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Spurious learning and bouncing back: Resilience and simulation modelling applied to the COVID-19 pandemic

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ABSTRACT

This paper aims to provide a window opportunity to share a reflection and learning from different countries and from other disciplines with the focus on resilience. There is also an attempt to theorize the concept of learning from spurious success and failure in the context of COVID-19. The main emphasis is to provide understanding of the causal factors and the identification of improved measures and modelling approaches to prevent and mitigate against future pandemics. Proposed decision tools of resilience and bowtie modelling as enablers for decision makers to prevent hazards and protect against their consequences.

1. Introduction

In this paper, the corona pandemic - COVID-19 is investigated. In doing so, resilience modelling is addressed, and its affiliated 4 Rs (robustness, redundancy, resourcefulness, and rapidity). Moreover, decision tools such as simulations and bowtie models are proposed to encourage systems thinking by making it easier for decision makers to anticipate the consequences of their actions.

The paper is organised as follows. In Section 2 a literature review is provided in terms of common features of disasters, the report on Global health Security Score (GHS) Index, and causation analysis. Section 3 represents the proposed methodology. Section 4 is related to modelling learning from other countries. Section 5 is related to discussions of results, which includes both bowtie and resilience modelling. Finally, Section 6 provides concluding remarks.

2. Literature review

There are common features that exist in many disasters. For example; Fukushima nuclear disaster [1], Bhopal [2], and the recent COVID-19 [3]. They all show that right questions where not asked beforehand, reduction of cost over time compromised safety, and slow and muddled reaction delayed adequate response. They also show how disasters can have a direct impact on the environment and global sustainability. The disasters also involve socio-technical factors as well as effects on both lives (health), and livelihoods (economy).

2.1. Report on global health security score (GHS) index

The Global Health Security Score (GHS) index was constructed and published in 2019 with the intention to measure the resilience of the national health system in terms of preparation and response to pandemics. It was jointly developed by John Hopkins Centre for Health security together with the Nuclear Threat Initiative. It consists of 140 questions., which cover six criteria: (i) prevention, (ii) detection and reporting, (iii) rapid response, (iv) health system, (v) compliance with international norms, and (vi) risk environment. Each criterion is described below [4]:

1. *Prevention: Prevention of the emergence or release of pathogens.*
2. *Detection and Reporting: Early detection and reporting for epidemics of potential international concern.*
3. *Rapid Response: Rapid response to and mitigation of the spread of an epidemic.*
4. *Health System: Sufficient and robust health system to treat the sick and protect health workers.*
5. *Compliance with International Norms: Commitments to improving national capacity, financing plans to address gaps, and adhering to global norms.*
6. *Risk Environment: Overall risk environment and country vulnerability to biological threats.*

The 195 countries across the globe were then categorised in the GHS index into 'most prepared', more prepared', or 'least prepared', and an overall percentage was provided to each country and they were then orderly ranked.

What is interesting is that this exercise that lead to the conception of the GHS report was completed just prior to the discovery of COVID-19 in December 2019 Corona (COVID-19) virus pandemic outbreak. So, such data from both the GHS report and the outcome of COVID-19 pandemic so far can, and after almost one year of the pandemic, provide a good platform to check resilience and learning from failures among different countries. A study by [5] examined GHS score and compared

Fig. 1. 2 × 2 Grid of 4 processes and outcome combinations [adapted from [7] Dahlin et al., 2018, to COVID-19].

performance of five countries with respect to COVID19 and concluded that some countries invested more in health resources in the treatment of severe patients, where others focused on extensive testing. Another study showed that among the six dimensions of the GHS index, Rapid Response and Detection and Reporting have the largest impacts on the GHS Index score, whereas Risk Environment and Prevention have the smallest effects [6]. The same study also performed an analysis of the 10 leading countries overall and how their individual scores are compared.

