Innovation in Crisis: the role of 'exaptive relations' for medical device development in response to COVID-19

Steffan James
steffan.james@southwales.ac.uk
South Wales Business School, University of South Wales, UK
Llantwit Road, Pontypridd CF37 1DL, UK

Zheng Liu (corr.)
zliu@cardiffmet.ac.uk
Cardiff School of Management, Cardiff Metropolitan University, UK
Western Ave, Cardiff CF5 2YB, UK

Victoria Stephens
victoria.stephens@southwales.ac.uk
South Wales Business School, University of South Wales, UK
Llantwit Road, Pontypridd CF37 1DL, UK

Gareth RT White
gareth.white@cranfield.ac.uk
Cranfield University
College Road, Cranfield, Bedford MK43 0AL, UK

ABSTRACT

The COVID-19 pandemic has resulted in huge disruption to the healthcare sector. In response to this, there have been collaborative efforts between many different public and private organizations to foster medical innovations. The effect of crisis upon innovation, particularly medical innovation, remains a debatable subject. In addition, the role of inter-personal relations is becoming more widely acknowledged as a critical feature of innovation. Drawing upon exaptation literature, the study aims to understand the nature of the micro-relations within medical innovations that are undertaken in response to COVID-19. The findings of this paper contribute to the limited literature that examines the performance of medical innovation in response to crisis. In addition to confirming the importance of exaptive pools, exaptive events, and exaptive forums in fostering serendipitous developments, the study makes a contribution to theory by identifying a further form of serendipitous encounter that is 'exaptive relations'.

KEYWORDS: *Innovation; Exaptation; COVID-19; medical innovation*

Innovation in Crisis: the role of 'exaptive relations' for medical device development in response to COVID-19

1. Introduction

Since their inception around thirty years ago (Watkins *et al*., 2015), research into National Innovation Systems (NIS) has gradually shifted from examinations of macro economic factors and systems (Etzkowitz, 2003; Etzkowitz and Leydesdorff, 2000), toward meso-level studies of regional and sectoral systems of innovation (Ornelia, 2015; Guan and Chen, 2012; D'Este and Patel, 2007; Siegel, Waldman, Atwater and Link, 2003). Most recently, research has focussed upon the micro-relationships between actors and this has revealed the importance of individuals in the success of innovative collaboration (White *et al.,* 2019; Winsor and Hall, 2018; Razak and White, 2015; Leven, Holmstrom and Mathiassen, 2014; Carayannis and Rakhmatullin, 2014).

Much of the literature suggests that systems of innovation are implemented and utilised in periods of relative stability whereas a much smaller body of literature discusses their application as a mechanism for dealing with pressing economic dilemmas. For instance, Filippetti and Archibugi (2011) found variations in the effect that economic crises have on innovation, with different industries and systems of innovation performing differently. Etzkowitz (2012) commented upon the use of an approach in the USA to respond to the economic crisis of the 1930's. Similarly, Rodrigues and Melo (2012) discussed how a region of Portugal addressed the impact of the 2007-8 global economic crisis, and Oksanen and Hautamaki (2014) described the response to Nokia's closure of its research centre in a city in Finland.

In 2020-22 the world is experiencing unprecedented change due to the COVID-19 pandemic. At the time of writing, there have been over 4.9 million deaths and 242 million infections reported worldwide (World Health Organization, 2021). The global economy has contracted by around 5% (World Bank, 2020) and 195 million people are expected to become unemployed (ILO, 2020), far more than were affected during the 2007-8 global financial crisis.

The nature of the COVID-19 pandemic meant that the crisis was, in fact, several crises – public health (Pollard et al., 2020), economic (Borio, 2020), and supply chain (Armani et al., 2020). Frequently, for-profit product innovation has been replaced by crisis-driven innovation of products in order to respond quickly to calls for help (Netz et al., 2022). Medical innovations have been at the forefront of public interest during the pandemic as research has sought to find practicable testing solutions and antivirus treatments. There is much debate over the general process of innovation within medical devices. For instance, it is claimed that regulations inhibit transformational change (Suter et al., 2020), the process is unnecessarily lengthy, complex and expensive (Laurell, 2018), institutional boundaries are frequently unclear (Gulbrandsen, 2016; Djellal and Gallouj, 2007), and the economic benefits are uncertain (Frankovic, et al., 2020). Furthermore, the effect of crisis upon medical innovation remains a contested point, with Hu et al. (2021) suggesting that it can accelerate the process, whereas Peterson et al. (2016) claim that it merely increases innovation uncertainty.

This paper reports upon a study of the innovation activities that arose in response to the COVID-19 pandemic in 2020. Drawing upon exaptation theory as a mechanism of serendipitous innovation, it aims to understand the nature of the micro-relations within medical innovations that are undertaken in response to COVID-19. The research indicates the importance of active and dormant pre-existing inter-personal relationships, as well as the deliberate and unexpected forging of new relationships in the development process. Through this, the study proffers a contribution to exaptation theory by identifying 'exaptive relations' and furthers our understanding of how medical innovations were developed in response to the COVID-19 crisis.

The remainder of the paper is organized as follows. In Section 2, the relevant literature on serendipity and exaptation is reviewed. Section 3 explains the research methodology. Section 4 reports key findings from the case studies. Important implications of the findings are discussed in Section 5 followed by the conclusion section.

2. Literature Review

2.1 Serendipity and Exaptation

Discussions of social and organizational innovation often include the concept of serendipity (Cisnetto and Barlow, 2020; Leckel, Veilleux and Dana, 2020; Sauer and Bonelli, 2020; Fink, Reeves, Palma and Farr, 2017; Heger and Rohrbeck, 2012; Anokhin, Wincent and Frishammar, 2011; Kakko and Inkinen, 2009; Knoben, Oerlmans and Rutten, 2006; Koh, 2000; Godoe, 2000). It is also a feature of the process of research (Murayama, Nirei and Shimizu, 2015; McKelvey, Zaring and Ljungberg, 2015; Cunha, Clegg and Kamoche, 2012; Boudreau, Lacetera and Lakhani, 2011; Buenstorf, 2009; Rahmandad, 2008; Graebner, 2004; Nelson, 2003). Serendipity is invariably conceptualised as a non-planned, coincidental, or accidental event that results in some beneficial outcome (Wareham, et al., In-Press; Kakko and Inkinen, 2009).

Exaptation is a form of serendipitous innovation that is becoming an increasingly valuable theoretical lens in business and management studies (Andriani and Kaminska, 2021; Beltagui, Rosli and Candi, 2020; Galvin, Burton and Nyuur, 2019; Andriani, Ali and Mastrogiorgio, 2017; Andriani and Cattani, 2016; Andriani and Carignani, 2014; Katila and Ahuja, 2002; Baldwin and Clark, 2000). It is a term that was first used in biology to indicate the unintended utilization of a feature for what it was not originally intended (Garud, Gehman and Guiliani, 2016; Gould and Vrba, 1982). The process of technological exaptation differs from that found in the natural world since humans have "*the power to induce exaptation*" (Garud, Gehman and Giuliani, 2016, p150). Consequently, Garud, Gehman and Guiliani (2016) even venture that there is a need to focus on the exaptive capacity of humankind to address the pressing global environmental needs that have, paradoxically, been brought about by previous human technological exaptation. In the context of technology innovation, exaptation refers to products, technologies and designs that are developed for one function but are later utilized for an alternative purpose (Andriani and Cattani, 2016; Liu, Beltagui, Ye, 2021).

