The Theory of Technological Response and Progress in Chaos

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Abstract:

Chaos initiates rapid response mechanisms, and this forces all relevant actors to readjust and adapt to these sudden changes in the environment. The novel coronavirus (COVID-19) pandemic has demonstrated that current national and organisational response mechanisms are inadequate regarding scientific and technological capabilities and approaches. Technologies are one of the key response mechanisms for such chaos. Previous studies theorised on the various manners in which chaos occurs and leads to significant effects concerning its stages and cycles. However, no studies exist on the way technologies respond and progress during a chaotic event. Thus, the aim of this study was to develop the first Theory of Technological Response and Progress in Chaos (TRPC) and examine the case of technological development during the COVID-19 pandemic. This study uses grounded theory as a methodology, with a mixed-method approach that included quantitative and qualitative approaches. We implemented machine learning and text mining to aid in the stages of the grounded theory approach. As a result of the TRPC theory development process, we identified three types of technologies (survival, essential and enhancement technologies) and five types of periods (stable, initial, survival-dominant, essential-dominant and enhancement-dominant periods) that are specific to chaos-technology interactions. The policy implications of our study demonstrate that a required technological base and know-how must be established before a chaos event emerges. Our theory helps for responses and policy development for future chaos.

Keywords: Chaos Theory, COVID-19, Technological Response, Grounded Theory, Theory of Technological Response and Progress in Chaos

1. Introduction

Chaos is characterised by fast-emerging phenomena triggered by small-scale and sudden events (Levy, 1994). Chaos is a recurring phenomenon that requires continuous preparation, adaptation and resilience by humanity. These are largely unpredictable, uncontrollable and unstable conditions. Chaotic and complex environments trigger rapid response mechanisms, and this forces all relevant actors to readjust and adapt to these sudden changes in the environment (Stanley, 2020). However, the novel coronavirus (COVID-19) pandemic has demonstrated that current national and organisational response mechanisms are inadequate concerning scientific and technological capabilities and approaches. Although COVID-19 is one of the major pandemics of the 21st century, it is not the first chaos event that has occurred in this century (e.g. the severe acute respiratory system outbreak [SARS]), and the central issue has been unpreparedness regarding such rapidly developing health concerns (van Barneveld et al., 2020). Technological innovations, whether already available or developed in response to an emerging situation, are one of the primary mechanisms to aid in mitigating the impact of chaos. A study by Larkin (2003) demonstrated how technologies responded to resolve or minimise the impacts of SARS. Therefore, it is important to understand how technologies are used to respond to newly emerging chaos.

The OECD Committee for Scientific and Technological Policy (CSTP) oversees science, technology and innovation (STI) policy responses to COVID-19 and, to date, they have provided details on greater than 300 policy initiatives (OECD, 2021a). For the COVID-19 pandemic, many nations implemented initiatives for technological applications to control and prevent the spread of the virus (OECD, 2020). The rapid technological adoption of digital technologies, such as artificial intelligence (AI), to respond to COVID-19 and maintain the STI ecosystems' operations may accelerate the widespread use of these technologies in STI and policymaking (OECD, 2020). The STI specific initiatives include open science commitments, interoperability and standardisation initiatives, computing resources for COVID-19, modelling (epidemiology), AI-powered search engines, genomics, and clinical research and crowdsourcing platforms (OECD, 2021b). The above-mentioned policies and initiatives further signify the importance of technological response and development during the chaos period. However, a systematic technological intervention does not exist to generalise the relationship between technologies and chaotic environments.

Previous studies regarding the examination of chaos and its progress identified the nature and characteristics of the process. The studies in this field analysed how chaos emerges, creates disorder and leads to new order (Lyapunov, 1992; Gunderson and Holling, 2001). The Lyapunov Exponent is used to detect chaotic behaviour in a dynamic process that creates order and disorder in a complex system (Lyapunov, 1992). Gunderson and Holling (2001) introduced the Panarchy concept to explain the cyclic process of chaos and order, and how one leads to the other. Hung and Tu (2014) investigated how technological change occurs during chaotic and complex behaviour by examining longitudinal patent data using the chaos theory with predictive methods. Their findings demonstrate that a shift from old to new technologies leads to a chaotic process. However, to the best of our knowledge, no studies or theoretical framework exist that describe how technologies respond and develop during the immediate outbreak of chaos. Furthermore, it is unclear what the stages of technological development are in response to chaos. The Scientific Foresight Unit of the European Parliamentary Research Service provided an analysis of 10 key technologies regarding COVID-19 (Kritikos, 2020). However, this was not an empirical study; it provided a list of technologies but without a holistic or systematic approach concerning chaos. This indicates that there is a requirement for an empirical study to be conducted to examine chaos-related and COVID-19-specific technologies.

Considering the gap in the literature, the aim of this study was to develop the first Theory of Technological Response and Progress in Chaos (TRPC) and examine the case of technological development during the COVID-19 pandemic. The research objectives of this study were to:

- Identify the key technologies that act as a response mechanism during the chaos event, specifically in the case of COVID-19,
- Examine how technologies evolve, develop and diffuse in an immediate crisis and a chaotic environment,
- Theorise various types and periods of technological response and progress during the emergence of chaos and the stages that unfold,
- Develop policy-oriented recommendations and establish technological foundations to address subsequent chaos events.

Our research provides **two** key contributions to previous studies. **Firstly**, following the indications of the OECD (2021a) and considering the study conducted by the European Parliamentary Research Service (EPRS) (Kritikos, 2020), we identified the key technologies that are significant for chaos and COVID-19 response using our machine learning and text intelligence approach. Accordingly, we mapped all technological developments using clustering approaches, and we examined the technological progress within the immediate chaos period using social media data. **Secondly**, we have contributed to the chaos studies and the relationship between chaos and technological development by establishing the first theoretical foundation using the grounded theory approach, hereafter referred to as the Technological Response and Progress in Chaos (TRPC) theory. As part of the TRPC theory, we present three periods of technological response in the following sequence: 1) survival technology, 2) essential technology and 3) enhancement technology. Moreover, we illustrate the evolving technological importance and priorities as the periods of technological progress proceed under rapidly developing chaos.

This paper is structured as follows: the literature review section includes an analysis of the chaos theory and COVID-19 crisis. Next, the relevant theories and conceptual models for chaos and technological response are reviewed with illustrative cases. We conclude the literature review section by discussing research gaps and limitations. The methodology section provides information regarding the grounded theory approach that was applied and explains the details of the social media-based data retrieval method. The results section consist of two parts: a presentation of the technological clusters for COVID-19 and a description of the proposed TRPC theory. Finally, we summarise the key implications and present a technology policy based on the key findings.

2. Literature Review

2.1 Chaos Theory and COVID-19: 'The bat effect'

Chaos theory refers to random or unpredictable behaviours in systems, which are governed by deterministic laws (Levy 1994). Chaos theory is frequently explained with 'sensitive dependency', explaining sensitivity to the smallest changes (Stanley, 2020). Arguably, this notion was first introduced by Aristoteles when he observed that 'the least initial deviation from the truth is multiplied later a thousandfold' (Aristotle OTH, 271b8). Subsequently, Lorenz's (1963) well-known paper, entitled 'Deterministic Nonperiodic Flow', presented a more concrete discussion on how small disturbances may grow exponentially to produce substantial effects on a physical system's behaviour. The temporal nature of chaos suggests that unexpected consequences emerge from modest events, where the consequences are much larger in scale compared to their root causes (Lyapunov, 1992). The so-called butterfly effect is the iconic image of chaos theory, and it has been applied in many disciplines ranging from natural sciences to business studies (Zeraoulia, 2011; Skiadas and Skiadas, 2017).

Chaos is characterised by fast-emerging phenomena triggered by small-scale and sudden events. These are largely unpredictable, uncontrollable and unstable. They may contain certain patterns, which may allow for limited prediction and short-term forecasting. However, creating long-term planning in chaos is extremely difficult. Guidelines are required to cope with the complexity and uncertainty in chaos (Levy, 1994). Understanding the nature of chaos and its impacts on complex socio-economic and technological systems can help policy and strategy makers to mitigate the negative impacts of disruptions while generating opportunities to explore innovative solutions. In many ways, the space between chaos and order is where innovation, creativity and leadership thrive (Kaur et al., 2020; Jadav and Trivedi 2021).

Arguably triggered by the 'bat effect', the COVID-19 pandemic has rapidly spread globally, infecting countless individuals and claiming millions of lives. Over a short period, the pandemic affected world societies in all spheres of life, from health to employment, commerce, education, transportation, production and consumption, and tourism, among others. Questions remain regarding how fast the virus spreads, what the short- and long-term health effects will be, how long it will last, and when it will be contained (Postavaru et al., 2021). Due to its origin, growth, complexity, unpredictability and impact, the COVID-19 pandemic is a 'chaotic event'.