2.2. Causation analysis

When studying causation of major disasters, there is an inherent assumption that they are caused by erroneous actions; which is in line with the cause and effect principle. However, there is possibility that erroneous processes can produce good outcomes, and correct processes lead to adverse outcomes [7]. Fig. 1 is an adapted version of the table provided by [7], where boxes 1 and 2 along the diagonal are considered what is expected (the signal); correct processes, behaviour and routines are expected to lead to success, whereas faulty processes, behaviour, and routines will lead to failures. The exception happens in boxes 2 and 3, in the off-diagonal combinations, where a faulty process leads to success termed as 'spurious success' i.e. we get away with it, and conversely successful process lead to a failure termed as 'spurious failure' i.e. correct processes are associated with adverse outcomes. Such fake outcomes are considered as noisy learning environment since cause-effect analysis becomes unclear, and leads to a disability to learn. According to [7], research in this area tend to be scarce.

3. Methodology

The paper is based on an empirical work, a report and a case study. For the sources of the empirical work, this consists of the outcome of a set of workshops related to the impact of COVID-19 on resilience, productivity and sustainability, which were delivered to over 250 managers from SMEs in the UK. The second source of empirical work was a master's programme on reliability and asset management, where the students, who are mainly working in industry, were asked to use a bowtie modelling approach to investigate the risk of COVID-19 in terms of preventative and protective measures and discuss relevant safety barriers (controls) to mitigate against threats and consequences. Such empirical work provided insight to the impact of COVID-19 on different businesses. As for the report, this was based on an international global health

Table 1
Summary of empirical data.

Data sources	Sample size, summaries and key insights
Set of workshops.	- On impact of COVID-19 on resilience, productivity and sustainability. - Workshops were delivered online to over 250 managers from SMEs in the UK.
Master's programme.	- On reliability and asset management. - Students, who are mainly working in industry, were asked to use a bowtie modelling approach to investigate the risk of COVID-19. - Models included preventative and protective measures and discuss relevant safety barriers (controls) to mitigate against threats and consequences.
Report.	- Report on international global health security that was published just prior to COVID-19 pandemic and was aimed at assessing national public health across different nations.
Case studies.	- On how different countries have coped with the Pandemic.

security report that was published just prior to COVID-19 pandemic and was aimed at assessing national public health across different nations. In terms of the case study, the case of COVID-19 pandemic disaster is investigated by outlining lessons learnt (Table 1).

4. Modelling learning from other countries

Table 2 shows that the top ten countries in terms of COVID-19 infections, which constitute 5 % of the total number countries ($n = 195$), had among them 65 % of the World's infections, and 60 % of the World's deaths due to COVID-19. The same table also shows the GHS score awarded to these countries in 2019 just prior to the discovery of COVID-19.

Now by considering the top 10 worst affected countries in terms of number of total infections and deaths rates, and taking the GHS score of them as a threshold using the geometric mean (GM). The GM was employed as it is more adequate for describing proportional and exponential rates of growth, and also arithmetic mean gives a distorted

Table 2

Total number of COVID-19 (Coronavirus) infections and deaths among the most impacted countries worldwide (top 10 among total 195 countries), as of December 22, 2020 (adapted from Statista @ https://www.statista.com/statistics/), and [4].

	Total infections	Deaths	Population	GHS 2019 Score
World	77,920,539	1713,152	7800,000,000	
USA	18,487,519	326,954	331,000,000	83.50 %
India	10,094,801	146,414	1380,004,385	46.50 %
Brazil	7264,221	187,322	212,559,417	59.70 %
Russia	2906,503	51,912	145,934,462	44.30 %
France	2479,151	60,900	67,000,000	68.20 %
UK	2073,511	67,616	67,886,011	77.90 %
Turkey	2043,704	18,351	84,339,067	52.40 %
Italy	1964,054	69,214	60,461,826	56.20 %
Spain	1830,110	49,260	46,754,778	65.90 %
Argentina	1547,138	41,997	45,195,774	58.60 %
Total top 10	50,690,712	1019,940	2441,135,720	
Percentage of World	65 %	60 %	31 %	

measure of the central tendency in the presence of outliers [6].

$$GHS_s = \left(\prod_{e_s=1}^{E_s} i_{e_s} \right)^{\frac{1}{E_s}}, \qquad s = 1,..,10 \qquad (1)$$

Then GHS score threshold between good and bad countries in terms of processes, equates to 60.15 %

Ideally in the grid one would employ the same notion for the threshold in terms of outcomes (using deaths rates from COVID-19) by the similar equation, as follows:

$$D_s = \left(\prod_{e_s=1}^{E_s} d_{e_s} \right)^{\frac{1}{E_s}}, \qquad s = 1,..,195 \qquad (2)$$

Where D_s is the cumulative death rate toll of each country due to COVID-19.