The concept of exaptation has been discussed as the principle that governs the creation and exploitation of new markets through entrepreneurship (Dew and Sarasvarthy, 2016; Dew, Sarasvarthy and Venkataraman, 2004), the means by which

internet video firms outperform their competitors (Ching, 2016), the utilization of domestic capabilities across international boundaries (Santangelo and Stucchi, 2018), how the assets of the banking sector have been repurposed over time (Marquis and Huang, 2010), as a mechanism for innovation that can be promulgated by social entrepreneurship (Ganzaroli, De Noni and Pilotti, 2014) and digital innovation (Beltagui, Rosli, and Candi, 2020; Schiavone et al., 2022).

Some studies have examined the concept of exaptation in manufacturing, where products have been repurposed through the identification of new partners (Adner, 2017), which have helped to enhance manufacturing flexibility (Liu, Beltagui and Ye, 2021). Nevertheless, Liu, Beltagui and Ye's (2021) study is based upon secondary data and does not reflect the in-depth details of intentions or micro relationship among the innovation actors.

While technological exaptation is a driving force of novel production and short-term innovation (Andriani and Kaminska, 2021; Ardito, Coccia, and Messeni Petruzzelli, 2021), it can also multiply technological options and generate innovation cascades (Andriani and Carignani, 2014). Exaptation constitutes a problem-solving approach through which serendipitous discoveries and technologies bifurcate into new markets and alter industry trajectories (Meyers, 2007; Andriani and Cattani, 2016).

Exaptation may affect processes and not merely the products that are the results of those processes (Andriani and Carignani, 2014). Consequently, it can help to develop technologies that enable the resolution of complex problems (Andriani, Ali, Mastrogiorgio, 2017). It also manifests in different degrees of magnitude from radical transformations to smaller, incremental changes (Andriani and Carignani, 2014). The nature of problem-driven innovation to address COVID-19 challenges, often without clear strategic plan (Ardito, Coccia and Petruzzelli, 2021), is consistent with the concept of technological exaptation (Tria et al., 2014), which does not rely on deliberate innovation (Andriani and Cattani, 2016).

Garud, Gehman and Guiliani (2016) provide an operationalisable theoretical framework of exaptation in their identification of three environs that may bring about unintended, novel discoveries. These are 'exaptive pools', 'exaptive events' and 'exaptive forums'. 'Pools' represent knowledge bases, such as patents, that persist over time yet may not currently be utilized in the formulation or design of a novel device. When these patents are 'coupled' with other knowledge bases, technologies or devices, resembling De Rond's (2014) identification and combination of 'correct pairs', then some novel arrangement may emerge. 'Events' are instances where different knowledge bases are brought together deliberately, "*where people from different vantage points interact with one another*" (p.133), in order to stimulate the identification and development of innovations. Although, as Lane *et al*. (2020) highlight, they must share some 'common knowledge' to enable shared understanding. 'Forums' are "*entanglements*" of people with different perspectives, that persist over time, with the goal of facilitating the cross-fertilization of ideas.

2.2 Medical Innovation

Empirical studies of medical innovation in response to the pressures of Covid-19 are currently limited. For instance, Chesbrough (2020) commented upon the importance of open innovation, and Ramamurti (2021) examined rapid and reverse techniques. Innovations that attempt to tackle COVID-19 challenges require collaboration and an

ability to develop new relationships (Kuckertz et al, 2020) and the support from mission-oriented innovation policy (Reale, 2021). However, innovation approaches under emergency situations and crisis are generally underexplored (Chesbrough, 2020).

There is a small body of literature that makes a direct connection between medical innovation and exaptation. Liu, Beltagui and Ye (2021) investigated the acceleration of medical devices product innovation during the pandemic. They suggested that the open-sourced design and external collaboration enabled companies to freely share existing ventilator designs and thus achieve product design exaptation to meet the critical demands of speed and quality. Ardito, Coccia, Petruzzelli (2021) addressed technological exaptation in the drug development to treat COVID-19 infected patients. Two drugs were selected as the research setting, which were originally developed to treat other diseases, and were adapted for COVID-19 treatment (Ardito, Coccia, Petruzzelli, 2021). Their findings define the concept of exaptive distance between the source and destination domains of technological space (Andriani and Cattani, 2016; Ardito, Coccia and Petruzzelli, 2021). Specifically, longer exaptive distance can be a potential driving force of short-term product innovation and solutions with rapid and effective response to unexpected problems (Ardito, Coccia, Petruzzelli, 2021). However, the study is also based on secondary data, which cannot explain other important non-technological factors.

2.3 Summary

There is little work on the interface between crisis and exaptation, and in general, how innovation can be performed in times of crisis is still a new topic (Chesbrough, 2020). Empirical studies such as detailed in-depth case studies are needed to explore the role of exaptation during real-time crises (Liu, Beltagui, Ye, 2021). In addition, the nature of medical innovations is a widely debated subject, especially during times of crisis (Peterson et al., 2016; Hu et al., 2021).

Exaptation is an apposite theoretical lens for investigating problem-driven innovations that arise in response to complex co-evolutionary issues (Andriani and Cattani, 2016; Andriani, Ali, Mastrogiorgio, 2017). The current framework by Garud, Gehman and Guiliani (2016) emphasises the tangible factors of technological exaptation, in terms of pools, events and forums. There is also a considerable, and growing, literature that identifies the importance of the 'micro-relations' that occur between individuals that are involved in innovation activities (White *et al.,* 2019; Winsor and Hall, 2018; Razak and White, 2015; Leven, Holmstrom and Mathiassen, 2014; Carayannis and Rakhmatullin, 2014). Consequently this investigation aims to understand the nature of the micro-relations within medical innovations that are undertaken in response to COVID-19.

3. Methodology

In order to explore the origins of COVID-19 motivated innovations and the micro-relations between collaborators, the study adopts an interpretive approach to inductively exploring three cases of medical innovations variously driven by the needs of the COVID-19 pandemic. Interpretive study is most useful in exploring and expanding new theoretical insight into organizational practice (Ciulli and Boe-Lillegraven 2020; Langley and Abdallah 2011) and affords the means of

understanding the viewpoints of different actors (Moraes, Kerrigan and McCann 2020; Spiggle 1994). In addressing the research aim, this study places emphasis upon gaining first-hand understanding of the experiences of three development teams and is therefore a "*good fit*" with an interpretive approach (Karakas, Sarigollu and Uygur 2017, p.733).

Case study method is used to gain in-depth information of a research site and enable its contextually accurate interpretation (Yin, 2013; Davies 2009). The method also enables the acquisition of data from multiple sources that allows the triangulation of findings (Longoni and Cagliano 2018; Goulding 2001). The cases, discussed in detail in the following section, consisted of the development of a novel oximeter (Case 1), the production of personal protective equipment (PPE visors) using 3D printing technology (Case 2), and the development of a rapid diagnostic test (Case 3).

Semi-structured interviews with key personnel at the heart of each of the three medical innovations were used to gather rich data (Denscombe, 2010; Fox, 2009; Johnson and Onwuegbuzie, 2004; Seidman, 1998) with four project leaders. The interviews, each of around one hour duration, were conducted and transcribed by the researchers in order to minimise misinterpretation (Opdenakker, 2019).