Great effort has been made to understand the nature and causes of the virus and how the pandemic could be controlled. During this chaotic process, radical measures have been taken to control the spread of the virus and prevent loss of lives. These measures disrupted individual and organisational systems to a large extent, which resulted in the COVID-19 pandemic becoming a global scale socio-economic concern. Managing a major global pandemic such as COVID-19 requires all countries and regions to implement different but synchronised measures to decrease its socio-economic effects in the short, medium and long -term. As the pandemic has progressed, numerous studies have been conducted. The initial research focused on developing medicines, vaccines and other cures for COVID-19. However, during the pandemic technological solutions have been proposed to address a wide variety of emerging challenges. To examine the various types of interventions during the COVID-19 process, it is important to understand the process of chaos and its stages.

2.2 Relevant Theories and Conceptual Models for Chaos and Technological Response

Most of the studies that focus on innovation and technology development in relation to chaos demonstrate that these development processes are chaotic. For example, according to Cheng and Van de Ven (1996), 'the innovation process is either random or chaotic' (p.598). Hung and Lai (2016) studied the progress of technological change regarding its chaotic and complex behaviour and examined patent data using the chaos theory with predictive methods. In contrast to these studies, we considered chaos as a contextual factor and focused on the technological responses to rapidly emerging chaos. More specifically, we examined how technological responses are developed during the various stages of chaos, from emergence to the post-chaos stages. Hence, this study employed the theories that have cyclical natures and address different phases of socio-economic and technological evolution that involve a stage of chaos. Four complementary theoretical and conceptual models were selected, which create a basis for the technological response to chaos theory, as follows:

1. Vickers' 'Appreciative Systems' theory (Vickers, 1965; 1970; 1973)
2. The Lyapunov Exponent (Lyapunov, 1992)

3. Gunderson and Holling's 'Panarchy' theory (Gunderson and Holling, 2001)
4. The Order-Chaos model in an innovation process (Hung and Lai, 2016)

Their commonality lies in the fact that each cyclical process has a phase of chaos with increased complexity, where systems organise and reorganise themselves as events unfold. Vickers' 'Appreciative Systems' theory portrays the relationships between changing conditions and adaptation (Vickers, 1965; 1970; 1973). The starting point of the Appreciative System is the interacting flux of events and ideas unfolding over time. This is Vickers' 'two-stranded rope', in which the strands are inseparable and continuously affect each other as parts of a complex system. Each cycle of the strand is composed of positive and negative synergistic relationships between social, technological, economic, ecological, political and value/cultural systems, which lead to chaos and order. Through communication within this complex context, the system is established, situations are perceived, judgements about the perceived situation are made, ideas are developed, and actions are determined as part of the events stream. This is a recursive view in which the flux of events and ideas generates a new appreciation, and appreciation itself leads to actions while improving the standards.

The Lyapunov Exponent (LE) is the principal criteria of chaos and represents the growth or decline that creates order and disorder in a system. The LE uses empirical data to detect chaotic behaviour in dynamic processes. One or more LE are observed across time series and phase plots (*k*). A positive result ($\lambda>0$) indicates that nearby trajectories diverge; the system is sensitive to initial conditions and is, therefore, chaotic (a characteristic of a chaotic pattern). Zero exponents ($\lambda=0$) characterise a marginally stable process, and a negative result ($\lambda<0$) indicates that the time series is either fixed point, periodic or random (Cheng and Van de Ven,1996). Typically, chaos emerges when the initial values of a time series that are close together separate exponentially. Jayanti and Sinha (1998) used LEs to explain the implementation of innovation in high-technology manufacturing through a chaos-based empirical study. The authors demonstrated the process of transitioning from a Negative Metal Oxide Semiconductor (NMOS) technology to a Complementary Metal Oxide Semiconductor (CMOS) technology in a wafer fabrication plant over 125 weeks (50 weeks involved chaotic patterns which were followed by a stabilisation period). The LE has also been used to illustrate and detect chaotic patterns in the process of technological change. Hung and Tu (2014) used two quantifiers, including correlation dimensions and LE, to examine the signs and degrees of chaotic technological dynamics through a study on the development of electronic displays from 1976 to 2010 (using patent data).

The emergent dynamics may shift situations from order to disorder, stability to disruption and continuity to discontinuity. This process is explained by the 'Panarchy' theory, which was introduced by Gunderson and Holling (2001) and later expanded by Holling (2001) and has implications for ecological, political, institutional and management systems. The process of Panarchy consists of the following stages:

1. Stability, growth and accumulation (up to the COVID-19 pandemic), the resultant rigidity of the system, increasing vulnerability and fragility, and decreasing resilience – growth to collapse (Omega stage).
2. Change and variety (during the COVID-19 pandemic, from the initiation to the containment), collapse of a highly fragile system due to a crisis, resultant chaos, and responses (many ideas and innovations are tested and several of them will be successful to shape the principles of the emerging new order). Chaos at this stage also creates opportunities for novelty and renewal for growth during the next phase (Alpha stage).
3. Resilience (the process after the COVID-19 pandemic) and the emergence of a new system (at a higher level of order, stability and growth, until the next crisis when it becomes too rigid).

Finally, the Order-Chaos model described by Hung and Lai (2016) explains the technological progress in relation to chaos in a staged process. This model assumes that there are dominant technologies that follow the S-curve trajectory over time. When the technology enters the 'sunset' stage, new technology will begin to emerge to replace the old one. The period during which the old and new technologies meet is known as the 'chaos zone' because, at this stage, the industry and market are considered to be unpredictable. Similar to the Panarchy concept, during a period of chaos, many technologies are proposed and they must compete with each other in the following stage. The dominant technology then replaces the old one and reshapes the industry, thus, the next stage of 'order' begins. Following this pattern, the process of innovation is a continuous interchange of order and chaos in the subsequent stages.

A joint representation of the four above-mentioned theories and models is presented in Figure 1 and each is portrayed with its respective cycle.

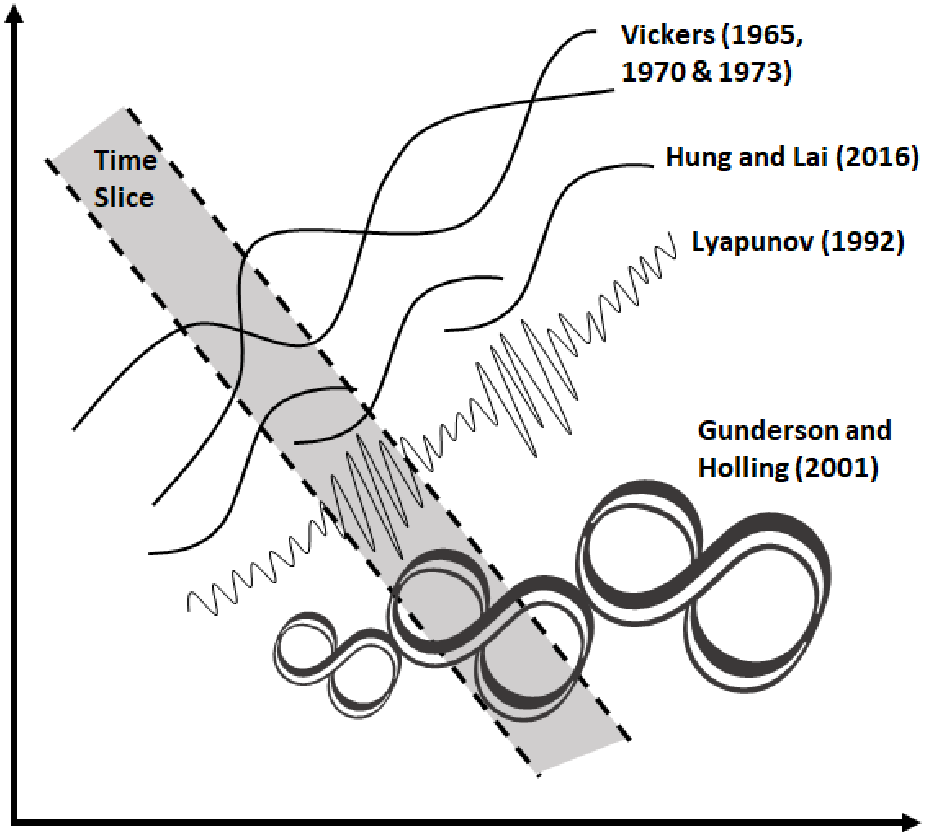

Figure 1. A representation of the theories and models used and the focused 'time slice' of the present research

As Figure 1 illustrates, most of the studies that focus on technology development and chaos consider the process over a longer timeframe, during which the old and established technologies are replaced by new ones in a chaotic context of nonlinear behaviour and temporal dynamics. The dark shaded zone in Figure 1 is superimposed on the chaos stages of each model and corresponds to a 'time slice' i.e. the period during which chaos emerges, resulting in an immediate response and changes in the environment. We focused on this time slice in the present study. In certain cases, the duration of this period may span years and, in other cases, months or weeks. For instance, Hung and Lai (2016) considered the development of printers during the 1976–2012 period using patent application data. In these studies, the world was assumed to contain complexities and disorder, where there was a continuous requirement to manage the 'unexpected'. However, in certain cases, this time slice of chaos can have an extremely short duration and immediate responses must be developed to address the rapidly emerging chaos. This stage between the emergence of chaos and the introduction of order was termed 'CHAORD' by Jourdain and Nagel (2020). CHAORD is the stage where innovation is possible, steady leadership is essential, and emergence is likely.