However, in our case we use the top ten worst performing countries as they represent an adequate sample size to base our analysis since they equate for roughly 60 % of the death toll and constitute around 5 % of the number of countries in the world, which are total of 195 countries.

$$GHS^* = \left(\prod_{s=1}^{10} \prod_{e_s=1}^{E_s} i_{e_s} \right)^{\frac{1}{E}} \qquad (3)$$

$$D^* = \left(\prod_{s=1}^{195} \prod_{e_s=1}^{E_s} d_{e_s} \right)^{\frac{1}{E}} \qquad (4)$$

Where,

$$E = \sum_{s=1}^{195} E_s \qquad (5)$$

The top ten countries in terms of cumulative deaths toll are mapped against their equivalent GHS score as shown in Fig. 2, with a threshold between low and high score of GHS at 60.15 % as derived from Eq. (1). The worst top ten countries were chosen as a valid representative sample of worst performers although they constitute just 5 % of the total number of countries in the World, they have been affected by 65 % of total infections in the World and constitutes 60 % of total deaths due to COVID-19 in the World.

In assessing response to the COVID-19 pandemic in developing countries, early preventative measures in countries such as Vietnam and South Korea were quite successful in containing the spread of the pandemic. This was achieved through the enactment of polices such as safe physical distancing, mandatory wearing of masks in public areas, and other policies to reduce the severity of the spread and the likelihood of infection [8]. Enablers to such successful response included swift learning and continuous adaptation by correcting policy errors made as new knowledge became available. In addition, South Korea, as an outcome of their experience with previous epidemics such as MERS, passed legislations back in 2015 that facilitated the enactment of viable track and trace systems which subsequently had a significant impact on the preparedness of their public health emergency. On the other hand, other countries did not respond swiftly enough to contain the spread of the pandemic. Political leaders in some countries initially denied the seriousness of the threat due to various reasons such as cultural prejudice, overconfidence in, and misinformation about, an easy way around through herd immunity, as well as being distracted by social media that played up conspiracy theories [8].

Now focusing on a sample of countries in box 2 (spurious failure) of Fig. 3 such as the UK, there could be many reasons for being located in this box. There has been a recorded session by the BBC of the British Parliament (24th November 2020) where the Secretary of State responsible for health and social care was questioned about lessons learnt from COVID-19 in the UK. Among the issues discussed were the timing and duration of lockdowns and whether to implement circuit breakers (short and harsh lock downs), measures taken to ensure compliance, and trade-off decisions around whether to keep schools open. Another issue was about whether the government is following, or guided by scientific advice, and the background of membership of such committee of advisors. A further discussed issue was related to how to deal with a national holiday such as Christmas period, and the different calibrations of the tier-based system among different regions. Another discussed issue related to logistics chains of virus testing and the involvement of universities labs and ability to scale up their capacities, as well as lessons learnt from South Korea in their ability to have IT systems in place for test, track and trace, which took a lot of effort to implement in the UK. A further discussed issue was the cooperation between local and national (and between public and private sectors) systems with respect to contact and tracing systems, and the logistics involved in pilot testing of software systems to comply with standards and regulations in terms of identity assurances and checking self-isolations which proved to be very complicated [9].

On reflection, and guided by the ranking criteria used in the GHS index, here are few that can be attributed as causal factors, mainly: inadequate rapid response, fragmentation in opinions, and inconsistencies in policies. Let us take each one of them in some detail.