The interview questions comprised generalist, context-discovery questions such as 'How did the project arise' and 'How did this project differ from the work you normally do', and questions that were initially operationalized from the literature taking the form and 'What other individuals and organizations did you collaborate with' (Halcomb and Davidson, 2006; Lynch, 2000; Charmaz, 2006). Further questions were developed during each interview in order to probe interesting and emergent themes (Wright, Zammuto and Liesch 2017; Harris 2007), including for example "*How is the innovation process different before and after the COVID-19 pandemic?*" and "*What helped you to do it?*"

The cyclic development and refinement of interview questions (Bositis, 1988; Becker, 1958; Miles, 1979; Sanday, 1979; Schwartz and Schwartz, 1955), along with the use of analytical triangulation through using multiple researchers to code the data (Gronhaug and Olson, 1999; Eden and Huxham, 1996; Jick, 1979), improve the robustness of interpretive research and assist in achieving theoretical saturation (Guest *et al.,* 2012; Glaser and Strauss, 1967). Consent was obtained from each participant prior to beginning data collection (Van den Hoonard, 2003), project names and details have been anonymised, and all participants are referred to using the convention [P1]…[P3] in the analyses (Duclos, 2019).

The interviews were transcribed (Step 1) and independently thematically analysed (Step 2) by all four researchers following each interview (Guest *et al.*, 2012). This generated the 'Initial Codes' that were collectively reviewed by the researchers until consensus of the 'Initial Themes' was reached. Analysis continued until the point of theoretical saturation had been achieved and no new themes were emerging from the data (Step 3) (Locke 2001; Strauss and Corbin, 1998). Finally, Stage 4 comprised the merging and reduction of the dominant themes that resulted in the compilation of the 'Final Themes' (Table 1).

Table 1. Data Coding Structure

Initial Codes				Initial Themes	Final Themes	Contribution
Researcher 1	Researcher 2	Researcher 3	Researcher 4			
Old contacts	Previous contacts	Previous collaborators	Old colleagues	Long-standing relationships	'Live' Long-Standing Relationships	Exaptive Relations
	Former workmates		Friends		'Reignited' Long-Standing Relationships	
Project collaborators	Colleagues	Colleagues	Friends (collaborators)	Colleagues	Current Relationships	
Other projects		Other projects	Colleagues			
			Other departments			
Seeking skills or knowledge	Proactively seeking help	Seeking assistance	Needing help	New Relationships	New Relationships	
Who to ask?	Facing resistance	Difficulty finding help	Not knowing what we need to know	Challenges to forging new relations		
Colleagues	Help from within organisation	Aided by other departments	Help from unexpected places	Internal sources of unexpected help	Unexpected Relations	
Collegiality	Going beyond duty		Fortunate encounters			
Surprising sources of assistance	Help from outside the organisation	Friends-of-friends	Media links	External sources of unexpected help		

4. Findings

This section aims to outline the findings of the case analysis. First, the details of each of the three cases are briefly described before the concept of exaptive relations is identified and discussed through the case data.

4.1 Case Study 1 - Oximeter

The first case study concerns the development of a novel oximeter. As the severity of the COVID-19 pandemic became apparent in March 2020, evidence was emerging that using a CPAP (continuous positive airway pressure) as an earlier intervention alternative to full ventilation could result in fewer mortalities. The use of these machines requires continuous monitoring of oxygen levels in the blood creating a global demand for oximeters that could not be met using existing supply chains. Additionally, it was noted that patients were conscious at unusually low oxygen levels and patients would likely be using the devices outside normal clinical settings, meaning the oximeters would require additional functionality. The requirement,

therefore, was a design manufacturable at low cost using alternative supply chains with higher accuracy at lower blood oxygen levels.

The project was initiated by the Welsh government to meet the demand for oximeters to support the use of CPAP machines in treating patients with COVID-19. As the project developed and the team gained a better understanding of the problem, they realised that the product was sufficiently unique to be commercialised for new markets apart from the immediate COVID-19 demand. Further, it was identified that although the demand due to the pandemic had subsided, there was a potential requirement for oximeters in the winter, which was not stated in the initial scope of the project, but recognised by others during the project.

The motivation for the entire team was identified as a sense of duty to help save lives. There was a recognition that this was due to operating in a crisis and it was understood that when normality would resume, they would face more barriers and hinderances. Some of these came to the fore after the initial phase of the project, when the team were looking to commercialise the product. In identifying their cause, a differentiation was made between institutions and the individuals which form those entities. This project was ended in Oct 2020.

4.2 Case Study 2 – 3D Printed Visors

The second case concerns the production of visors with 3D printer. The project was led by a university researcher from electricity and electric engineering background. It started in late March 2020 when there was a severe shortage of PPE in the UK. Driven by passion and sense of responsibility, and with various machineries and facilities including a 3D printer available, the project team of engineers who previously worked closely at the university were quickly formed. The visor prototype was designed based on the examining of existing products on the market. Factors such as product quality, the easiness of production, the availability of raw materials and the production capacity of 160 per day were also taken into consideration during the design. Advice was sought from colleagues with science and computing background. Soon as the first prototype was developed, marking the most critical step, it came to mass production immediately. The production took place inside the university with the participation of aircraft maintenance and mechanical technicians, who brought expertise in 3D printing, laser printing and assembly to the team.

This project of visor design and development was internally supported by the school and university regarding the use of resource and funding. Aware of the urgency and significance of the project to the society, colleagues across the university responded efficiently, creating no barriers to the project. There was no engagement with external industry partners, apart from purchasing raw materials for 3D printing. Instead of targeting the NHS, the team prioritised and approached care homes and special needs schools who were in large need of PPE and were not under the spotlight. The project ended in the end of May 2020, when the global supply chain of PPE had been established, providing users easier access to cheaper products, and thus the project goal was achieved. The team eventually delivered 2400 visors to 84 different institutions in South Wales region, and donated the rest for free.

4.3 Case Study 3 – Rapid Diagnostic Test

The third case concerns the development of a diagnostic test that could more rapidly test for the underlying SARS-CoV-2 virus. The project started in March 2020. Led by a team of university researchers specialising in micro-biology, molecular genetics and electronic engineering, the test is designed to provide affordable and accurate 'point of care testing', which means bringing the testing and diagnosis closer to the patient. Administered in a local setting, the test would have the ability to indicate whether the patient is infected within 20-30 minutes of the test. Its approach also minimised the need for expensive equipment, thus ensuring it was cost-effective, as well as fast. Through such capabilities, the test is designed to enable widespread distribution across populations including healthcare workers, care home settings, as well as within rural populations, and thus facilitate large scale community testing. Using alternative method and components to existing tests, the innovation avoided bottlenecks associated with the supply of traditional components. The University team worked with the local health board to access samples in order to validate the test, as well as industrial partners to manufacture the device. At the time of interviewing, the project was undertaking a clinical study to evaluate the performance of the prototype diagnostic device.