The COVID-19 pandemic represents a rapidly emerging and evolving chaos event with a sudden, unexpected and forced disruption which requires intervention over a short period. The initial challenge of this pandemic was to determine how to produce sufficient masks and ventilators. Next, it was crucial to determine how self-isolation could be achieved while maintaining the basic functions of socio-economic life, such as accessing food and other essential goods and services. Subsequently, solutions were developed to facilitate the continuation of social and economic life for, education, businesses and public services. Finally, at present, steps are being discussed for innovating towards more resilient systems against the future instances of a pandemic or any other similar disruptions and chaos. Therefore, we considered that the process of technological response and progress in the period of CHAORD emerged in consecutive stages and occurred in a narrow time slice.

2.3. Technological Responses to Chaos and Complexity

Having reviewed the theories regarding technological progress during a chaos event and the complexity of the theories and relevant stages, we next examined cases where technological progress was analysed in relation to chaos, crises and complexities. Whether natural or man-made, disasters such as earthquakes, hurricanes, volcanic eruptions, wildfires, wars, pandemics, and economic shocks create an abundance of chaos, claim lives and cause social disturbances. The flagship publication of the United Nations International Strategy for Disaster Reduction (UNISDR), titled 'the Global Assessment Report on Disaster Risk Reduction (GAR)', estimated that as of 2013, the direct cost of disasters in the 21st century was $2.5 trillion (GAR, 2013). Moreover, this figure is at least 50 per cent higher than previous estimates. From aerial robotics to big data analytics, technological innovations (whether already available or developed in response to an emerging situation) present opportunities to expedite and magnify the impact of humanitarian relief efforts through greater efficiency and responsiveness. Furthermore, these technological innovations mean that more people can be provided with aid sooner and more cost-effectively, which results in more lives being saved and normalisation and improvement of their living conditions.

According to Yoo (2018), technologies can aid in the response to crises in four ways: (i) they can access areas that people cannot and can be used to support high-risk rescue operations, (ii) they can enable connectivity to facilitate the delivery of life-saving information, (iii) mobile technologies, social media and digital communities can be used to develop a real-time and deeper understanding of requirements, resulting in more efficient responses, and (iv) big data analytics technologies can be used to collect crucial information and intelligence, and prioritise and optimise the development of responses. Sakurai and Murayama (2019) highlighted the crucial role of information technologies concerning the various stages of disaster management, including disaster response, recovery, preparedness and risk reduction. Tim et al. (2017) reported that during Hurricane Sandy in 2012, social media platforms such as Facebook, Twitter, YouTube and Instagram were used extensively to support traditional disaster response mechanisms by providing situational awareness and two-way communication. Moreover, geo-tagged Instagram photos facilitated an understanding of the location and severity of the disaster. This information aided the disaster response agencies in coordinating their relief efforts.

In early 2003, Severe Acute Respiratory Syndrome (SARS) emerged. This was a viral respiratory disease caused by a SARS-associated coronavirus. The virus was first identified at the end of February 2003, during an outbreak in China, and spread to four other countries (WHO, 2021). Larkin (2003) reported on several of the cutting-edge technologies that were developed to combat SARS. Among those technologies was an infrared sensor that could determine a person's body temperature without physical contact. In the early 2000s, this sensor was used to measure the body temperatures of large numbers of individuals in railway stations, airports and harbours, to control the spread of SARS. A technology known as 'grid computing' was also used to combat SARS. This technology aided in sharing and secure storage of X-ray images and medical information about patients and allowed healthcare professionals to remotely view files and collaborate on diagnoses and clinical decisions.

Following the SARS epidemic, the novel coronavirus (SARS-CoV-2, or COVID-19) pandemic emerged at an unexpected time and on an unprecedented scale. Compared to SARS, COVID-19 was more severe and had a larger geographical spread. As COVID-19 became a global pandemic and a major global health concern over a short period, with severe social and economic impacts, there was an immediate requirement to contain the virus. Based on the SARS experience and the previous studies and technological developments, the role of technology in addressing the challenges caused by COVID-19 was widely recognised since the beginning of the pandemic. Numerous technological responses were developed to mitigate this chaotic event based on the available technologies (e.g. an infrared sensor for contactless temperature measurement), and processes for developing new technologies were initiated over a short period.

Since the SARS outbreak, due to post-chaos effects on technology and technological developments and investments, improved versions of previous technological solutions have emerged, in addition to completely new technologies. A recent report by the European Parliament provided a list of the top 10 technologies to combat COVID-19 (Kritikos, 2020). These were AI, blockchain, open-source technologies, telehealth technologies, three-dimensional printing, gene-editing technologies, nanotechnology, synthetic biology, drones, and robots. Each of these technologies was discussed in relation to COVID-19, in addition to their potential impacts, developments and policy implications. The report was prepared for the members and staff at the European Parliament to provide them with the necessary background material to aid in their parliamentary work. Due to the magnitude of the pandemic and far-reaching impacts on most spheres of life, the spectrum of technologies available to mitigate the impacts of COVID-19 was much broader. This indicates that further empirical research is required to identify the dominant technologies that can be used to combat COVID-19.

2.4 Research Gaps and Limitations

Having reviewed the relevant studies, theories and cases, we identified the following research gaps and limitations:

- **Contextual gap:** few studies exist that focus on COVID-19 and chaos-specific technologies, and these studies were not conducted on an empirical basis, hence, there is a requirement for an examination of the technological domains to identify what they are and how they are clustered.

- **Theoretical gap:** No theory exists regarding the immediate technological responses and progress that occurs in a narrow time slice (the selected period for this study), from the unexpected breakout stage of chaos to the order stage (CHAORD). Although models and theories exist that are relevant to chaos and technological development, there is no theoretical foundation concerning how technologies respond at different periods with different categories of technologies during the emergence and unfolding stages of chaos.

Considering the gaps and limitations in the literature, we aimed to develop a theory that describes the progress and technological responses in relation to chaos. Based on this theory, we examined COVID-19 specific clusters of technologies within the selected time slice during the period from the breakout of chaos to the implementation of technological responses.

3. Methodology

This study used grounded theory as a methodology with a mixed-method approach that included quantitative and qualitative methods. We used the quantitative method to assist with the qualitative step to build the TRPC theory. Accordingly, we integrated machine learning and text mining approaches to the qualitative data analysis following the steps of the grounded theory approach. We believe our methodological process increased the validity and reliability of the work and allowed us to examine an extremely large dataset. For the grounded theory, we followed the studies conducted by Glaser and Strauss (1967), Shah and Corley (2006), Hoda et al. (2010) and Tie et al. (2019). Based on the suggested steps described in these studies, Figure 2 below illustrates each step that was included in the mixed-method approach. The study initiated with a literature review to facilitate an understanding of the overall concepts in this field. We developed the overall research question and established the required database and type of data that would be collected. The details of the quantitative and qualitative steps regarding our application of the grounded theory process are presented in the following sections.

