key stakeholders (universities, civil society, and the private sector among others) in PPE production.
Guarcello and Raupp [41]	Taking the widespread adoption of telemedicine as an example of innovation processes, the paper identifies which key innovation determinants are participating in the innovation adoption process and what type of contextual conditions are relevant for its development
Hanisch and Rake [42]	In the trials concerning drug testing, we find that drug repurposing is a predominant innovation strategy
Dąbrowska et al. [43]	This paper illustrates how GetUsPPE, a community-driven platform, emerged during the crisis as a response to the PPE shortage and rapidly established an ecosystem that brings together a diverse group of community-based stakeholders to combat the scarcity of medical consumables.

Second, to explore more ongoing details in practice, we search the secondary documents including news, industry reports, secondary interview videos and scripts, and academic conference abstracts for innovation cases and examples. In the context of crisis, innovation strategies normally include prevention and preparation before a crisis, response during the crisis, and learning and revision after the crisis [44]. For a thorough investigation, our search follows innovation alongside the crisis [11,45] which includes: (1) Prevention: innovations to prevent the spread of the virus; (2) Monitoring: innovations to monitor and trace the spread of the virus; (3) Containing: innovations to isolate and slow down further spread of the virus; (4) Treatment: innovations for disease treatment and vaccine production; (5) Recovery: innovations for recovery from the crisis and prevention of the next wave of the pandemic. As the pandemic is not over yet, recovery-related innovation can overlap with prevention and monitoring on a continuous base. The number of innovation projects are narrowed down against our criteria, for which innovation should involve multiple innovative actors, meaning adopting an open innovation strategy. Combinedly, we identify 11 types of innovation projects, which are 3D printed and "do it yourself" (DIY) PPE (e.g., university 3D printed visor projects, open source PPE design, PPE design alliance, 3D Crowd), PPE product and process repurposing (e.g., manufacturers contributing to PPE production), testing technology development (e.g., university testing technology projects), contact tracing (e.g., digital tracing systems, such as COVID Near You, NHS Track, and Trace App), E-quarantine (e.g., e-fencing), rapid hospital construction, telemedicine and IoT/AI based healthcare (e.g., digital healthcare systems), ventilator design and production (e.g., VentilatorChallengeUK consortium, CoVent-19 Challenge), drug and treatment development (e.g., critical drugs, Crowd fight COVID-19), vaccine development (e.g., Oxford vaccine, Moderna vaccine), and other healthcare, business, and community support (e.g., crowdsourcing projects like TopCoder, InnoCentive, and EUvsVirus hackathon). The features and activities of these innovative projects are identified in Table 2.

Table 2. Emerging themes of open innovation strategy.

Project	Open Innovation Activities (Key Themes)
3D-printed and DIY PPE	- Passion and sense of civic duty to accelerate innovation to support the community (A) - Users sharing designs of masks and hand sanitizer through online platforms (A, B) - Open-source design of face shields and making them openly available for user download and 3D printing (B, C) - Open-source PPE platform to link supply, demand, and engineering teams (B) - PPE design based on similar products in the market/reverse engineering (C) - Using facilities and manufacturing devices originally brought for other purposes (C) - Working with broader partners, including those who normally would not collaborate (D) - Alliance among manufacturers, volunteer community of printers, designers, engineers to co-design PPE (A, D)
PPE product and process repurpose	- Companies converting from their original process to making hand sanitizer (C) - Reverse engineering existing products and share the design with existing manufacturers (C) - Forming new alliances with firms' design capability and manufacturing flexibility, based on shared purpose (D)
Testing technology development	- Using existing patients which were developed for testing other diseases (C) - Approaching wider collaborators through personal relation, professional network, the health board, and the government network (D) - Mutual trust and civic duty to take the risk at early stages when the technology was not ready (D)
Contact tracing	- Mobile App technology with the features of trace, alert, check-in, symptoms, test and isolate (B) - Creating geospatial dashboards to track COVID-19 statistics in real time on national and international scales (B) - Online website to invite the public to report current symptoms in real time, and use of crowdsourced data to visualize current and potential hotspots for the pandemic (A, B)
E-Quarantine	- Smart system to monitor patient conditions remotely, especially those in home-quarantine. (B)
Rapid hospital construction	- Modular prefab design (C) - Using BIM (Building Information Modeling), including Autodesk Revit and Navisworks for digital modeling, Enscape for model rendering, and Civil 3D for field leveling and site planning, which helped to visualize designs, integrate specialties, and share data in real time. (B)