Rapid response: According to GHS index 2019, the UK scored the second highest overall score among 195 countries. And as discussed earlier, it was found that the largest impacts on the GHS Index score are: (1) Rapid Response, and (2) Detection and Reporting [6], which are basic ingredients of resilience, with Rapid Response has the largest impact, which is fine so far. However, when examining what consti-
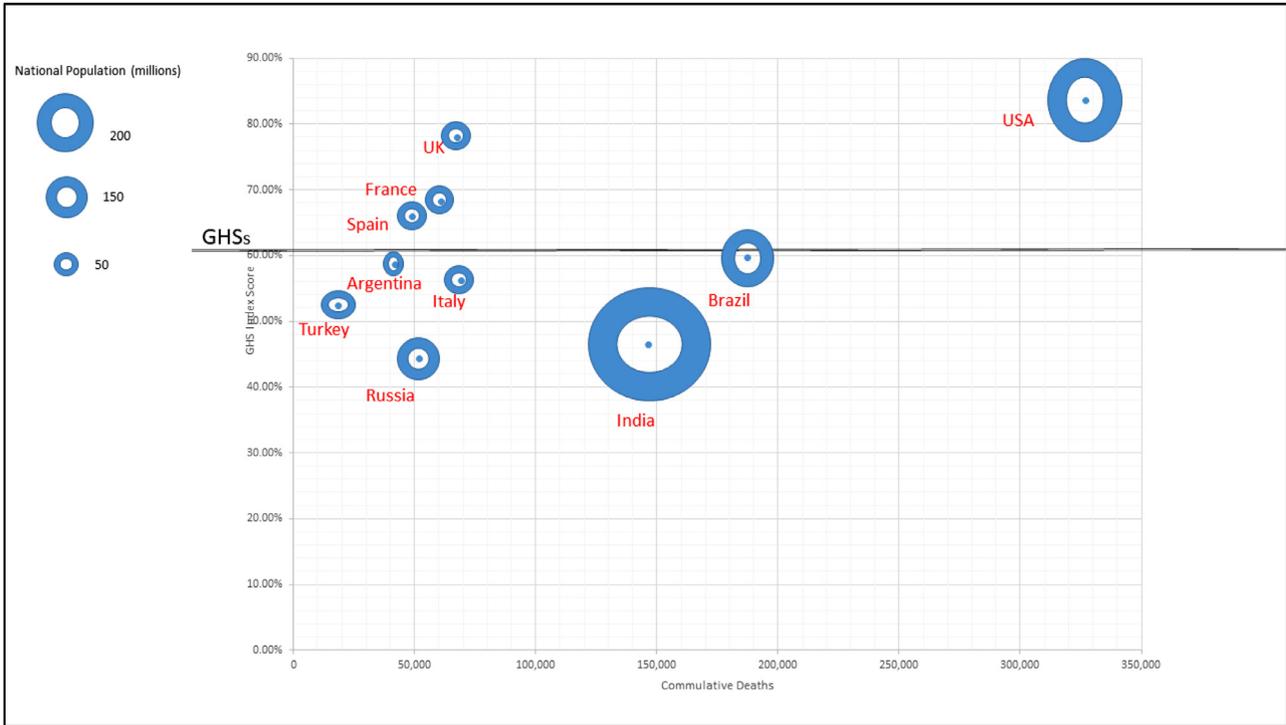
Fig. 2. Top ten countries in terms of cumulative deaths toll mapped against their equivalent GHS score (inspired from [5]).
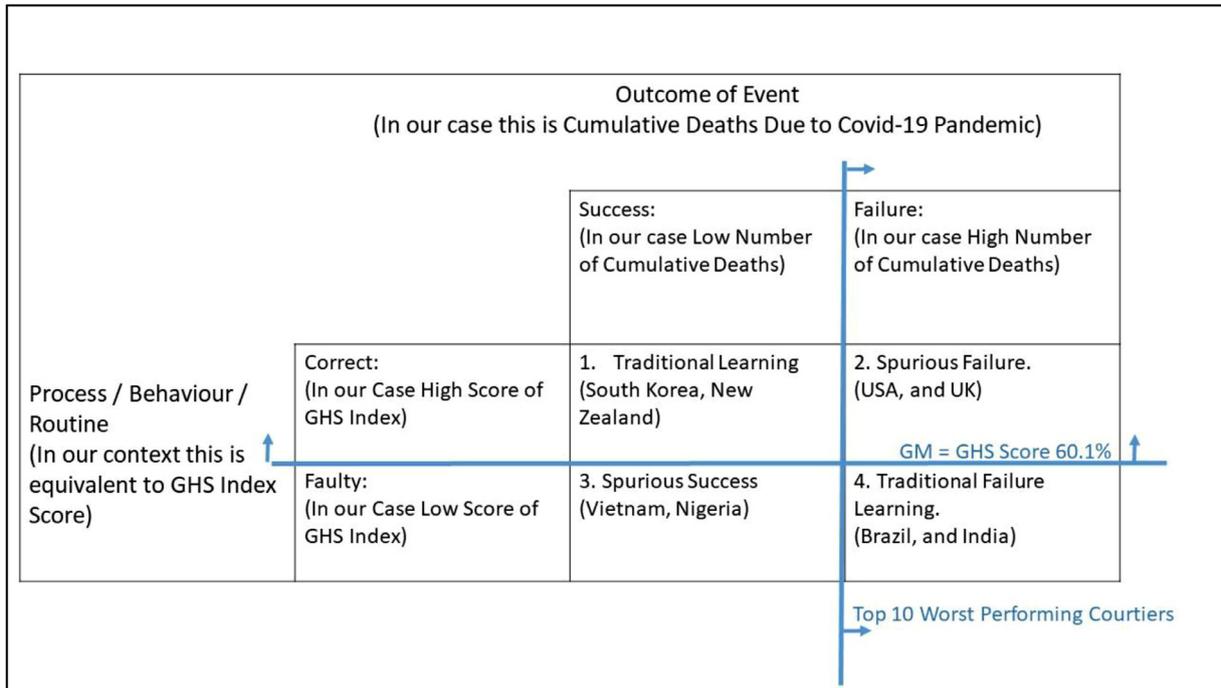