The test was developed through adapting a pre-existing platform technology for detecting bacterial pathogens that cause urinary tract infections (UTIs). A collaborative project on this platform technology with the local health board had been ramping up before the effects of the COVID-19 pandemic were felt in Wales, and paved the way for its adaptation towards the COVID virus. Its adaptation for use in the COVID context gained momentum as a result of a serendipitous telephone conversation with a colleague from the local health board, in which the University researcher's plan to adapt the technology to diagnose the COVID virus was mentioned only in passing. Nonetheless, this triggered and signalled external interest in the innovation, which further triggered permission and support from the University. University researchers reported the extent to which the 'normal' bureaucratic barriers to innovative research projects were largely removed, and financial and human resources effectively mobilised across the University to expedite the innovation process. This was made possible by an increase tolerance for risk among university sponsors, alongside the researchers' own sense of civic duty.

5. Discussion

The analyses provided confirmatory evidence of the important roles that are played by exaptive pools, forums and events in the forging of links and sharing of knowledge between individual and institutional actors prior to COVID-19. For brevity, these are summarised in Table 2.

Table 2. Confirmatory Findings of Exaptive Pools, Events, and Forums

Confirmatory Analyses			
	Exaptive Pools	Exaptive Events	Exaptive Forums
Case 1	CPAP developed and used to treat sleep apnoea, could treat COVID-19 if oxygen levels can be monitored.	Welsh government had previously worked with the team and could also facilitate the bringing together of external experts in prototyping, manufacturing, medical device legislation, patents, and grants.	Welsh government network of contacts.
Case 2	Knowledge/skills of 3D printing and engineering in related and unrelated products.	Previous collaborative engineering projects which can be related to the new project	Existing communication channels and collaborations inside university.
Case 3	The 'platform technology' that was to be used for a range of specific purposes, firstly UTI testing, then COVID testing.	Two members of research team had previously decided to collaborate to bid for a Welsh Government grant – to work on a new innovation related to rapid UTI detection/treatment.	The Welsh Crucible Programme. Medical/life sciences industry conferences brought the university researchers together with industry collaborators for the UTI project.

5.1 Exaptive Relations

Existing literature has addressed the importance of exaptive events, pools and forums in innovation (Garud, Gehman and Guiliani, 2016). Our data analysis identifies the importance and nature of 'exaptive relations' that exist between university research members as well as between university, industry and government actors.

Many of these relationships existed months, or even years, prior to the COVID-19 pandemic, while other new relationships were formed, by design or by accident. These 'exaptive relations' are found to take four distinct forms:

Longstanding/well-established relations that were 'live' and 'active' at the time that the COVID-19 crisis hit.

Other longstanding relationships were 'dormant' at the time that the COVID-19 crisis hit, and which then came to be re-ignited/re-enlivened in light of the innovation demands presented by the COVID-19 crisis.

Other 'new' relationships were forged 'in the moment' during the process of developing the innovations. These were also deliberately sought in order to gain access to knowledge and expertise as well as to garner support from internal and external gatekeepers.

Finally, a further type of relationship was found to exist that was not the result of a deliberate act of seeking expertise or support, but rather emerged serendipitously.

5.2 Deliberate – Long-Standing Relationships

In cases 1 and 3 it was apparent that longstanding pre-existing relations that were live at the time that COVID-19 hit were instrumental in compressing the time it took to operationalize the innovation. In case 3, two members of the research team were already working together on a separate innovation project related to the diagnosis of urinary tract infections (UTIs). This relationship had in fact been initiated as a result of an exaptive event (the Welsh Crucible Programme), and led to the development of a platform technology for the diagnosis of UTIs. When COVID-19 hit, the existing relationship (along with the platform technology) facilitated a swift pivot to the development of a rapid test for COVID-19.

In case 1, this was expressed in terms of the significance of being able to swiftly put together a team to innovate in response to the need for a high-accuracy, low-cost oximeter machine, using non-traditional components through new supply chains.

> *So we put quickly identified a team....now a team is absolutely essential to deliver in any project, errr, whatever it is. So we pulled in together an Electronics guy, a firm guy and a mechanical guy and myself as the optical guy. So we put a team quickly together and, errr, we then examined the design, quickly, errr, what was out there, was a prior art and quickly mimicked a system within two weeks based on, errr, off the shelf components, but were separate to the normal supply chain.* – Case 1 interviewee

In all three cases there was extensive reliance upon existing professional relationships. For instance, Cases 1 and 2 emphasised the need to be able to quickly identify and coordinate the technical expertise that was available within the university:

> *We pulled in together an Electronics guy, a firm guy and a mechanical guy and myself as the optical guy…because I knew what skills existed in the university.* – Case 1 interviewee

> *I'm from the School of Engineering, all the technicians all work together.* – Case 2 interviewee

Case 2 also stressed the value that was derived from existing relationships that had been forged with various support staff within the university:

> *I work with security because I am doing some special events for the School of Engineering and so on…so I knew them all.* – Case 2 interviewee

> *I have contacts with people in the US.* – Case 3 interviewee

> *I'd also had a conversation with this guy who's our contact in [Health Board] because I know him anyway from another project.* – Case 3 interviewee

It is self-evident that existing relationships between technical experts should be leveraged during times of crisis innovation. Such relationships are formed through the formation of organizational structure as well as being the intended product of exaptive events and forums.

However, it is pertinent to note the significance of the relationships that exist with non-technical staff (as in Case 2) that are also vitally important. These constitute a

group of 'operational' inter-personal relationships that appears to be overlooked in the study and practice of systems of innovation.

5.3 Deliberate – Reignited Relationships

In addition to 'live' relationships that were active at the time that the pandemic hit, Cases 1 and 3 also illustrate the instrumentality of weak or dormant relations that pre-dated the pandemic, but became re-enlivened and further established because of the COVID-19 crisis.

In case 3, University researchers spoke of the instrumentality of connections with contacts at both the local government, and industry relations with a contact in local government (the health board) existed due to a separate ongoing project:

> *I hadn't spoken to him in months, he'd phoned up because of something entirely different (we were co-supervising a PhD student) …and it was really only as an aside that I mentioned the COVID stuff…* – Case 3 interviewee

The relationship was instrumental to the rapid diagnostic test innovation because of the support it provided to requests for backing from the University:

> *He was just so interested that it then gave us a bit more incentive to go back to the university and go 'actually, look, there's external interest in this…the university believed in us because we had the link with the health board.* – Case 3 interviewee

Additionally, a key industry contact who facilitated the development of the diagnostic device, was known through attendance at a medical/life sciences industry conference which the University researcher had attended a few months before the outbreak of the COVID-19 pandemic:

> *I got chatting with them and basically talking about the UTI application, so that was in November, before COVID. But then I just called them, somewhere early Spring and said, you know, 'we could work together on this'.* – Case 3 interviewee

This is comparable to Case 1, wherein University researchers spoke of transient, and seemingly inconsequential interactions prior to the pandemic that became instrumental during the pandemic. Speaking of the medical clinician who originated the application of CPAP principles for early intervention in COVID patients, the lead University researcher stated,

> *Someone said I knew him…but I didn't know him to be honest with you,…I hadn't spoken to him. I think I might've bumped into him some place before, which he remembers, I don't. We had some interactions but I couldn't remember,* – Case 1 interviewee

Recognition of the temporal element of relations that may be instrumental in exaptive innovation (i.e. longstanding, or historic relations) suggests that the concept of exaptive relations provide a useful link between the environs that may bring about novel discoveries that have already been identified in the literature, (i.e. pools, events, and forums), and the success of innovation activities in the context of crisis, as demonstrated in our case studies.