Table 2. *Cont.*

Project	Open Innovation Activities (Key Themes)
Telemedicine and IoT/AI based healthcare	- Telehealth; robust surveillance system; technology-driven diagnostic and clinical decision-making tools; measurable tracking devices to measure physiological parameters; interactive chat service providing information about COVID-19; Telemedicine administered through virtual chat bots (B) - IoT enabled healthcare with big data, cloud computing, smart sensors, software, AI, actuators, VR/AR, transforming from telemedicine to virtual ward, and smart hospitals (B)
Ventilator design and production	- Online challenge platform to create CAD assemblies and prototypes of ventilators (A, B) - Training and data sharing through digital technologies (B) - Quick product design based on similar products and existing technologies (C) - Forming a consortium with companies across various industries based on skills and capabilities (D) - Mutual trust, can-do and will-do attitudes (D)
Drug and treatment development	- Developing drugs to treat COVID-19 based on drugs originated to treat other diseases which are distant from the COVID-19 domain (C) - Online call for scientific community to share medical treatment related resources and data to fight against the decease (A, B)
Vaccine development	- Gathering and structuring data, using machine learning to make faster decisions (B) - Emergent discovery from previous vaccine technologies for other diseases (C) - Building technology platforms and inserting the new genetic code into the preexisting platform, which helped to accelerate vaccine development (C) - Cooperation of a broad set of global stakeholders, including governments, vaccine developers and public-health organizations (D) - Quickly forming university–industry partnership with the support from government (D)
Other healthcare, business and community support	- Hackathon ideation challenge for the community to collect ideas to help people, governments, and organizations during the pandemic (A, B) - Online call for ideas to be transformed into entrepreneurial projects relating to medical and PPE, data analysis, telemedicine, home care, diagnostics, therapy and post-therapy, cybersecurity, logistics, smart working etc. (A, B) - Online platform to create COVID-19 related challenges and require solution or idea submission (A, B) - Call for ideas and technological projects to continuously monitor the disease, as well as solutions to help the economy to recover (A, B)

Then we conduct thematic analysis, following the procedure of generating initial codes from the text, sorting the different codes into potential themes by providing shorter lists of categories, grouping categories together, and reviewing and refining themes [46]. The analysis is compared with the literature review, including the types of open innovation [12], the ambidextrous model of product and service [21], and the nature of explorative and exploitative innovation [21] are concerned during the data analysis. Four themes are finalized as the findings of this paper.

4. Findings and Discussions

Through data analysis, four key themes relating to open innovation in the healthcare sector in response to the COVID-19 era are synthesized as: (A) Crowdsourcing and social innovation; (B) digitalization and platform innovation; (C) modularity, design, and technology exaptation; and (D) relationship, network and ecosystem.

4.1. Crowdsourcing and Social Innovation

Through exploring crowdsourcing projects globally, it is found that crowd involvement as innovation partners can effectively generate ideas and find solutions to fight against the COVID-19 crisis [24]. These can be further categorized as community crowdsourcing, open crowdsourcing, and crowdsourcing via a broker [24].

Community crowdsourcing connects the focal organization with a community with specific resources or required knowledge [47]. For instance, Kaggle allows scientists to share complex data analysis problems to encourage the best solution [48], and thus its rich resource of 47,000 scientific articles about COVID-19 helped the medical community to develop new insights [24]. CoVent-19 Challenge is another such example as an eight-week Grand Challenge engaging engineers, innovators, and designers to foster the development of ventilators [24]. With close links to a community with specific skills and knowledge, community crowdsourcing can accelerate science and technological projects.

In contrast, open crowdsourcing works better for information and knowledge discovery and distribution, where all individuals and users can contribute with ideas or knowledge. This is seen in the cases of most tracking and testing related initiatives, such as COVID Near You and COVIDTesting [24]. Another example is the European Innovation Council led EUvsVirus, a three-day online hackathon connecting 30,000 people from the civil society, innovators, partners, and investors across Europe to develop solutions to the COVID-19 related challenges, resulting in 2000 project submissions. While demonstrating openness at a societal level, coordination and skill gaps in the participants remain a problem [49]. Furthermore, crowdsourcing via a broker is seen in InnoCentive, where challenges are set, requiring solution and idea submission via the platform [24]. In other words, problem creators and solvers are connected by the online intermediaries.

Technical context apart, crowdsourcing shows the nature of user and social innovation, especially in the modes of open crowdsourcing and crowdsourcing via a broker. They demonstrate a bottom-up innovation approach, especially when the problem is emerging and complex. Innovation can come for nonconventional sources, especially when the users will benefit from the innovation [2]. For example, 3D Crowd is an online community of 3D printing engineers, designers, and enthusiasts based in the UK formed in March 2020 [50]. They share ideas and designs online together, getting 3D printers installed in workshops, homes, schools, and colleges across the country. During the pandemic, they scaled up from 1000 to 8000 volunteers with around 2500 3D printers working tirelessly 24/7 to fulfil the community need, creating a huge, volunteer-led, distributed print farm [50]. Crowdsourcing can result in a large community of volunteers who work together around a common goal to fight the pandemic and support each other. It provides networking opportunities, investigation of emerging social issues that are traditionally not well-defined in crowdsourcing related projects, and raises the awareness of responsible innovation [51,52] for the public concern.