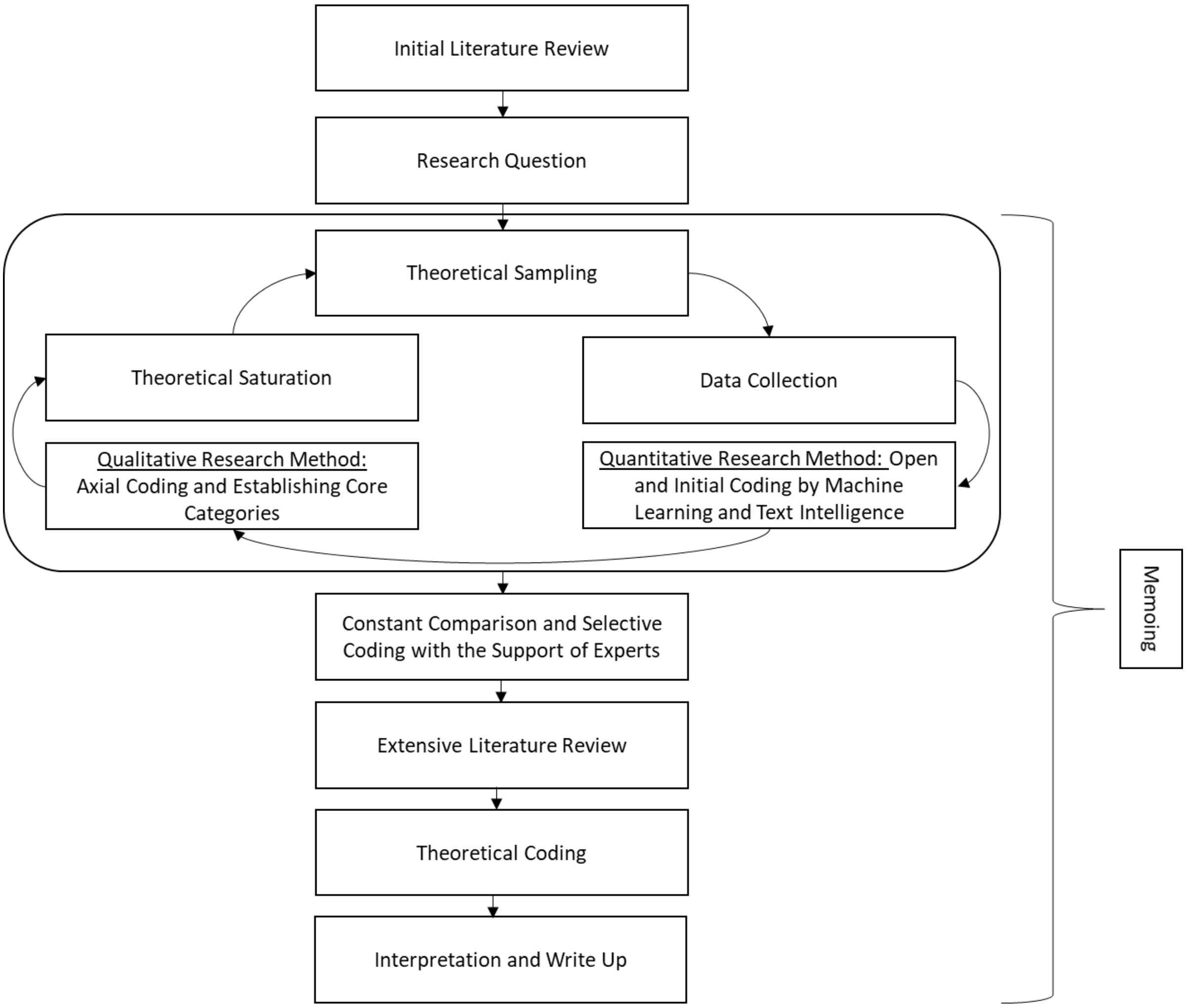

Figure 2. The steps of the grounded theory process

3.1 Quantitative Research Method

The quantitative research method used in this study was based on text intelligence and machine learning approaches. These approaches were used as part of the grounded theory process to help with the theoretical sampling, to identify the appropriate sample and to complete the data collection steps. The quantitative method phase consisted of four stages: 1) Data retrieval, 2) Preprocessing, 3) Data analysis and 4) Data visualisation. The key steps in this study were:

- Data (microblogs) collection using the Twitter API.
- Data cleaning and preprocessing e.g. the removal of unnecessary symbols and duplicates.
- Tokenization, stop word removal and stemming to further prepare the data.
- Labelling of tweets and the selection of relevant data using the Naïve Bayes Classifier.
- Preparation of the data for further analysis e.g. the creation of new categories, term frequency (TF) and term frequency-inverse document frequency (TF-IDF) statistics.
- Co-occurrence calculations, centrality and time-series analyses
- Visualisation of the analyses using the clustering approach and smart local moving algorithm, and a line chart that considered the conceptual framework.
- Labelling of the clustering and establishment of the open and initial coding for the qualitative research method.

3.1.1 Data Retrieval and Preprocessing

For this study, we required a dynamic data source so that immediate results specific to chaos could be examined. Hence, a big data source such as social media (e.g. Twitter) was the most suitable option as it would be time-consuming to produce scientific literature or patents during the chaos period. However, social media outputs (e.g. microblogs) were immediately available and reflected the activities of all the relevant stakeholders, including public and private organisations. Social media is a source of data in which technology providers, adopters and users are within the same platform. Hence, we selected social media data for this research, and an explanation of how we approached the analysis of this data is provided in the following section.

The initial dataset retrieved consisted of 118,659 microblogs (tweets) that were obtained from the Twitter platform during the date range 16.12.2019 (the first documented COVID-19 hospital admission date [Huang et al. 2020]) to 30.06.2020 (the point of theoretical saturation) using the Twitter API with the following search query:

#coronavirus OR #covid OR covid19 OR #corona OR #coronav OR #quarantine OR #stayhome OR #socialdistancing OR #staysafe OR #pandemic OR #coronavir OR #lockdown OR #CoronavirusOutbreak OR #COVID19 OR #newnormal) AND (#technology OR #tech OR #EmergingTech OR technology).

The initial data retrieved were cleaned by removing duplicates (retweets) and using classifiers on 85,105 tweets. Similarity measurements were used to remove the duplicates, and the retweets with greater than 95% similarity were removed. A classification step was used to remove the irrelevant data (e.g. the microblog had a relevant hashtag or term but not the relevant technology information), so that the required data could be selected from the large dataset. The classification method in this case was used as a preprocessing step to select the valid data based on the focus of the study (Ozcan et al., 2020). To prepare the training data, a total of 2,000 randomly selected tweets were labelled as 'relevant' or 'not relevant'. The remaining data were labelled via the Naïve Bayes Classifier using bag of words (Shimodaira, 2014). A total of 33,554 irrelevant microblogs were removed as a result of the above-mentioned process. The final data examined consisted of 51,551 tweets (microblogs). To ensure a reliable process, two of the authors conducted separate labelling processes and labelled 1,000 tweets each.

Before the application of the classifier step, we prepared the required corpus of data via further processing and cleaning. All hyperlinks, e-mail addresses, user tags, emojis, hashtags and punctuation characters were removed. After the tokenization process, the list of terms was prepared by Term Frequency (TF) using stemming and lemmatization steps. The results were further cleaned using stopwords, and the stopwords list was updated to retain the COVID-19 technologies and remove the generic terms. A Principal Component Analysis (PCA) step was implemented to reduce the dimensions with a minimum of 80% data coverage and 95% data representation (the selected terms represented 95% of the overall data). As a result of the preprocessing step, 254 terms were selected.

3.1.2 Data Analysis and Visualisation

Based on the selected terms, a co-occurrence matrix was created using cosine similarity. The co-occurrence matrix was further analysed using centrality measures (closeness, betweenness and degree). The centrality measurements were further analysed and visualised using VOSviewer software. The terms were positioned in eight clusters with discrete positioning using the clustering-based visualisation step of VOSviewer (which uses the smart local moving algorithm [Waltman and Van Eck, 2013]). The node sizes were adjusted based on the degree of centrality. The visualisation results were further analysed by linking clusters to the database (to microblogs). Accordingly, seven labels were created as follows: 'medical technologies', 'mobile technologies', 'software technologies', 'remote & virtual technologies', 'retail technologies, 'unmanned vehicle technologies' and 'distributed ledger technologies'. Based on in-betweenness centrality, nine central technologies were identified, including AI, robotics and platform technologies.

3.2 Qualitative Research Method

Regarding the TRPC theory results, following the grounded theory approach, we first coded the listed technologies based on their applications. After obtaining the axial coding results, we recognised that all these technologies could be grouped into categories by linking them to the database based on how each one responded to the chaos. Following the selective coding process, we coded all the other technologies based on these categories. To increase the reliability of the results, the coding process was performed by each author separately and the results were subsequently compared. In the next step, as part of the theoretical sampling to expand the data coverage and analysis, we coded all the other technologies by repeating the previously mentioned quantitative approach. After this step, as part of a constant comparison and selective coding process, we collaborated with six experts from various domains, including technology analysts, foresight specialists and relevant academicians (those who were involved in the domain of technology and innovation management). These experts were asked to individually categorise the technologies and applications in relation to how they were used to respond to COVID-19. During this step, the experts confirmed the prior coding and overall results.

Once all the coding was completed, we positioned all these technologies across the timeline by month using the posting dates of the microblogs. After positioning all these technologies on the timeline, we observed that the previously identified technology categories appeared at different times. Each of these periods was named appropriately by examining its characteristics. After this step was completed, we established the initial TRPC model.

To establish the theory, we conducted an extensive literature review with a focus on various periods of technological response to chaos (the preliminary literature review and final extensive literature review are illustrated in section 2). This step was crucial to enhance the findings of our theory and establish the final model based on the technology types and periods. Previous studies were crucial for the identification of the different stages of chaos, from its emergence to order, and it was important to position our theory relative to other models and time scales.

As part of the final coding step, theoretical coding was utilised to categorise all codes into three types of technologies and five types of periods. These technology types and periods were integrated into the final TRPC theory, in which all technological relationships and chaos were established in relation to the timeline.

For the final step, the newly established TRPC theory was explained in detail to illustrate different technological categories and response periods. These technologies were also illustrated with examples concerning how they responded to the chaos and how they progressed during this period. Each technology category and period was defined and explained in relation to the previous studies and models. Theoretical memos were included in each relevant section to explain the foundations and to facilitate the TRPC theory development process.