5.4 Deliberate – New Relationships

In each case, existing technical and operational relationships, as well as more fortuitous links, were essential in enabling the innovation activities. However, these 'passive' relations were not sufficient, by themselves, to facilitate the successful completion of the projects. All three project teams also engaged in much more 'active' searches to establish new relations with other individuals and institutions that possessed specialist resources. In Case 1, the Welsh Government was highlighted as an essential element of the project through its role as a 'broker' or relationships. While it was not necessarily a source of direct knowledge or assistance, except in the form of funding for some activities, it was an essential conduit for linking up resources and demands, or "*correct pairs*" (De Rond, 2014, p.353):

> *I've got to be honest that was impressive, the way those guys come forward when you got a problem and say 'have you spoken to this one, talk to this one, right, talk to that one'.* – Case 1 interviewee

In all instances, the teams highlighted the frequent difficulties that they had in establishing links with relevant institutions and emphasised the need to be proactive. In particular, Case 2 identified that there has been little coordination of support for care homes since "*nobody actually reached out at that level*":

> *We started approaching the care homes and there was a huge response because they were struggling to get the visors.* – Case 2 interviewee

> *We were just trying to work with the health board to process some samples. That was key because even now other universities are struggling to get any kind of clinical samples whatsoever because they don't have that relationship.* – Case 3 interviewee

Case 3 also questions the efficacy of the existing mechanisms for exaptive events and forums through identifying the gulfs that persist between some institutional actors:

> *I've been to scientific conferences and then I've been to policy conferences, and the two just don't connec*t. – Case 3 interviewee

5.5 Unplanned Relationships/Encounters

While existing technical and operational relationships were important features of all three cases, each was also notable for the emergence of events that were predicated upon relationships that could not have reasonably been intended or predicted. In Case 2, one of the staff of the Finance Department had seen articles in the media that discussed the use of 3D Printing technologies to produce the frames for visors (part of the personal protective equipment that was required by healthcare workers). It was entirely coincidental that this person had previously placed an order for 3D Printing equipment for the Engineering Department for making model rockets. This individual instigated the discussion to utilise this equipment for the production of visors:

> *One of my colleagues placed the order, so when she received the order…she said by using this 3D printer, you can print some visors, right?* – Case 2 interviewee

Case 1 was remarkable for the commitment of other staff in the department who volunteered their services:

> *If you want for us to come on seven days, we are happy to come and actually get things done.* – Case 1 interviewee

Following an article in the local press, [a local facility specializing in cancer treatment] approached the Case 3 team and offered their assistance in clinical testing, an activity that had become a bottleneck to the success of the project:

> *They saw us on the news and so we've been talking to them for quite a few months as well.* – Case 3 interviewee

5.6 Types of Exaptation

Findings relating to exaptive pools, events, forums and relations are summarised as Table 1. Our perception of the literature is that it portrays serendipitous innovation as comprising two distinct dimensions. One consists of the motivation behind the innovation that may be either intended/deliberate or unintended/emergent. The other consists of the nature of the 'correct pairs' that are being melded. We view 'Pools' as repositories of codified knowledge that are to be combined and considered, whereas 'Forums' facilitate the interaction between human agents. However, it would be remiss to conceive of these as being mutually explicit environs. For instance, the ability to identify the 'correct pairs' of codified knowledge that exist within patents undoubtedly requires human action and interaction, which logically may give rise to the establishment of inter-personal relations. Similarly, the interactions between human agents in 'Forums' requires the sharing or recombination of knowledge bases in order to result in innovation. This inter-dependence between inter-personal relationships and knowledge bases is self-evident in the 'Events' that deliberately combine different knowledge-bases through direct interaction between individuals and, one would hope, sustained inter-personal relationships post-event.

From the above data analysis and discussion and in line with the contexts of exaptation in the literature (Garud, Gehman and Guiliani, 2016), we define Exaptive Relations as:

> *Exaptive relations refers to relations which function to mobilize, support or progress science-based innovations in ways, and with results, that were not anticipated ex ante. These can be long-standing pre-existing personal and professional relations, as well as emerging and unplanned relations, which are not intended to develop for specific project-oriented collaboration, but expanded, adapted and repurposed for a brand-new collaboration.*

We conceptualize and extend the literature as shown in Figure 1. Types of exaptation identified in the literature (pools, events and forums) and in our analysis (relations) are related to each other in terms of a continuum.

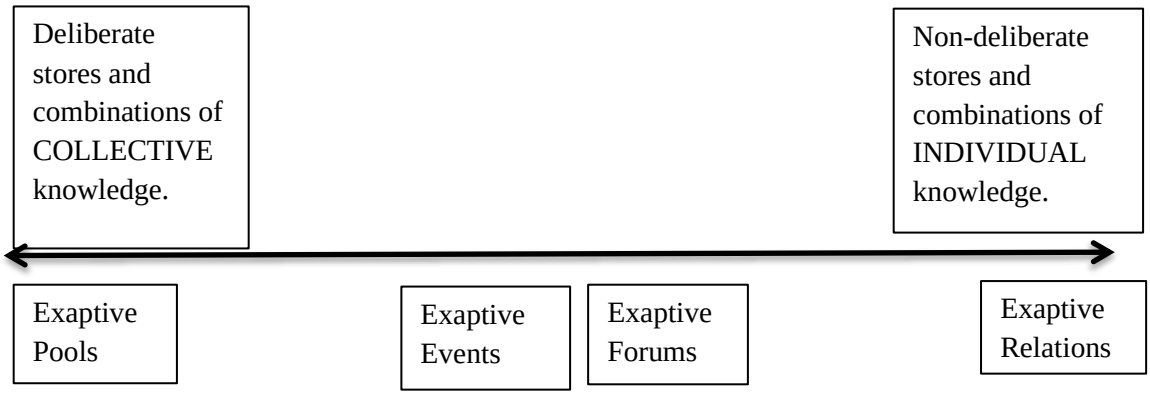

Figure 1. Types of Exaptation

6. Conclusion

This paper examines the development of three medical devices in response to the COVID-19 pandemic. Drawing upon exaptation theory it provides confirmatory evidence of the important role of exaptive pools, events and forums. It also identifies the critical importance of inter-personal relationships throughout the development process. These take the form of pre-existing active and dormant relationships, new relationships that are forged deliberately out of necessity, and the formation of new and unexpected relationships. Collectively these are termed 'exaptive relations' and proffer a contribution to exaptation theory. The study contributes to the literature that increasingly identifies the importance of micro-relations in the efficacious enactment of innovation, and also to the comparatively limited literature that explores innovations that are undertaken in response to crisis.

Since this research was undertaken during the unprecedented time of a global pandemic, the findings require confirmation under other conditions. While this study is concerned with the performance of innovation response to crisis there does not appear to be any reason why 'exaptive relations' should not be found to be present, and important, in other non-crisis scenarios. Furthermore, it is well-known that inter-personal relationships vary widely across different cultures and valuable research could therefore be made that explores the nature of 'exaptive relations' in other contexts.

This study is somewhat limited through its adoption of an interpretive approach, although the findings were confirmed through the adoption of multiple cases and researchers as well as participant validation. Future research could probe the nuances of 'exaptive relations' through extended interpretive approaches such as participant observation, while there is also opportunity to operationalize deductive methods.