As seen from the above examples, crowdsourcing and social innovation serve as a quick and effective form of inbound open innovation strategy in crisis. With the wide connection and digital tools, crowdsourcing can quickly attract various innovative actors to work on problems and challenges, contributing with ideas, knowledge, resources, and solutions in a cost-effective way. The outcome of innovation can also be distributed rapidly to the wider society due to the nature of social innovation and risk sharing. Community crowdsourcing and crowdsourcing via a broker can define specific problems or calling for contribution from well-defined skills and expertise, e.g., scientists, engineers, designers, DIY makers, and investors. However, open crowdsourcing and social innovation provide collaborative approaches for further prevention and recovery, rather than providing fundamental breakthrough solutions to manage the crisis.

The main characteristic that distinguishes these ideas from other factors of production is that they are completely non-rivalrous. Knowledge spillovers are intended within the community and do not have to be generated by purposeful R&D activities. The non-rivalry nature means that it is easy to spread a good idea based on the open innovation strategy which can be thought of as having positive externalities at the economy level.

4.2. Digitalization and Platform Innovation

The impact of COVID-19 on new technologies is significant. In the healthcare sector, there are numerus innovations in terms of tracking systems, technology-based social distancing, mobile app-based contact tracing systems, telemedicine, robot-based healthcare administration systems, video consultations, e-quarantine technology [53], robot-based patient care [54], digital quick response (QR) code check-in systems, and AI-based temperature scanning. The adoption of existing technologies to develop new products and services has been observed in the projects of technology-based social distancing and contact tracing technology. Meanwhile, process innovation is another area which interacts with digitalization, as seen in the cases of telemedicine, digital check-in, and AI-based services. Even for the rapid hospital construction projects, digital technologies have been adopted to design modulars, visualize processes, and share the data in real time, allowing quick construction concurrently instead of the traditional consecutive approaches in China, Mexico, and the UK [55].

By interviewing medical experts and hospital administrators, it is found that digital and contactless healthcare service has surged during the pandemic [56]. Through applications of Industrial 4.0 technologies including AI, IoT, big data, 3D printing, and VR/AR, telemedicine with contactless smart services have already been implemented [56]. The results also indicate that a hybrid healthcare service will emerge in the post COVID-19 era, where innovative contactless healthcare services continuously provide advanced service efficiently, due to the digital technology acceleration [56]. Already, there has been a 'Virtual Ward' model in the UK to offer a systematic approach to provide enhanced support using local intelligence for vulnerable people in the community, especially those with the most complex medical and social needs [57]. In the long term, a smart healthcare system can be created with digital track and trace, data analysis, and remote monitoring, AI-based patient care, virtual wards, smart hospitals [58], and smart city systems with the characteristics of connectivity, real-time responses, flexibility, and accuracy on a large scale.

Digital transformation not only refers to the adaptation of technologies to improve the process and service, but it also means new business models, such as digital platforms, which are a type of outbound open innovation. The examples of crowdsourcing demonstrate the ability of online crowd to perform specific task or problem-solving activities [59]. Crowdsourcing via a broker can link those who define challenges and those who provide solutions. Digital technologies have connected multiple sides of users, such as patients and doctors, demonstrating digital transformation either through the commercialization of digital technologies and the digitalization of process. Similar examples are observed in online alliances, such as the Ohio Manufacturing Alliance who connects three inter-related workstreams: (1) Demand Lead acts as the primary contact for health care providers in need of essential PPE to gather information, such as products needed, priorities, quantities, and specifications; (2) Supply Lead serves as the primary contact for manufacturers, suppliers, and vendors that have volunteered to gather information on companies' geographic reach, capabilities, capacity, retooling needs, and on-hand inventories of products and raw materials; and (3) Engineering Team is in charge of product development, assessing open-source designs, rapid prototypes, testing new designs, offering design-for-manufacturing support, etc. [60].

Digital transformation seems to change the open innovation process, linking internal and external resources. It also facilitates a non-linear process, in which various innovative actors including suppliers, universities, manufacturers, and users can co-create knowledge. Crowdsourcing based on the Internet is inbound open innovation, whereas outbound open innovation is observed in most digital platforms. Overall, digital technologies can be categorized as a coupled open innovation strategy, where data are captured, shared, and connected from various sources, generating result analysis and patterns quickly.

4.3. Modularity, Design, and Technology Exaptation

This theme emerges mainly in PPE design and development, testing technology development, and treatment development. The concept of exaptation can be like adaptation, which refers to further developments to achieve a particular function [9]. However, exaptation specifically means products, technologies, and design which are developed for one function, but later discovered to be for another [9,61].

Rather than deliberate innovation from scratch, innovations based on exaptation do not have a strategic plan [62]. This is demonstrated in UK manufacturing companies, who instead of producing their normal range of products, repurpose the manufacturing process to make hand sanitizers, PPE, and medical devices during the pandemic. Exaptation can be achieved through product design capability and manufacturing flexibility, which depends on innovation ecosystems involving supply, demand, cooperation, and competition [9,63]. With modular design, existing knowledge, and technology pools, innovation can be scaled up rapidly. Meanwhile, reverse engineering from existing products with open-source design are founded to be efficient in the production of PPE with 3D printers [9,64]. Open platforms can facilitate the sharing and exaptation of knowledge from various partners in PPE and ventilator design projects [9].