Fig. 3. 2 × 2 Process and outcome combinations with identification of a representative sample of two countries in each of the 4 quadrants.

tutes the Rapid Response criterion in the GHS scoring index, indicators in this category include: (i) exercising response plans, (ii) linking public health and security authorities, (iii) assessment of emergency preparedness and response planning, (iv) emergency response operation, (v) access to communications infrastructure, (vi) risk communication, and (vii) trade and travel restrictions. An exercise response plan was carried out by the UK in 2016 called Cygnus, which simulated a pandemic of H2NS influenza virus, which turned out to be an almost similar sce-

nario to COVID-19, and it involved all major government departments. However, looking deeper into this exercise, one can claim that it anchored the learning on the spread of influenza, whereas COVID-19 was more than ten times stronger in both spread and lethality. Hence it can be classified as a 'wrong learning', or even 'negative learning', as it has affected assumptions made later on in the real situation. It seem that the simulation exercise was implemented efficiently but not effectively, as it did not make right assumptions in its design as it also focused more on

corrective rather than preventative measures. Also, there has been criticism that the recommendations from the outcome of the Cygnus exercise have not been fully implemented later on, which included concerns about lack of PPEs and other relevant infrastructure facilities. Moreover, there has been media reports about criticism that such exercise did not include in its scope financial and economic concerns [10], which then became a major influencing factor that affected the lock down policies later on. In addition, whilst the UK started embracing test and trace systems by end of April 2020, countries such as South Korea, Taiwan and Singapore have embraced this strategy much earlier. And it was admitted [9] that even with that delay the ramping up of such strategy took a linear trajectory whilst the virus was spreading at an exponential rate.

Fragmentation in Opinions: The negotiations and opinions about Brexit caused deep fragmentation among both the general public and policy makers. Such fragmentation became a normalised feature, 'normalisation of deviance', using Vaughan's term [11]. This fragmentation in opinion was then similarly experienced in response to COVID-19 and caused some delay in decision-making to respond in terms of adequate travel restrictions, and lock down. Moreover, countries such as USA and Brazil have experienced polarisation and deep political divisions, and subsequently they have been badly affected by the pandemic especially when a delay was also found in the decision-making especially with respect to a delay in a swift response, which is a basic ingredient of resilience.