4. Results

This chapter consists of two sections. Firstly, in section 4.1, the COVID-19 specific technologies were examined to identify central technologies and to map the technological landscape that was used to mitigate the chaos. In section 4.2.1, we used these results to identify the chaos-specific technology types. In section 4.2.2, we examined how these technologies responded and progressed across various periods. Finally, based on these results, the TRPC theory was developed, illustrated and explained in detail.

4.1 Technological Clusters for COVID-19 Response

Figure 3 presents the key areas where technologies showed rapid development in response to the COVID-19 pandemic. These technologies were separated into seven clusters according to their areas of application. These clusters were medical, retail, unmanned vehicle, mobile, remote and virtual, software, and distributed ledger technologies. We also identified overlapping groups of technologies and the areas in which these technologies overlapped, for example, the intersection between the medical and mobile technologies regarding telehealth applications. Central technologies were represented in each cluster and these technologies appeared to be the primary method to combat COVID-19. These central technologies were: AI, machine learning, cloud technologies, platform technologies, unmanned vehicles, robotics and 3D printing.

Theoretical Memo 1: *The results suggested that several of these technologies had higher priority compared with others concerning the chaos response and considering their various roles and characteristics. Several of the technology clusters showed more intensive development as shown by the density of the terms, such as medical technologies compared to the distributed ledger technologies.*

By examining the clusters individually, we identified the focus areas of each technology. Regarding the medical technologies, we observed the application of 3D printing for personal protective equipment (PPE), UV light for disinfection and a COVID-19 detector based on an infrared temperature sensor. Regarding the mobile technologies, we observed applications concerning tracking and contact tracing. Regarding the retail technologies, we observed various applications related to the supply chain, safety and online shopping. Regarding the software technologies, we observed many applications that replaced human involvement with AI, machine learning and deep learning applications. Cybersecurity and cloud technologies were other areas where the technologies showed rapid progress and response to COVID-19. For the remote and virtual technologies, we observed that education was one of the key focus areas. Unmanned vehicle technologies showed various applications for delivery and transportation, and many other concepts were developed, from self-driving cars to autonomous travel suites, to help the tourism industry survive and rebound from COVID-19. Most of the distributed ledger technologies involved the implementation of financial applications.

Theoretical Memo 2: *The results demonstrate that technologies play various roles in response to the COVID-19 pandemic, hence, these technologies can be categorised based on their function in chaos. Additionally, evidence suggests that chaos triggers the development of new concepts that may lead to technological progress.*

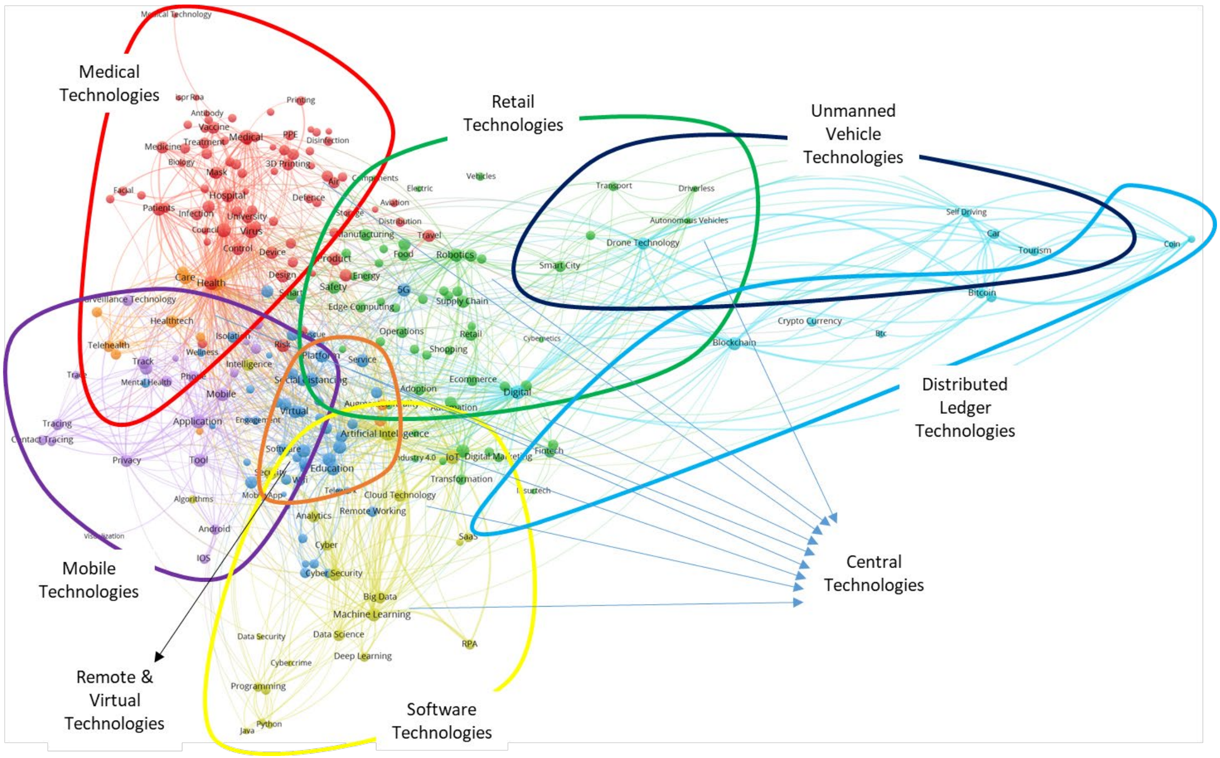

Figure 3. A Map showing the landscape of the COVID-19 technologies

Based on the interpretations and memos provided above, we recognised that there was a need to create chaos-specific technology types and periods to demonstrate how these technologies respond and progress during immediate chaos. The next section describes the development process for the TRPC theory.

4.2 Technological Response and Progress in Chaos (TRPC) Theory

Following the mapping of the technological landscape, in this section, we identified and labelled the various types of technologies and explained and illustrated how these technologies occurred at different times.

4.2.1 *The technology categories*

Based on the axial, selective and theoretical coding steps, and the analysis process (as described in the methodology section), we further examined the role of the previously mentioned technologies regarding their role in chaos how they responded to it. Following this process, we completed a detailed analysis and coding to categorise all the technologies and applications according to their chaos relevant purpose. If the function of a technology was to help society combat COVID-19, it was coded as a 'survival' technology. If the function of a technology was to help a business or society to perform its vital activities, it was coded as an 'essential' technology. If the function of a technology was to enhance the activities and processes during the COVID-19 period, it was coded as an 'enhancement' technology. Hence, there were three categories of technology: 1) survival, 2) essential and 3) enhancement technologies.

Survival technologies can be defined as types of technology that act as a response mechanism to chaos to sustain life. In society, in response to chaos, we require technologies that are widely and readily available. This category is the most crucial one, in which the involvement of different types of actors occurs from public to private arenas and from citizens to organisations. The involvement of the actors in the survival technologies illustrates various process innovations in which the existing technologies (e.g. manufacturing technologies) are adapted to the chaos-oriented needs. For a technology to be widely available and adapted across a variety of conditions, it must be affordable for the relevant stakeholders for immediate procurement and use. Accordingly, we concluded that the three characteristics that survival technologies must have are: 1) availability, 2) adaptability and 3) affordability (the 3A characteristics). The 3A characteristics of technologies are key for the immediate response to chaos because it is extremely challenging to develop completely new technologies during a short period. Therefore, existing technologies are transferred with rapid prototyping or application developments to minimise the impacts of the chaos or eliminate the effects of the chaos. For example, in the case of COVID-19, 3D printers were used as a key survival technology for the production of a variety of materials, tools and hardware (please see the Medical Technologies cluster in Figure 3).

Theoretical Memo 3: *We observed that several of the technologies played a critical role during the chaos as they targeted aspects of human survival. Without these technologies, greater loss of life would have occurred, increasing the level of impact of the chaos. To facilitate a rapid response, it is essential to be prepared with the required knowledge and technologies that bear the 3A characteristics. It is almost too late to adopt these technologies after the emergence of chaos.*

Essential technologies can be defined as those that are required for the continuity of key socio-economic activities. The function of the survival technologies is the continuity of human existence whereas the function of the essential technologies is the continuity of the operations of public and private organisations. For example, essential technologies consist of applications through which retail organisations can implement online and remote solutions and the education sector can provide services via virtual environments (please see the Mobile Technologies and Remote & Virtual Technologies clusters in Figure 3). Regarding the essential technologies, in most cases, previously available technologies gain momentum and are diffused across various sectors. For example, the accelerated diffusion of digitalisation can be observed many technologies such as virtual, cloud and mobile technologies are adopted. There is rapid involvement of the actors in essential technologies if the level of impact in a particular sector is high, however, extremely low involvement of certain sectors in the essential technologies is also observed. In such cases, there is no plausible solution to facilitate the operation of the sector, or the sector is a low-tech industry with a limited technological base and intensity. For example, a high level of involvement of the retail and education sectors can be observed, however, there is a low level of involvement of the construction, tourism and entertainment sectors.