University-initiated medical innovative projects, such as testing technology development, further confirm the importance of harnessing patents which were originally developed for another purpose [64]. By analyzing the development of two critical drugs, Remdesivir (a board-spectrum antiviral medication) and Tocilizumab (immunosuppressive drug), it is found that technological exaptation can solve unexpected problems during a crisis with a rapid and effective response [62]. These drugs were developed to treat other diseases, yet they were applied to COVID-19 patients. This further raises the attention that innovators should consider the potential of new technologies at their early stage with the conditions of uncertainty and incomplete knowledge [62,65]. In terms of vaccine development, the achievement required unprecedented mobilization and the cooperation of a broad set of global stakeholders in both the public and private sectors. The development of Moderna's vaccine from their mRNA platform to develop medicines for infections of the lung and many other organ systems, which can potentially be used for COVID-19 with modifications [66]. The innovation is a repeatable process, an "emergent discovery" that involves working back from future ideas [67].

Exaptive technology and design can be viewed as an outbound open innovation strategy, where the previously unused resource is deployed for new purposes and an unplanned market. The nature of technology and design exaptation can be linked to the resource-based view of an ecosystem by providing modulars, which can be used for more than one purpose. Also, innovation is an evolving, emerging process that can accelerate innovation and tries to meet the surge in demand, but innovators have no time for planning completely new designs or new technology in VUCA world.

4.4. Relationship, Network and Ecosystem

From a geographic perspective, the regional system of innovation involves universities, industries, and governments, as seen in the Triple Helix model. Through case studies on medical innovation projects from a UK university, it is seen that during the crisis, instead of relying on the formal university-industry collaboration mechanism, individuals and social networks play an important role to stimulate collaboration [64]. University staff can initiate innovation based on emerging relationships, including personal network and wider connection with the industry. These relations and network can facilitate open innovation strategy, eventually promoting the collaboration among innovative actors with a bottom-up evolving approach, rather than a planned pattern. In fact, the innovation response to COVID-19 generally relies on relational capabilities [68].

The development of vaccines also shows evidence of the collaborative network between universities and industries, which is supported by the government. For example, in April 2020, the University of Oxford started the partnership with the UK-based global biopharmaceutical company AstraZeneca for the further development and large-scale manufacturing of the COVID-19 vaccine, which was then trialed by the University. The partnership was quickly formed two weeks after the UK government launched its dedicated Vaccine Taskforce and provided funding support. This is crucial to the successful development, manufacturing, and distribution of the vaccine, and a key element of the partnership is the joint commitment to provide the vaccine on a not-for-profit basis during the pandemic [69].

As for product and process repurposing, the case of PPE and ventilator production demonstrates the harness of networks and the ecosystem [9]. From a dynamic evolution perspective, an ecosystem provides a boarder context to configurate a new supply chain. This is shown in the UK ventilator production project VentilatorChallangeUK [70], where a consortium of significant UK industrial, technology, and engineering businesses from across the aerospace, automotive, and medical sectors came together to produce medical ventilators for the UK in March 2020. They quickly designed two ventilators with existing materials and technologies and establishing new supply chains. The success largely lies in the skills, network and resources in UK-based global companies and their will-do attitude.

Although the innovation project can be a one-off project, with the nature of learning and iteration, resources and relationships are renewed, to be adopted in the next cycle of innovation when required [35]. Thus, the understanding of innovation systems and supply chain transformation in the context of changed business ecosystems is important for business to respond to unexpected disruptions and achieve long-term resilience. While relation and network as the soft side of innovation can be viewed mainly as outbound or coupled open innovation strategy, ecosystem provides the context of coupled open innovation in the form of alliance and consortium that are transformed from resource pools through systems of innovation, e.g., a university–industry partnership and Triple Helix.

4.5. Summary of the Findings

Though inbound and outbound open innovation strategies have been highlighted in the literature [13], our findings suggest that crowdsourcing and technology exaptation are particularly significant in times of crisis, compared to other forms of open innovation. In fact, crowdsourcing with social engagement represents a nonconventional way of generating solutions that can benefit the innovation themselves, e.g., users and the society. Technology exaptation represents rapid innovation in case of emergency when innovators have no time to plan new product development.

Additionally, innovation in times of crisis demonstrates features of collaboration beyond traditional supply chain and dynamic changes, which is consistent with the co-evolution view of business ecosystems [8,35]. Findings show that, rather than a clear separation of inbound and outbound open innovation, coupled patterns with co-creation, digital platforms, and alliances are key to flexibility and resilience during the COVID-19 pandemic. Apart from the hard side of innovation, such as pre-existing technology, patents, and products, soft side factors, such as personal relations, strategic alliances, and cross-industry consortium in either formal or informal ways [18] can be an important driving force to accelerate innovation.