Acknowledgement

The authors would like to acknowledge all interviewees from the three medical projects based in the region of South Wales. The authors would also like to thank Karen Young for her kind help with the interview transcription. Earlier versions of this paper have been presented at the South Wales Business School staff research

seminar, the Advances in Management and Innovation Conference Paper Development Workshop 2021, and the Community of Research Practice at Cardiff School of Management (Cardiff Metropolitan University), during which the authors received valuable feedback to improve the paper.

Declaration of Conflicting Interests

The authors declare that there is no potential conflict of interest with respect to the research, authorship and/or publication of this article.

Funding Statement

This research received no external funding.

References

Adner, R. (2017). Ecosystem as structure: An actionable construct for strategy. *Journal of Management*, 43(1), pp.39-58.

Andriani, P., Ali, A., Mastrogiorgio, M. (2017). Measuring exaptation and its impact on innovation, search, and problem-solving. *Organization Science*, 28(2), pp.320-338.

Andriani, P., Carignani, G. (2014). Modular Exaptation: a missing link in the synthesis of artificial form. *Research Policy*, 43, pp. 1608-1620.

Andriani, P., Cattani, G. (2016). Exaptation as a Source of Creativity, Innovation, and Diversity: introduction to the special issue. *Industrial and Corporate Change*, 25(1), pp. 115-131.

Andriani, P., Kaminska, R. (2021). Exploring the Dynamics of Novelty Production Through Exaptation: a historical analysis of coal tar-based innovations. *Research Policy*, 50(2), p.104171.

Anokhin, S., Wincent, J. and Frishammar, J. (2011). A Conceptual Framework for Misfit Technology Commercialization. *Technological Forecasting & Social Change*, 78, pp. 1060-1071.

Ardito, L., Coccia, M., Messeni Petruzzelli, A. (2021). Technological exaptation and crisis management: Evidence from COVID-19 outbreaks. *R&D Management*, 51(4), pp. 381-392.

Armani, A.M., Hurt, D.E., Hwang, D. et al. (2020) Low-tech solutions for the COVID-19 supply chain crisis. *Nat Rev Mater*, 5, 403-406 https://doi.org/10.1038/s41578-020-0205-1

Baldwin, C.Y., Clark, K.B. (2000). *Design Rules: The Power of Modularity* (Vol. 1) Boston, MA: MIT Press.

Becker, H.S. (1958). Problems of inference and proof in participant pbservation. *American Sociological Review*, 23(6), pp. 652-660.

Beltagui, A., Rosli, A., Candi, M. (2020). Exaptation in a digital innovation ecosystem: The disruptive impacts of 3D printing. *Research Policy*, 49, p.103833.

Benner, M., and Sandström, U. (2000). Institutionalizing the triple helix: research funding and norms in the academic system. *Research Policy*, 29, pp.291-301.

Borio, C. (2020). The COVID-19 economic crisis: Dangerously unique. *Business Economics* (Cleveland, Ohio). 55 (4), pp. 181–190.

Bositis, D.A. (1988). Some observations on the participant method. *Political Behaviour*, 10(4), pp. 333-348.

Boudreau, K.J., Lacetera, N., Lakhani, K.R. (2011). Incentives and problem uncertainty in innovation contests: An empirical analysis. *Management Science*, 57(5), pp. 843-863.

Brem, A., Radziwon, A. (2017). Efficient Triple-Helix collaboration fostering local niche innovation projects: A case from Denmark. *Technological Forecasting and Social Change*, 123. 10.1016/j.techfore.2017.01.002.

Buenstorf, G. (2009). Is commercialization good or bad for science? Individual-level evidence from the Max Planck Society. *Research Policy*. 38, pp. 281-292.

Carayannis, E.G., Rakhmatullin, R. (2014). The quadruple/quintuple innovation helixes and smart specialisation strategies for sustainable and inclusive growth in Europe and Beyond. *Journal of Knowledge the Economy*, 5(2), pp. 212-239.

Charmaz, K. (2006). *Constructing Grounded Theory: A Practical Guide Through Qualitative Analysis*. London: SAGE Publications.

Chesbourgh, H. (2020). To recover faster from COVID-19, open up: Managerial implications from an open innovation perspective. *Industrial Marketing Management*, 88(7), pp.410-413.

Ching, K. (2016). Exaptation dynamics and entrepreneurial performance: Evidence from the internet video industry. *Industrial and Corporate Change*, 25(1), pp. 181-198.

Cisnetto, V., Barlow, J. (2020). The development of complex and controversial innovations. Genetically modified mosquitoes for malaria eradication. *Research Policy*, 49, p.103917.

Ciulli, F., Kolk, A., Boe-Lillegraven, S. (2020). Circularity Brokers: Digital Platfrom Organizations and Waste Recovery In Food Supply Chains. *Journal of Business Ethics*, 167, pp. 299-331.

Clauss, T. et al. (2022) Temporary business model innovation – SMEs' innovation response to the COVID‐19 crisis. *R&D management*. 52 (2), pp. 294-312.

Cunha, M.P., Clegg, S.R., Kamoche, K. (2012). Improvisation as "real time foresight". *Futures*, 44, pp. 265-272.

Davies, I. A. (2009). Alliances and Networks: Creating Success in the UK Fair Trade Market. *Journal of Business Ethics*, 86, pp. 109-126.

Denscombe, M. (2010). *The Good Research Guide: For Small-Scale Social Research Projects* (4th ed). Berkshire: McGraw-Hill Education.

De Rond, M. (2014). The structure of serendipity. *Culture and Organization*, 20(5), pp. 342-358.

D'Este, P., Patel, P. (2007). University-industry linkages in the UK: what are the factors underlying the variety of interactions with industry? *Research Policy*, 36, pp. 1295-1482.

Dew, N., Sarasvathy, S.D. (2016). Exaptation and niche construction: Behavioural insights for an evolutionary theory. *Industrial and Corporate Change*, 25(1), pp. 167-179.

Dew, N., Sarasvathy, S.D., Venkataraman, S. (2004). The economic implications of exaptation. *Journal of Evolutionary Economics*, 14, pp. 69-84.

Djellal, F. & Gallouj, F. (2007). Innovation in hospitals: a survey of the literature. *The European journal of health economics*, 8(3), pp.181–193.

Duclos, D. (2019). When ethnography does not rhyme with anonymity: Reflections on name disclosure, self-censorship and storytelling. *Ethnography*, 20(2), pp.175-183.

Eden C., Huxham C. (1996). Action Research for Management Research. *British Journal of Management*, 7, pp. 75-86.

Etzkowitz H. (2003). Innovation in innovation: The Triple Helix of university-industry-government relation. *Social Science Information*, 42(3), pp. 293-338.

Etzkowitz, H., Leydesdorff, L. (2000). The dynamics of innovation: from National Systems and "Mode 2" to a Triple Helix of university–industry–government relations. *Research Policy*, 29(2), pp. 109-123.

Filippetti, A. & Archibugi, D. (2011) Innovation in times of crisis: National Systems of Innovation, structure, and demand. *Research policy*, 40 (2), pp.179–192.

Fink, T.M.A., Reeves, M., Palma, R., Farr, R.S. (2017). Serendipity and strategy in rapid innovation. *Nature Communications*, 8(1), p.2002.

Fox, N. (2009). *The NIHR research design service: Yorkshire. Using interview in a research project*. [Online] www.rdsyh.nihr.ac.uk/wpcontent/uploads/2013/05/15_Using-Interviews-2009.pdf [Accessed 6 October 2021).