Theoretical Memo 4: *The essential technologies are those that are crucial for the continuity of socio-economic activities. The areas of application of these technologies are also critical for their accelerated progress and diffusion.*

The enhancement technologies can be defined as those that help organisations to improve their current offerings and advance their competitive position but are not essential for the operation of the company. These are the most radical types of technologies and the level of R&D involved and the implications for businesses operations are the greatest. In the case of COVID-19, we observed accelerated R&D investments and applications in AI, robotics and unmanned vehicles (please see the Unmanned Vehicles Technologies and Distributed Ledger

Technologies clusters in Figure 3). The enhancement technologies can be viewed as strategic technologies and companies can use them to transform the negative impact of chaos into an advantage.

Theoretical Memo 5: *The enhancement technologies enable organisations to advance their position in a competitive environment or improve the quality and efficiency of their offerings. Organisations can perform their main operations without these technologies, however, they can be used to help differentiate their offerings.*

Theoretical Memo 6: *The three categories of technologies mentioned previously are conditional regarding their areas of application. For example, the application of 3D printing in the medical sector is a survival technology (PPE devices), however, its application in a business operation (manufacturing of 3D based components) is an essential technology. Additionally, the survival category mainly benefited from existing technologies with 3A characteristics that acted as a response mechanism whereas the essential and enhancement technologies categories lead to technological progress.*

In this section, we defined and illustrated each category of technologies. In the following section, we discuss the technology response periods and explain the TRC theory.

4.2.2 *The technology response and development periods*

After the coding procedure for all the technologies and applications was completed, we positioned them across the timeline to observe the response and progress periods. The results demonstrated that the three categories of technologies emerged at different periods. We named these periods according to the previously described chaos theories and the role of these technologies at different times. Five periods emerged regarding how these technologies responded to the chaos and we labelled them as 1) the stable period, 2) the initial response period, 3) the survival-dominant period, 4) the essential-dominant period and 5) the enhancement-dominant period (Figure 4).

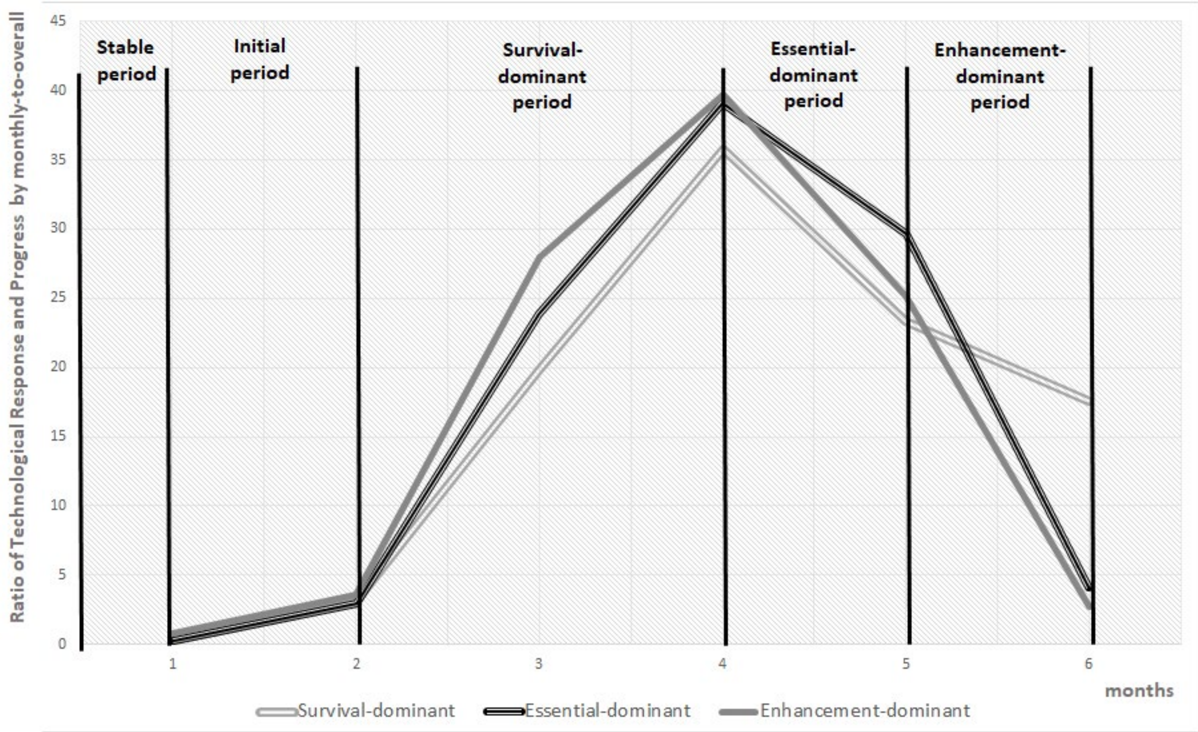

Figure 4. Periods of the TRPC Theory

As described by the Lyapunov Exponent (Lyapunov, 1992), before the initiation of chaos, the activities of society and businesses were stable and there was no abnormality in the system that required a response. Once the chaos initiated, the initial response period involved a societal response and was followed by the three remaining technological response periods. However, compared to other chaos models, there were no distinct periods as these categories of technologies emerged simultaneously at different times. Hence, we named them based on their technological dominance at different times.

After the stable period (no chaos), the process began with the initial period and society and organisations became aware of the impacts of chaos and initiated responses by conducting early discussions and developing concepts. During this period, there was no actual response, however, solutions were proposed to the rapidly emerging issues and disruptions. As there was a high level of uncertainty, many of these discussions involved clarifying the issue.

After the initial response, the issue (COVID-19) was well-recognised and its potential impacts on society were identified. Next, during the survival-dominant period, the society provided an initial response to mitigate the chaos. During this period, survival-oriented rapid responses were initiated over a short period, and existing technologies with 3A characteristics were primarily used to respond to the chaos. Additionally, initial solutions and concepts were proposed via advanced technologies with limited applications. As illustrated in Figure 4, all three categories of technologies were apparent during this period, however, the survival technologies were dominant. We also observed the development of all other technologies. However, as the chaos emerged rapidly during the COVID-19 pandemic, we observed different levels of significance of the technologies. For example, as part of the survival technologies category, PPE, ventilators and track & trace types of technological applications were implemented with priority. As part of the essential technology category, digital and remote applications were initiated by organisations in limited-use cases. Moreover, as part of the enhancement technologies category, the application of advanced concepts such as AI and machine learning were discussed.

During the essential-dominant period, the dominance of technologies shifted towards essential technologies and survival technologies were still a high priority. The enhancement technologies were the lowest priority during this period, however, the conceptual development of advanced technologies continued. We observed the transformation of organisations so that they could operate and adapt to the new conditions. Many organisations promoted existing solutions that were suitable for the chaos period. Specific to the businesses, several companies followed in-house R&D to adjust how they delivered their offerings to customers. The companies that could favourably respond to the chaos, such as those that had completed a digital transformation, improved their technologies to deliver better value or scale up their chaos-specific solutions. For example, in the case of the essential technologies, the companies that had an online shopping and e-commerce system in place were able to adjust and scale up their offerings to gain an advantage during this period (please see the Mobile Technologies and Remote & Virtual Technologies clusters in Figure 3). In the case of survival technologies, we observed a wider application of relevant technologies during this period. We observed new organisations becoming involved in similar technologies and applications, such as PPE and ventilator production (please see the Medical Technologies cluster in Figure 3). In the case of the enhancement technologies, many concepts were developed and initial investments were made concerning the implementation of drones for deliveries and autonomous vehicles for transportation (please see the Unmanned Vehicles Technologies cluster in Figure 3).

During the enhancement-dominant period, the development of enhancement technologies shifted from concepts to actual applications, and the survival and enhancement technologies lost priority, however, they were more established because they displayed each of the 3A characteristics. As society and businesses became better equipped to respond to the chaos, the order of the technological priority shifted towards the enhancement technologies. Companies improved their offerings to gain a competitive advantage and focused on the enhancement technologies. During this period, we observed the application of enhancement technologies to improve on previously available solutions or facilitate new radical solutions according to the chaos-oriented issues and requirements. For example, in the case of the enhancement technologies, AI, machine learning and big data were used to advance previously used approaches and enhance the early detection, diagnosis and monitoring of COVID-19 (please see the Software Technologies cluster in Figure 3). Regarding the essential technologies, we observed a wider application of these technologies across various sectors and the sectors and organisations that had been lagging caught up during this period. For example, regarding legal services, remote technologies were implemented during this period to facilitate online court and tribunal services (please see the Remote and Virtual Technologies cluster in Figure 3). In the case of the survival technologies, we observed vaccination-related developments such as mRNA-based solutions (please see the Medical Technologies cluster in Figure 3).