In general, social innovation and crowdsourcing platforms function as inbound open innovation strategy. Digitalization along with social innovation and inbound crowdsourcing platforms not only transform the open innovation strategy during the pandemic but can also be dominant after the pandemic. Thus, they represent a potential iteration process, encouraging innovation culture, society engagement, and long-term accumulation of the ecosystem resource pool, which can be transformed to the next-round product, process, or business model innovation [35]. Thus, the concept and knowledge structure of ecosystems provide a good background of understanding the new features of open innovation strategy. In fact, the ecosystem affects the acceleration of innovation during the crisis due to product complexity and the relationship among complexity exaptation and the ecosystem [9], and provides the potential for long-term, sustainability-oriented innovation [71]. As crises also normally affect rural areas significantly, the concept of rural sustainability should be supported by good financial conditions of rural hospitals, which helps to provide better access to medical services [72].

5. Conclusions

With the COVID-19 pandemic quickly transforming business models and society, bringing significant disruptions, it is time for us to rethink about open innovation in response to crises. The issue is underexplored by the existing literature on innovation management. Joint efforts and open and collaborative approaches are essential in the fight against the disease [24]. Open innovation will also have a significant role to play in recovering from the pandemic [2]. Issues, such as urgent responses, resource restrictions, and VUCA need to be taken into consideration, which requires opening up and sharing knowledge across various sectors [2].

This paper explores the open innovation strategy in crisis by studying the responses of the healthcare sector to COVID-19. Our findings include four important themes, addressing the hard and soft sides of open innovation strategies from inbound, outbound, and coupled innovation aspects. Alongside open innovation are the theories of business ecosystems and Triple Helix, with the latter explaining how innovation can be planned and optimized through governments' top-down planning as well as the bottom-up contributions by universities or industries and the civil community. In other words, while the current open innovation studies focus on the continuous improvement and awareness to achieve a better normal, our findings explain the importance of using open innovation strategies in crisis for resilience and quick responses, thus providing important insights into the design of regulatory policy for creating and adopting the 'new normal'.

Furthermore, the implications of our findings have policy orientation and are therefore also directed towards an audience of practitioners, private sector institutions, and research sectors, as we address fundamental issues concerning technological progress and growth. First, in terms of product design and development, companies can start with modular design, and use it as the potential resource pool through exaptation [35]. Second, university-industry partners, university entrepreneurial systems, and the Triple Helix model can be the key mechanism through which new products, processes, and industrial systems in the context of a broader ecosystem are transformed to the wider economic system. Thus, organizations can explore opportunities to collaborate with diverse expertise, expanding the network through formal and informal links including personal links. Third, the digital platform provides a source of innovation. In VUCA world, organizations can build up solutions via crowdsourcing based on digital technologies. Digital transformation also accelerates innovation alongside harnessing the power of online communities. Fourth, as for the policymakers, during crisis, mission-oriented policy is required [26]. However, in the long term, for healthcare, businesses, and society to recover, it needs collaborative approaches with an emphasis on sustainability-oriented innovation [71] which can be achieved through social-innovation-related open innovation approaches.