Frankovic, I. et al. (2020) Medical innovation and its diffusion: Implications for economic performance and welfare. *Journal of macroeconomics*. [Online] 66.

Galvin, P., Burton, N., Nyuur, R. (2020). Leveraging inter-industry spillovers through DIY laboratories: Entrepreneurship and innovation in the global bicycle industry. *Technological Forecasting & Social Change*, 160, p.120235.

Ganzaroli, A., De Noni, I., Pilotti, L. (2014). The Role of Social Entrepreneurship in Leveraging Exaptation in Locked-In Industrial Districts: the case of Idrogenet in the Industrial District of Lumezzane. *Innovation: The European Journal of Social Science Research*, 27(3), pp. 254-274.

Garud, R., Gehman, J., Giuliani, A.P. (2016). Technological exaptation: A narrative approach. *Industrial and Corporate Change*, 25(1), pp. 149-166.

Glaser, B.G., Strauss, A.L. (1967). *The Discovery of Grounded Theory: Strategies for Qualitative Research*. New York, NY: Aldine Publishing Company.

Godoe, H. (2000). Innovation regimes, R&D and radical Innovations in telecommunications. *Research Policy*, 29, pp. 1033-1046.

Gould, S. J., Vrba, E. S. (1982). Exaptation-A missing term in the science of form. *Paleobiology*, 8(1), pp. 4-15.

Goulding, C. (2001). Grounded Theory: A Magical Formula or a Potential Nightmare. *Marketing Review*, 2(1), pp. 21-34.

Graebner, M.E. (2004). Momentum and Serendipity: How acquired leaders create value in the integration of technology firms. *Strategic Management Journal*, 25, pp. 751-777.

Gronhaug, K., Olson, O. (1999). Action research and knowledge creation: Merits and challenges. *Qualitative Market Research*, 2(1), pp. 6-14.

Guan, J., & Chen, K. (2012). Modelling the relative efficiency of national innovation systems. *Research Policy*, 41(1), pp. 102-115.

Guest, G.S., MacQueen, K.M., Namey, E.E. (2012). *Applied Thematic Analysis*. UK: Sage Publications.

Gulbrandsen, M. et al. (2016) Hospitals and innovation: Introduction to the special section. *Research policy*, 45 (8), pp. 1493-1498.

Halcomb, E J., Davidson, P.M. (2006). Is verbatim transcription of interview data always necessary? *Applied Nursing Research*, 19, pp. 38-42.

Heger, T., Rohrbeck, R. (2012). Strategic foresight for collaborative exploration of new business fields. *Technological Forecasting & Social Change*, 79, pp. 819-831.

Hu, X. et al. (2021) Crisis-Induced Innovation: Quality Upgrading in Chinese Industrial Clusters. *Journal of Law, Economics, & Organization*, 37 (3), pp.571–606.

ILO (2020). *ILO Monitor: COVID-19 and the world of work. Second edition.* [Online]. Available at https://www.ilo.org/wcmsp5/groups/public/---dgreports/---dcomm/documents/briefingnote/wcms_740877.pdf (Accessed 2 November 2021).

Jick, T.D. (1979). Mixing qualitative and quantitative methods: Triangulation in action. *Administrative Science Quarterly*, 24(4), pp. 602-611.

Johnson, R.B, Onwuegbuzie, A.J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Researcher*, 33(7), pp. 14-26.

Kakko, I., Inkinen, S. (2009). Homo creativus: Creativity and serendipity management in third generation science and technology parks. *Science and Public Policy*, 36(7), pp. 537-548.

Karakas, F., Sarigollu, E., & Uygur, S. (2017). Exploring the Diversity of Virtues Through the Lens of Moral Imagination: A Qualitative Inquiry into Organizational Virtues in the Turkish Context. *Journal of Business Ethics*, 141, pp. 731-744.

Katila, R., Ahuja, G. (2002). Something old, something new: a longitudinal study of search behavior and new product introduction. *Academy of Management Journal*, 45(6), pp. 1183-1194.

Katz, B., Wagner, J. (2014). *The Rise of Innovation Districts: A New Geography of Innovation in America*. USA: Metropolitan Policy Program at Brookings.

Knoben, J., Oerlmans, L.A.G., Rutten, R.P.J.H. (2006). Radical changes in inter-organizational network structures: The longitudinal gap. *Technological Forecasting & Social Change*, 73, pp. 390-404.

Koh, A. (2000). Business creativity: A preliminary assessment of the East Asian quest for creativity. *Technological Forecasting & Social Change*, 64, pp. 85-100.

Kuckertz, A., Brändle, L., Gaudig, A., Hinderer, S., Reyes, C.A.M., Prochotta, A., Steinbrink, K., and Berger, E.S. (2020). Startups in times of crisis – A rapid response to the COVID-19 pandemic. *Journal of Business Venturing Insights*,13, e00169.

Lane, J.N., Ganguli, I., Gaule, P., Guinan, E., Lakhani, K.R. (2021). Engineering Serendipity: when does knowledge sharing lead to knowledge production? *Strategic Management Journal*, 42, pp. 1215-1244.

Langley, A., & Abdallah, C. (2011). Templates and turns in qualitative studies of strategy and management. In D. Bergh & D. Ketchen (Eds.), *Building Methodological Bridges: Research Methodology in Strategy and Management* (6, pp. 201-235). Bingley: Emerald Group.

Laurell, H. (2018). An international new venture's commercialization of a medical technology innovation: The role of institutional healthcare settings. *International marketing review*. 35(1), pp. 136–163.

Leckel, A., Veilleux, S., Dana, L.P. (2020). Local open innovation: A means for public policy to increase collaboration for innovation in SMEs. *Technological Forecasting & Social Change*, 153, p.119891.

Leven, P., Holmstrom, J., Mathiassen, L. (2014). Managing research and innovation networks: evidence from a government sponsored cross-industry program. *Research Policy*, 43, pp. 156-168.

Liu, W., Beltagui, A., Ye, S. (2021). Accelerated innovation through repurposing: exaptation of design and manufacturing in response to COVID-19. *R&D Management*, 51(4), pp.410-426.

Locke, E.A. (1976). The nature and causes of job satisfaction, in *M.D. Dunnette* (Ed.), *Handbook of Industrial and Organizational Psychology*. Chicago: Rand McNally.

Longoni, A. & Cagliano, R. (2018). Sustainable Innovativeness and the Triple Bottom Line: The Role of Organizational Time Perspectives. *Journal of Business Ethics*, 151, pp. 1097-1120.

Lynch, M. (2000). Against reflexivity as an academic virtue and source of privileges knowledge. *Theory, Culture & Society*, 17, pp. 26-54.

Marquis, C., Huang, Z. (2010). Acquisitions as Exaptation: the legacy of founding institutions in the U.S. commercial banking industry. *Academy of Management Journal*, 53(6), pp. 1441-1473.

McKelvey, M., Zaring, O., Ljungberg, D. (2015). Creating Innovation Opportunities Through Research Collaboration: an evolutionary framework and empirical illustration in engineering. *Technovation*, 39-40(1), pp. 26-36.

Meyers, M. A. (2007). Happy Accidents: Serendipity in Major Medical Breakthroughs in the Twentieth Century. Arcade: NewYork, NY.