Theoretical Memo 7: *As explained in this section, the technological response periods did not emerge in separate waves but overlapped with each other and a single category of technologies was dominant over the others. Technological developments during the chaos were different compared to the stable conditions and there was rapid development in earlier periods followed by a decline in the final period, for example, in the case of the survival and essential technologies (Figure 4). Under normal circumstances (e.g. the life cycle of a product), the initial development of a technology would be spread out over time and there would be a longer maturity period, however, during the chaos period, we observed a much more rapid response and progression. A comparison of the enhancement-dominant period with previous periods demonstrates a distinction between technological response and progress and also how chaos can accelerate technological progress.*

5. Discussion and Policy Implications

As demonstrated by the TRPC theory, there are three types and five periods of technologies. Our results demonstrate that, based on the dominant technologies, all the periods overlap with each other and the dominant technologies change over time. Moreover, using this information, we identified the strategies, implications and overall policies that can be developed. In this section, we provide further information concerning the key elements of our theory and how it relates to previous theories and studies.

If our findings were to be compared to the theory of Maslow's Hierarchy of Needs (1943), during a chaos event, the survival technologies would be at the bottom of the pyramid, then essential technologies would be in the middle of the pyramid and the enhancement technologies would be at the top of the pyramid. Regarding the criticisms of Maslow's theory, in terms of the order and needs (e.g. is it always that a person requires a need before another or do they need them in every condition?), a distinct order does not exist, however, that dominance of the technologies in each phase shifts. The technological needs overlap with each other, however, one type of technology dominates. We believe the proposed theory would not be altered based on different conditions, as chaos refers to complete disorder as a result of unpredictable behaviour. Hence, we would still expect conditions in which society, businesses and governments are similarly affected by future chaos (see Gunderson and Holling's [2001] Panarchy theory which demonstrates how events shift from order to disorder in a chaotic environment) and that technology would be required to respond as demonstrated by the TRPC Theory.

During such an imminent and short period of chaos (please see the time slice presented in Figure 1), it was apparent that the development of new technologies and applications was extremely challenging. Therefore, we identified a different technological response and progress, as shown in Table 1. We created a TRPC matrix in which incremental and radical technological innovations were for response and progress. Incremental technological innovations (ITIs) are technologies that are developed in response to the chaos and are based on improvements to previous technologies. Radical technological innovations (RTIs) are technologies that are developed for the first time radical technologies that have been implemented for the first time in an area in response to chaos. The characteristics of ITIs and RTIs are illustrated with response and progress logic in Table 1.

As part of the TRPC Theory, we observed two types of technological responses that were caused by ITIs and RTIs. However, these technologies had different characteristics when chaos and technology interactions were considered, as shown in Table 1. Accordingly, we observed that ITIs were used for immediate response and these technologies primarily had 3A characteristics. The technologies were adjusted to fit the requirements regarding the scale of production and delivery. The ITIs were mostly used during the survival- and essential-dominant periods. Conversely, the RTIs were required when previous technologies were not adequate for the response and significant improvements were required to fit the purpose. The RTIs were the primary reason that technological progress occurred, whereas the ITIs were the main reason for the diffusion and accelerated adoption of technologies.

Table 1. Chaos & Technology Interaction Matrix in the TRPC

Chaos & Technology Interaction	**Response in Chaos**	**Progress in Chaos**
Incremental Technological Innovations (ITIs)	• Immediate response • Implementation of technologies with 3A characteristics • Use of existing technologies • Scale adjustments to address the requirements of chaos • Involvement of diverse actors • Mostly survival and essential technologies	• Accelerated adoption of technologies • Diverse applications of technologies • Technological innovations that are based on previous solutions • Diffusion of knowledge and technology into private and public sectors
Radical Technological Innovations (RTIs)	• Chaos-specific in-house R&D and new technologies • Existing radical technologies are mostly adopted for various conditions and requirements • The immediate application of radical technologies that are suitable for the chaos • Significant improvements to existing technologies in relation to the required volume and velocity	• Accelerated development of technologies and innovations • Mostly enhancement technologies • Radical technologies that are developed or adjusted for the first time in response to the chaos • Great emphasis on advanced technologies such as AI, robotics and unmanned vehicles • Mostly large organisations or SMEs with a prior connection to the radical technologies are involved

Our research contributes to the relevant theories and models (as reviewed in section 2) through the investigation of a short time slice during a chaos event (the COVID-19 pandemic) and demonstrates how technologies responded and developed during this time. Accordingly, by focusing on this time slice, we identified characteristics that were not mentioned in previous studies. We identified separate technology-specific chaos periods rather than generic chaos-oriented stages, as highlighted in other studies (Vickers, 1965; Lyapunov, 1992; Gunderson and Holling, 2001). Additionally, specific to the COVID-19 pandemic, a study by Kritikos from EPRS (2020) listed 10 key technologies, such as AI, blockchain and robots. We examined all the technologies on this list. However, there was no clear evidence for Gene-editing and Synthetic Biology technologies although they were partially included in the Medical

Technologies cluster (Figure 3). Additionally, we identified key technology clusters such as Mobile Technologies, Retail Technologies and Remote & Virtual Technologies (Figure 3) that were not identified in the EPRS study (Kritikos, 2020) and these technologies were critical for the technological response period.

Regarding the policy implications of our study, the results show that national and organisational level technology strategies are required as part of the preparation and response processes for chaos. At a national level, concerning immediate response to chaos, our results demonstrate the significance of the technologies that had 3A characteristics. Hence, nations must encourage such practices and preparation by organisations. Regarding the survival technologies and period, organisations must have dynamic capabilities, as theorised by Teece and Pisano (2003). Organisations must have the required knowledge and preparation in advance to facilitate the required rapid response. In addition to the results demonstrated by Teece and Pisano (2003), the results of the present study signify the importance of transferable and key technologies for such chaos and periods. For example, companies should have access to technologies such as 3D printing and develop prior knowledge before a chaotic event occurs. Our findings support the Resource-Based View (RBV) theory (Barney, 1991) and the Dynamic Capability (DC) theory (Teece and Pisano, 2003). In general, large firms that had access to key resources were better prepared to respond to the chaos, and those companies demonstrated improved development. Moreover, the companies that had prior knowledge and involvement responded more rapidly to the chaos. At a national level, we observed the same result i.e. the nations that had the required technological base showed superior progress. Accordingly, for companies to display improved response mechanisms to chaos, in particular, technologies that bear 3A characteristics must have prior development and the relevant knowledge must be established. To encourage this, a new policy for future chaos events, with a focus on the relevant technological basis and preparations, may be required. Regarding the required progress of radical technologies (as explained previously), national research funds must encourage organisations to become involved in technology developments. The results of our study demonstrate that chaos accelerates technological progress through the rapid adoption and diffusion of technologies into various fields. Hence, nations and organisations should view this rapid progress as an opportunity and establish the prior knowledge base and technologies before a chaotic event emerges. For example, nations should create special programs to aid companies to acquire and use technologies such as 3D printers, autonomous vehicles and AI. The nations and companies that had prior access and knowledge to these technologies were in a better competitive position after the chaos.

6. Conclusions

The aim of this study was achieved successfully through the development of the TRPC theory and an examination of the technological advancements in the case of COVID-19. Firstly, we identified a key cluster of technologies and the central technologies that were used to mitigate and respond to chaos. Secondly, using our empirical results and the coding procedure, we identified three categories of technologies (survival, essential and enhancement technologies) and five periods (stable, initial, survival-dominant, essential-dominant and enhancement-dominant periods). Finally, we extended the findings of our theory by comparing it with previous theories and studies, in addition to providing policy-oriented recommendations. The key findings of this study revealed detailed information concerning many important technological characteristics, such as 3A characteristics. Additionally, we explained in detail the Chaos & Technology Interaction Matrix which illustrates the ITIs and RTIs that are used as response and progress mechanisms.

Several key findings of this study concerned the theory and contextual information. We identified various categories of technologies and demonstrated that they had higher priority and different roles at separate times. Our results revealed that chaos triggers the development of new concepts and technologies, which leads to incremental or radical technological progress. Several of these technologies played a critical role, for example, the medical technologies in the survival technologies category targeted aspects related to human survival. In particular, for these types of technologies, we identified the essential 3A characteristics that are required for an immediate response, as it can be too late to adopt these technologies after chaos emerges. We also identified the essential technologies category which included technologies that are critical for the operation of organisations, and the enhancement technologies category which included technologies that aid companies to strengthen their position and to gain a competitive advantage.

Regarding the TRPC periods, our empirical results demonstrated that there were no distinct technological response periods but that they overlapped with each other and a single category of technologies was dominant (e.g. the survival-dominant period). We also identified different characteristics of technological progress during the chaos. In such conditions, the technological developments showed cycles of rapid development and decline.