Author Contributions: Conceptualization, Z.L., Y.S. and B.Y.; methodology, Z.L.; formal analysis, Z.L., Y.S. and B.Y.; investigation, Z.L., Y.S. and B.Y.; writing—original draft preparation, Z.L. and B.Y.; writing—review and editing, Y.S.; project administration, Z.L.; funding acquisition, B.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This paper is to be presented as a keynote speech of the Society of Open Innovation: Technology, Market, and Complexity (SOI) 2022 Annual International Conference. The publishing fee of this paper is funded by SOI 2022.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Verma, S.; Gustafsson, A. Investigating the emerging COVID-19 research trends in the field of business and management: A bibliometric analysis approach. *J. Bus. Res.* **2020**, *118*, 253–261. [CrossRef]
2. Chesbrough, H. To recover faster from COVID-19, open up: Managerial implications from an open innovation perspective. *Ind. Mark. Manag.* **2020**, *88*, 410–413. [CrossRef]
3. Chesbrough, H.W. Open innovation: A new paradigm for understanding industrial innovation. In *Open Innovation: Researching A New Paradigm*; Chesbrough, W., Vanhaverbeke, J.W., Eds.; Oxford University Press: Oxford, UK, 2006; pp. 1–12.
4. Phills, J.; Deiglmeier, K.; Miller, D. Rediscovering social innovation. *Stanf. Soc. Innov. Rev.* **2008**, *6*, 34–43.
5. Nambisan, S.; Wright, M.; Feldman, M. The digital transformation of innovation and entrepreneurship: Progress, challenges and key themes. *Res. Policy* **2019**, *48*, 103773. [CrossRef]
6. Shen, Z.X.; Sun, Y. Strengthening supply chain resilience during COVID-19: A case study of JD.com. *J. Oper. Manag.* **2021**. [CrossRef]
7. Moore, J.F. Predators and prey: A new ecology of competition. *Harv. Bus. Rev.* **1993**, *71*, 75–86. [PubMed]
8. Hou, H.; Shi, Y. Ecosystem-as-structure and ecosystem-as-coevolution: A constructive examination. *Technovation* **2021**, *100*, 102193. [CrossRef]
9. Liu, W.; Beltagui, A.; Ye, S. Accelerated innovation through repurposing: Exaptation of design and manufacturing in response to COVID-19. *RD Manag.* **2021**, *51*, 410–426. [CrossRef]
10. Harris, M.; Bhatti, Y.; Buckley, J.; Sharma, D. Fast and frugal innovations in response to the COVID-19 pandemic. *Nat. Med.* **2020**, *26*, 814–817. [CrossRef]
11. Ramamurti, R. Using Reverse Innovation to Fight COVID-19. Harvard Business Review. 2020. Available online: https://hbr.org/2020/06/using-reverse-innovation-to-fight-COVID-19 (accessed on 7 October 2021).
12. Chesbrough, H.W. *Open Innovation: The New Imperative for Creating and Profiting from Technology*; Harvard Business School Press: Boston, MA, USA, 2003.
13. Chesbrough, H.; Brunswicker, S. A fad or a phenomenon? The adoption of open innovation practices in large firms. *Res. Technol. Manag.* **2014**, *57*, 16–25.
14. Chiang, Y.-H.; Hung, K.-P. Exploring open search strategies and perceived innovation performance from the perspective of inter-organizational knowledge flows: Exploring open search strategies and perceived innovation performance. *RD Manag.* **2010**, *40*, 292–299. [CrossRef]
15. Chiesa, V.; Frattini, F.; Lazzarotti, V.; Manzini, R. Performance measurement in R&D: Exploring the interplay between measurement objectives, dimensions of performance and contextual factors. *RD Manag.* **2009**, *39*, 487–519.
16. Chesbrough, H. Bringing open innovation to services. *MIT Sloan Manag. Rev.* **2011**, *52*, 85–90.
17. Laursen, K.; Salter, A. Open for innovation: The role of openness in explaining innovation performance among U.K. manufacturing firms. *Strateg. Manag. J.* **2006**, *27*, 131–150. [CrossRef]
18. Felin, T.; Zenger, T.R. Closed or open innovation? Problem solving and the governance choice. *Res. Policy* **2014**, *43*, 914–925. [CrossRef]
19. Patrucco, A.S.; Trabucchi, D.; Frattini, F.; Lynch, J. The impact of COVID-19 on innovation policies promoting open innovation. *RD Manag.* **2021**. [CrossRef]
20. Yun, J.J.; Liu, Z. Micro and macro dynamics of open innovation with quadruple-helix. *Sustainability* **2019**, *11*, 3301. [CrossRef]
21. Yun, J.J.; Liu, Z.; Zhao, X. Introduction: Ambidextrous open innovation in the 4th Industrial Revolution. *Sci. Technol. Soc.* **2021**, *26*, 183–200. [CrossRef]
22. Yun, J.J. How do we conquer the growth limits of capitalism? Schumpeterian Dynamics of Open Innovation. *J. Open Innov. Technol. Mark. Complex.* **2015**, *1*, 17. [CrossRef]
23. Yun, J.J.; Zhao, X.; Hahm, S.D. Harnessing the value of open innovation: Change in the moderating role of absorptive capability. *Knowl. Manag. Res. Pract.* **2018**, *16*, 305–314. [CrossRef]
24. Vermicelli, S.; Cricelli, L.; Grimaldi, M. How can crowdsourcing help tackle the COVID-19 pandemic? An explorative overview of innovative collaborative practices. *RD Manag.* **2020**, *51*, 183–194. [CrossRef]
25. Saez-Rodriguez, J.; Costello, J.C.; Friend, S.H.; Kellen, M.R.; Mangravite, L.; Meyer, P.; Norman, T.; Stolovitzky, G. Crowdsourcing biomedical research: Leveraging communities as innovation engines. *Nat. Rev. Genet.* **2016**, *17*, 470–486. [CrossRef] [PubMed]
26. Reale, F. Mission-oriented innovation policy and the challenge of urgency: Lessons from COVID-19 and beyond. *Technovation* **2021**, *107*, 102306. [CrossRef]
27. Etzkowitz, H. Innovation in innovation: The triple helix of university-industry-government relations. *Stud. Sci.* **2003**, *42*, 293–337. [CrossRef]