Miles, M.B. (1979). Qualitative data as an attractive nuisance: The problem of analysis. *Administrative Science Quarterly*, 24(4), pp. 590-601.

Miller, K., McAdam, R., McAdam, M. (2016). A systematic literature review of university technology transfer form a Quadruple Helix perspective: toward A research agenda. *R&D Management*, 48(1), pp. 7-24.

Moraes, C., Kerrigan, F., & McCann, R. (2020). Positive Shock: A Consumer Ethical Judgement Perspective. *Journal of Business Ethics*, 165, pp. 735-751.

Nelson, R.R. (2003). On the uneven evolution of human know-how. *Research Policy*, 32, pp. 909-922.

Netz, J., Reinmoeller, P., Axelson, M. (2022). Crisis-driven innovation of products new to firms: the sensitization response to COVID-19. *R&D Management*, 52 (2), pp. 407-426.

Oksanen, K., Hautamaki, A. (2014). Transforming regions into innovation ecosystems: A model for renewing local industrial structures. *The Innovation Journal: The Public Sector Innovation* Journal, 19(2), pp. 2-16.

Opdenakker, R. (2019). Advantages and disadvantages of four interview techniques in qualitative research. *Open Journal System*, 7(4). Available at http://www.cpc.unc (Accessed 1st July 2020).

Ornelia, W.M. (2015). Determinants of university-firm R&D collaboration and its impact on innovation: A perspective from a low-tech industry. *Research Policy*, 44, pp. 1341-1359.

Pollard, C.A., Morran, M.P., Nestor-Kalinoski, A.L. (2020). The COVID-19 pandemic: A global health crisis. *Physiological Genomics*, 52 (11), PP. 549–557.

Rahmandad, H. (2008). Effects of delays on complexity of organizational learning. *Management Science*, 54(7), pp. 1297-1312.

Ramamurti, R. (2020) Using Reverse Innovation to Fight COVID-19. *Harvard Business Review*. Available online: https://hbr.org/2020/06/using-reverse-innovation-to-fight-COVID-19 (Accessed on 15 March 2021).

Razak A.A., White G.R.T. (2015). The Triple Helix model for innovation: A holistic exploration of barriers and enablers. *International Journal of Business Performance and Supply Chain Modelling*, 7(3), pp. 278-291.

Reale, F. (2021) Mission-oriented innovation policy and the challenge of urgency: Lessons from COVID-19 and beyond. Technovation, 107, p. 102306.

Rodrigues, C., Melo, A. (2012). The Triple Helix model as an instrument of local response to the economic crisis. *European Planning Studies*, 20(9), pp. 1483-1496.

Sanday, P.R. (1979). The ethnographic paradigm(s). *Administrative Science Quarterly*, 24(4), pp. 527-538.

Santangelo, G.D., Stucchi, T. (2018). Internationalization through exaptation: the role of domestic geographical dispersion in the internationalization process. *Journal of International Business Studies*, 49, pp. 753-760.

Sauer, S., Bonelli, F. (2020). Collective improvisation as a means to responsibly govern serendipity in social innovation processes. *Journal of Responsible Innovation*, 7, pp. 544-563.

Schiavone, F., Leone, D., Caporuscio, A., Lan, S. (2022). Digital servitization and new sustainable configurations of manufacturing systems. *Technological Forecasting & Social Change*, 176, p. 121441

Schwartz, M.S. and Schwartz, C.G. (1955). Problems in participant observation. *The American Journal of Sociology*, 60(4), 3, pp. 43-353.

Seidman, I. (1998) *Interviewing as Qualitative Research: A Guide for Researchers in Education and the Social Sciences*. New York: Teachers College Press.

Siegel, D. S., Waldman, D.A., Atwater, L.E.A., Link, A.N. (2003). Commercial knowledge transfers from universities to firms: improving the effectiveness of university-industry collaboration. *Journal of High Technology management Research*, 14, pp. 111-133.

Spiggle, S. (1994). Analysis and interpretation of qualitative data in consumer research. *Journal of Consumer Research*, 21(3), pp. 491-503.

Strauss, A., Corbin, J. (1998). *Basics of Qualitative Research Techniques and Procedures for Developing Grounded Theory* (2nd ed). London: SAGE Publications.

Suter, L. G. et al. (2011) Medical Device Innovation — Is 'Better' Good Enough? The New England journal of medicine. [Online] 365 (16), 1464–1466.

Tria, F., Loreto, V., Servedio, V.D.P., Strogatz, S.H. (2014). The dynamics of correlated novelties. *Scientific Reports*, 4, p. 5890.

Van den Hoonard, W.C. (2003). Is anonymity an artefact in ethnographic research? *Journal of Academic Ethics*, 1(2), pp. 141-151.

Wareham, J., Priego, L.P., Rosamanta, A.K., Mathiassen, T.W., Nordberg, M. and Tello, P.G. (2022). Systematizing Serendipity for Big Science Infrastructures: the ATTRACT project. *Technovation*, p.102374.

Watkins, A., Papaioannou, T., Mugwagwa, J., Kale, D. (2015). National innovation systems and the intermediary role of industry associations in building institutional capacities for innovation in developing countries: A critical review of the literature. *Research Policy*, 44, pp.1407-1418.

Winsor, B., Hall, H. (2018). Time in the Triple Helix: A foundation for innovation. *Journal of Management Policy and Practice*, 19(2), pp. 152-166.

White, G.R.T., Abdullah A, Cicmil S, Allen, R., Thomas, R. (2019). University-industry collaboration through knowledge transfer partnerships in the UK: an extension of Activity Theory. *The International Journal of Management*, 8(4), pp. 14-24.

World Health Organization (2021). *WHO Coronavirus (COVID-19) Dashboard*, Available at: https://COVID19.who.int/ (Accessed on 2nd Nov 2021)

Yin, R, K. (2013). *Case Study Research: Design and Methods.* SAGE, London.

Endnotes (Author Biographies)

Steffan James is a research fellow in manufacturing engineering systems at the South Wales Business School. His primary research focuses upon the adoption of emerging technologies in industry to improve efficiency and sustainability, collaborating with manufacturing businesses in East Wales as part of the ASTUTE programme. He has presented his work at the 2020 Society of Open Innovation Conference as well as the South Wales Business School Research Conference.

Zheng Liu (PhD) is a Senior Lecturer in Strategic Management at Cardiff Metropolitan University. Her research focuses on Open Innovation, Triple Helix Innovation, Business Ecosystem, and Sustainability. The results of her research have been published in several journals and book chapters. Zheng's current research investigates the transformation of supply chain in response to the COVID-19 pandemic. Since 2016, Dr. Liu has been collaborating with researchers from the Centre for Innovation and Development, Nanjing University of Science and Technology as a research fellow.

Victoria Stephens (PhD) is a Lecturer in Supply Chain Management at South Wales Business School, University of South Wales. Her work has been published in the Journal of Supply Chain Management, and current research interests include the role and use of metaphors and other novel approaches for thinking differently about issues related to sustainability and supply chain management.

Gareth RT White (PhD) (retired) is Research Lead for several public and private educational establishments. His research interests comprise operations improvement techniques, information systems management and social enterprise. His work is published in Technovation, IEEE Transactions on Engineering Management, Production Planning and Control, International Journal of Production Research, Technological Forecasting and Social Change, European Journal of Marketing and Tourism Management.