The results of our study provide theoretical and practical contributions to the literature. Regarding the theoretical contributions, our TRPC Theory provides the first theoretical foundation concerning the response of various categories of technologies at different times during the emergence and progression of a chaos event. Other relevant studies examined chaos in relation to generic principles and characteristics, however, our theory is the first to explain how technologies perform over an extremely short time slice during the immediate emergence of chaos. Accordingly, this time slice allowed us to identify various characteristics that were not mentioned in previous studies. Regarding the practical contributions of our study, by extending the policy-oriented recommendations of the OECD (2021a) and the EPRS analysis of COVID-19 specific technologies (Kritikos, 2020), we established key technology clusters and new technologies that were not previously identified using empirical data.

The key policy implication of our study concerns the need for policymakers to develop policies that will help to establish the required technological base and know-how before chaos emerges. As a result, a rapid response can be implemented to mitigate the chaos and transform it into a competitive advantage. We also revealed that this recommendation overlaps with the model of Dynamic Capabilities in the literature (Teece and Pisano, 2003). Furthermore, we recommend that nations and organisations establish a technological base that specifically includes technologies that bear 3A characteristics. These are the most crucial technologies for the survival- and essential-dominant stages. Moreover, the results of our study demonstrate that chaos accelerates technological progress through the rapid adoption and diffusion of technologies into different fields. Hence, nations and organisations should regard this rapid progress as an opportunity and establish the prior knowledge base and technologies before the chaos emerges. For example, policymakers should create special programs to aid organisations to acquire and use technologies such as 3D printers.

Concerning the limitations of this study, social media data has advantages over other data sources, such as the examination of dynamic areas and analyses of immediate responses to chaos. However, other researchers can examine publications and patent sources to augment our findings concerning scientific approaches and new inventions in relation to COVID-19 and other chaos-specific developments. We developed the TRPC theory by studying the COVID-19 pandemic, however, other researchers can utilise it to study other chaos-related conditions, such as chaos events that are caused by natural disasters. Other scholars can investigate the technological response and progress pattern in other rapidly emerging chaos events of an uncertain and complex nature to augment our findings.

References

Aristotle (1985) [OTH], On the Heavens,; in. J. Barnes (ed.), The Complete Works of Aristotle: The Revised Oxford Translation, Vol 1. Princeton: Princeton University Press.

Barney, J. (1991). Firm resources and sustained competitive advantage. *Journal of management*, *17*(1), 99-120.

Cheng, Y-T, and Van de Ven, A.H. (1996). Leaning the innovation journey: Order out of chaos?, Organization Science, vol.7, no.6, pp.593-614.

Chun Tie, Y., Birks, M., & Francis, K. (2019). Grounded theory research: A design framework for novice researchers. *SAGE open medicine*, *7*, 2050312118822927.

GAR (2013). From shared risk to shared value: the business case for disaster risk reduction. UN Global Assessment Report on Disaster Risk Reduction (GAR13).

Glaser, B. G. and Strauss, A. (1967). The discovery of grounded theory. Strategies for qualitative research. Chicago: Aldine

Gunderson L., and Holling, C.S., editors. (2001). Panarchy: understand- ing transformations in human and natural systems, Island Press, Washington (DC).

Hoda, R., Noble, J., & Marshall, S. (2010). Using grounded theory to study the human aspects of software engineering. In *Human Aspects of Software Engineering* (pp. 1-2).

Holling, C. S. (2001). Understanding the complexity of economic, ecological and social systems, Ecosystems, vol.4, pp.390-405.

Huang, C., Wang, Y., et al. (2020). Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China. *The lancet*, *395*(10223), 497-506.

Hung, S-C., and Lai, J-Y. (2016). When innovations meet chaos: Analyzing the technology development of printers 1976-2012, Journal of Engineering and Technology Management, vol.42, pp.31-45.

Hung, S-C., and Tu, M-F. (2014). Is small actually big? The chaos of technological change, Research Policy, vol.43, pp.1227-1238.

Jadav, J., & Trivedi, (2021) K. K. Vital Role of Technology on Fighting Covid-19 Pandemic, International Journal of Advanced Research in Science, Communication and Technology (IJARSCT), Volume 2, Issue 2, 114-117.

Jayanti, S. and Sinha,K.K. (1998). Innovation implementation in high technology manufacturing: a chaos-theoric empirical analysis, Operations Management, vol.16, pp.471-494.

Jourdain, K. and Nagel, J. (2020). Disruption and innovation sparked by COVID-19, Worldview Intelligence Blog. Available at: http://worldviewintelligence.com/disruption-and-innovation-sparked-by-covid-19/ (accessed on: March 12, 2021).

Kaur, N., Sahdev, S. L., Chaturvedi, V., & Rajawat, D. (2020). Fighting COVID-19 with Technology and Innovation, Evolving and Advancing with Technological Possibilities. *International Journal of Advanced Research in Engineering and Technology (IJARET, Volume 11, Issue 7*, 395-405.

Kritikos, M. (2020). „Ten technologies to fight coronavirus", European Parliamentary Research Service.

Larkin, M. (2003). Technology confronts SARS, The Lancet Infectious Diseases, vol. 3, p. 453 (doi:10.1016/S1473-3099(03)00677-7).

Levy, D. (1994). Chaos theory and strategy: Theory, application and managerial implications, Strategic Management Journal, vol.15, pp.167-178.

Lyapunov, A.M. (1992). The General Problem of the Stability of Motion, Taylor & Francis, London.

Maslow, A. H. (1943). A theory of human motivation. *Psychological review*, *50*(4), 370.

OECD (2020), Science, Technology and Innovation in Times of COVID-19: What Policy Responses for the Recovery? Available at: https://community.oecd.org/servlet/JiveServlet/download/174482-81-110465/Paunov_PlanesSatorra_Effects+Covid19+on+STI_June2020.pdf (accessed on: March 15, 2021).

OECD (2021a), STI policy and the COVID-19 crisis. Available at: http://www.oecd.org/sti/science-technology-innovation-outlook/STIP-and-COVID-19-crisis/ (accessed on: March 15, 2021).

OECD (2021b), Open science initiatives related to the COVID-19 pandemic. Available at: https://community.oecd.org/docs/DOC-172520 (accessed on: March 15, 2021).

Ozcan, S., Sakar, C. O., & Suloglu, M. (2020). Human resources mining for examination of R&D progress and requirements. *IEEE Transactions on Engineering Management*.

Postavaru, O., Anton, S.R. and Toma, A. (2021). COVID-19 pandemic and chaos theory, Mathematics and Computers in Simulation, vol.181, pp.138-149.

Sakurai, M. and Murayama, Y. (2019). Information technologies and disaster management - benefits and issues, Progress in Disaster Science, vol. 2, pp. 1-4.

Shah, S. K., & Corley, K. G. (2006). Building better theory by bridging the quantitative–qualitative divide. *Journal of management studies*, *43*(8), 1821-1835.

Shimodaira, H. (2014). Text classification using naive bayes. *Learning and Data Note*, *7*, 1-9.

Skiadas, C. H., & Skiadas, C. (Eds.). (2017). *Handbook of applications of chaos theory*. CRC Press.

Stanley, C. (2020). Living to Spend Another Day: Exploring Resilience as a New Fourth Goal of Ecological Economics. *Ecological Economics*, *178*, 106805.

Teece, D., & Pisano, G. (2003). The dynamic capabilities of firms. In *Handbook on knowledge management* (pp. 195-213). Springer, Berlin, Heidelberg.

Tim, Y., Shan, L.P., Ractham, P., and Kaewkitipong, L. (2017). Digitally enabled disaster response: the emergence of social media as boundary objects in a flooding disaster, Info Systems Journal, vol. 27, pp. 197-232.

Van Barneveld, K., Quinlan, M., Kriesler, P., Junor, A., Baum, F., Chowdhury, A., ... & Rainnie, A. (2020). The COVID-19 pandemic: Lessons on building more equal and sustainable societies. *The Economic and Labour Relations Review*, *31*(2), 133-157.

Vickers, G. (1965). The Art of Judgement: A Study of Policy Making, Chapman & Hall, London.

Vickers, G. (1970). Freedom in a Rocking Boat, Penguin Press, Middlesex, UK.

Vickers, G. (1973). Making Institutions Work, Halsted Press, New York, USA.

WHO (2021). Severe Acute Respiratory Syndrome (SARS). Available at: https://www.who.int/health-topics/severe-acute-respiratory-syndrome#tab=tab_1 (accessed on: March 12, 2021).

Yoo, T. (2018). 4 ways technology can help us respond to disasters, article published as part of the World Economic Forum Annual Meeting. Available at: https://www.weforum.org/agenda/2018/01/4-ways-technology-can-play-a-critical-role-in-disaster-response/ (accessed on: March 12, 2021).

Zeraoulia, E. (2011). *Models and applications of chaos theory in modern sciences*. CRC Press.