28. Carayannis, E.G.; Campbell, D.F.J. Mode 3 and quadruple helix: Towards a 21st century fractal innovation ecosystem. *Int. J. Technol. Manag.* **2009**, *46*, 201–234. [CrossRef]
29. Jackson, D.J. *What Is an Innovation Ecosystem?* National Science Foundation: Arlington, VA, USA, 2011. Available online: https://erc-assoc.org/sites/default/files/download-files/DJackson_What-is-an-Innovation-Ecosystem.pdf (accessed on 8 April 2021).
30. Mercan, B.; Göktaş, D. Components of Innovation Ecosystems: A Cross-Country Study. *Int. Res. J. Financ. Econ.* **2011**, *76*, 102–112.
31. Adner, R. Ecosystem as structure: An actionable construct for strategy. *J. Manag.* **2017**, *43*, 39–58. [CrossRef]
32. Jacobides, M.G.; Cennamo, C.; Gawer, A. Towards a theory of ecosystems. *Strateg. Manag. J.* **2018**, *39*, 2255–2277. [CrossRef]
33. Moore, J.F. *The Death of Competition: Leadership and Strategy in the Age of Business Ecosystem*; HarperBusiness: New York, NY, USA, 1996.
34. Teece, D.J. Next generation competition: New concepts for understanding how innovation shapes competition and policy in the digital economy. *J. Law Econ. Policy* **2012**, *9*, 97–118.
35. Shi, Y.; Lu, C.; Hou, H.; Zhen, L.; Hu, J. Linking business ecosystem and natural ecosystem together—A sustainable pathway for future industrialisation. *J. Open Innov. Technol. Mark. Complex.* **2021**, *7*, 38. [CrossRef]
36. Suresh, M.; Roobaswathiny, A.; Lakshmi Priyadarsini, S. A study on the factors that influence the agility of COVID-19 hospitals. *Int. J. Healthc. Manag.* **2021**, *14*, 290–299. [CrossRef]
37. Mallikarjuna, B.; Shrivastava, G.; Sharma, M. Blockchain technology: A DNN token-based approach in healthcare and COVID-19 to generate extracted data. *Expert Syst.* **2021**, e12778. [CrossRef] [PubMed]
38. Abidi, O.; Dzenopoljac, V.; Dzenopoljac, A. Discussing the role of entrepreneurial universities in COVID-19 era in the Middle East. *Management* **2021**, *26*, 55–66. [CrossRef]
39. Chiarini, A.; Grando, A.; Belvedere, V. Disruptive social manufacturing models: Lessons learned from Ferrari cars and Isinnova networks for a post-pandemic value creation path. *Prod. Plan. Control.* **2021**, 1–14. [CrossRef]
40. Abbassi, W.; Harmel, A.; Belkahla, W.; Ben Rejeb, H. Maker movement contribution to fighting COVID-19 pandemic: Insights from Tunisian FabLabs. *RD Manag.* **2021**. [CrossRef]
41. Guarcello, C.; Raupp, E. Pandemic and innovation in healthcare: The end-to-end innovation adoption model. *Braz. Adm. Rev.* **2021**, *18*, e210009. [CrossRef]
42. Hanisch, M.; Rake, B. Repurposing without purpose? Early innovation responses to the COVID-19 crisis: Evidence from clinical trials. *RD Manag.* **2021**, *51*, 393–409. [CrossRef]
43. Dabrowska, J.; Keranen, J.; Mention, A.-L. The emergence of community-driven platforms in response to COVID-19: GetUsPPE, a multi-sided platform that emerged during the COVID-19 pandemic, offers key insights on how to mobilize and leverage diverse actors to provide solutions in emergencies. *Res. Technol. Manag.* **2021**, *64*, 31–38. [CrossRef]
44. Coombs, W.T. *Ongoing Crisis Communication*, 4th ed.; SAGE: Thousand Oaks, CA, USA, 2015.
45. Northeastern Centre for Emerging. Markets Reverse Innovation to Fight COVID-19. 2021. Available online: https://damore-mckim.northeastern.edu/reverse-innovation-to-fight-COVID-19/ (accessed on 7 October 2021).
46. Braun, V.; Clarke, V. Using thematic analysis in psychology. *Qual. Res. Psychol.* **2006**, *3*, 77–101. [CrossRef]
47. Simula, H.; Ahola, T. A network perspective on idea and innovation crowdsourcing in industrial firms. *Ind. Mark. Manag.* **2014**, *43*, 400–408. [CrossRef]
48. Boudreau, K.J.; Lakhani, K.R. Crowdsourcing: A model for leveraging online communities. In *The Participatory Cultures Handbook*; Routledge: New York, NY, USA, 2013; pp. 120–129.
49. Bertello, A.; Bogers, M.L.; De Bernardi, P. Open innovation in the face of the COVID-19 grand challenge: Insights from the Pan-European hackathon 'EUvsVirus'. *RD Manag.* **2021**. [CrossRef]
50. 3D Crowd. 3D Crowd—1 Year On. 2021. Available online: https://www.3dcrowd.org.uk/3d-crowd-1-year-on/ (accessed on 24 October 2021).
51. Stilgoe, J.; Owen, R.; Macnaghten, P. Developing a framework for responsible innovation. *Res. Policy* **2013**, *42*, 1568–1580. [CrossRef]
52. Scherer, A.G.; Voegtlin, C. Corporate governance for responsible innovation: Approaches to corporate governance and their implications for sustainable development. *Acad. Manag. Perspect.* **2020**, *34*, 182–208. [CrossRef]
53. Laguipo, A.B.B. Smart Health System to Monitor People in COVID-19 Quarantine. 2020. Available online: https://www.news-medical.net/news/20200512/Smart-health-system-to-monitor-people-in-COVID-19-quarantine.aspx (accessed on 25 October 2021).
54. Zemmar, A.; Lozano, A.M.; Nelson, B.J. The rise of robots in surgical environments during COVID-19. *Nat. Mach. Intell.* **2020**, *2*, 566–572. [CrossRef]
55. Alderton, M. 3 Examples Of Modular and Prefab Hospitals Constructed to Fight COVID-19. 2021. Available online: https://redshift.autodesk.com/modular-hospitals/ (accessed on 25 October 2021).
56. Lee, S.M.; Lee, D. Opportunities and challenges for contactless healthcare services in the post-COVID-19 Era. *Technol. Forecast. Soc. Chang.* **2021**, *167*, 120712. [CrossRef] [PubMed]
57. National Health Service (NHS). A 'Virtual Ward' Approach to Supporting Vulnerable and at-Risk Groups in the Community. 2021. Available online: https://www.england.nhs.uk/nursingmidwifery/shared-governance-and-collective-leadership/nursing-COVID-19-catalogue-of-change/a-virtual-ward-approach-to-supporting-vulnerable-and-at-risk-groups-in-the-community/ (accessed on 25 October 2021).

58. Javaid, M.; Khan, I.H. Internet of Things (IoT) enabled healthcare helps to take the challenges of COVID-19 pandemic. *J. Oral Biol. Craniofac. Res.* **2021**, *11*, 209–214. [CrossRef]
59. Saxton, G.D.; Oh, O.; Kishore, R. Rules of crowdsourcing: Models, issues, and systems of control. *Inf. Syst. Manag.* **2013**, *30*, 2–20. [CrossRef]
60. Ohio Manufacturing Alliance. The Issue: Keeping up with PPE Demands Amid COVID-19. 2020. Available online: https://repurposingproject.com/ (accessed on 24 October 2021).
61. Gould, S.J.; Vrba, E.S. Exaptation—A missing term in the science of form. *Paleobiology* **1982**, *8*, 4–15. [CrossRef]
62. Ardito, L.; Coccia, M.; Petruzzelli, A.M. Technological exaptation and crisis management: Evidence from COVID-19 outbreaks. *RD Manag.* **2021**, *51*, 381–392. [CrossRef]
63. Ansari, S.S.; Garud, R.; Kumaraswamy, A. The disruptor's dilemma: TiVo and the U.S. television ecosystem. *Strateg. Manag. J.* **2016**, *37*, 1829–1853. [CrossRef]
64. James, S.; Liu, Z.; Stephens, V.; White, G. Innovation in Crisis: An Examination of the Interoperation of Triple Helix Actors in Response to COVID-19 Pandemic (Conference Abstract). In Proceedings of the Advances in Management and Innovation Conference, Online, 20–21 May 2021.
65. Scheiner, C.W.; Baccarella, C.V.; Bessant, J.; Voigt, K.I. Thinking patterns and gut feeling in technology identification and evaluation. *Technol. Forecast. Soc. Chang.* **2015**, *101*, 112–123. [CrossRef]
66. HBR IdeaCast. The Innovation System behind Moderna's COVID-19 Vaccine. 2021. Available online: https://hbr.org/podcast/2021/09/the-innovation-system-behind-modernas-COVID-19-vaccine (accessed on 20 October 2021).
67. McKinsey & Company. Moderna's Path to Vaccine Innovation: A Talk with CEO Stephane Bancel. 2021. Available online: https://www.mckinsey.com/industries/life-sciences/our-insights/modernas-path-to-vaccine-innovation-a-talk-with-ceo-stephane-bancel (accessed on 20 October 2021).
68. Kuckertz, A.; Brandle, L.; Gaudig, A.; Hinderer, S.; Reyes, C.A.M.; Prochotta, A.; Steinbrink, K.; Berger, E.S. Startups in times of crisis—A rapid response to the COVID-19 pandemic. *J. Bus. Ventur. Insight* **2020**, *13*, e00169. [CrossRef]
69. University of Oxford. About the Oxford COVID-19 Vaccine. 2020. Available online: https://www.research.ox.ac.uk/article/2020-07-19-the-oxford-COVID-19-vaccine (accessed on 12 October 2021).
70. VentilatorChallengeUK. VentilatorChallengeUK Consortium. 2020. Available online: https://www.ventilatorchallengeuk.com/ (accessed on 21 April 2021).
71. Liu, Z.; Stephens, V. Exploring innovation ecosystem from the perspective of sustainability: Towards a conceptual framework. *J. Open Innov. Technol. Mark. Complex.* **2019**, *5*, 48. [CrossRef]
72. Bem, A.; Siedlecki, R.; Predkiewicz, P.; Gazzola, P.; Ryszawska, B.; Ucieklak-Jez, P. Hospitals' financial health in rural and urban areas in Poland: Does it ensure sustainability? *Sustainability* **2019**, *11*, 1932. [CrossRef]