Inconsistencies in Policies: The very initial response of the UK in early March 2020 was to promote development of 'herd immunity' in the population, which means to permit the virus to spread, which prevailed as official policy with the assumption that the population would be asymptomatic or only with mild symptoms [8,5] until the study by Imperial College of London (ICL) which was published 17th March. It is claimed that many deaths could have been avoided if early preventative measures had been taken. It can also be claimed that such initial inconsistency in policy made subsequent adaptations, as part of the learning from within and from other countries, being criticised in the media and framed as inconsistency in policy. Moreover, this inconsistency caused blame of the 'scientific advice' in terms of its members and whether the government was following, or guided, by it, which again caused delay in response.

It seems that in the case of the UK response to COVID-19 so far and after one year of the outbreak, that both fragmentation in opinion and inconsistency in policies impacted both vicarious learning [12], and learning from failures and success [13,14], and this ultimately lead to some confusion between the noise and the signal [15]. Moreover, it seems that a sort of negative learning phenomena has occurred as an outcome of an anchoring type of bias, where initial piece of information, such as outcome of a simulation exercise, can influence future judgements; see [16] on biases in judgements, and [17] on biases in risk analysis. The other influencing factor that seems to have caused negative learning is the issue of following or guided by science, where do you draw the line? This is very similar to the NASA Challenger disaster case study, where one of the main lessons learnt were the confusion between management authority and engineering knowledge in the argument between NASA and its sub-contractor Morton-Thiakol [18], and which focused on whether to launch the shuttle due to engineering concerns about the cold affecting the O-ring on one hand, and the management downgrading that advice for sake of managerial and logistical concerns. Finally, such negative learning seem to have also occurred due to the infodemic [19], too much information, and even mis(infodemic) such as conspiracy theories [20], and so on. In a way negative learning is worse than no learning; as no learning promotes passive response, whereas negative learning promotes a response that can be classified as an error.

On the other hand when examining a sample of countries in box 3, such as Vietnam (with a population of 95.5 Million, they had 35 cumulative deaths of a total of 1454 infections) given their relative limited resources. And they were scored 49 % in GHS 2019 index. They employed early efficient measures prevention in terms of social distancing,

wearing PPEs and other preventative approaches [8]. As early as 28th January, the Prime Minister established a Rapid Response Team, and as early as 1st of February all flights to mainland China were suspended, and schools stopped in the capital Hanoi, and by 3rd March, financial directives towards extension of tax payment and other fiscal measures were put in place [21]. In addition, "*mass testing, tracing, isolation and treatment, have been able to check the contagion. Most impressive is that Vietnam officially manufactured the virus detection test kits (RT-PCR and real-time RT-PCR) on 5th of March 2020, and was able to manufacture 10, 000 test kits per day*" [21]. This was done without having to resort to draconian measures 'stay in shelter' lockdowns.

Also in order to demonstrate how resilience was realised in some sectors in Vietnam, such as tourism, a reported response from hotel managers was as follows: "*We don't know how long* COVID *will last, but we do know it will end. Then it will be time for the hotel to recover, so training and talent detection is a long-term strategy that can help us prepare ourselves to be ready to go back at once*", and "*We have used the lockdown time to do internal training for our employees. We apply new technologies, new models to our work, with young staff supporting older staff* " [22].

Such measures have been quite successful given that they were considered among the least prepared as they scored only 28 % under the dimension of Sufficient and Robust Health System To Treat The Sick & Protect health Workers of the GHS 2019 index. Nevertheless, the government had prompt and decisive responses including swift deployment of security forces, enactment of economic policies, and development of effective communication campaign.

5. Discussion and results

On the quality of the data reported in the GHS, and on reflection on the outcome of COVID-19, to its credit, the GHS index states that "*The average overall GHS Index score is 40.2 [using arithmetic mean] out of a possible 100. While high-income countries report an average score of 51.9, the Index shows that collectively, international preparedness for epidemics and pandemics remains very weak*" [4] (GHS, 2019 pp18). However, the GHS index has also received some strong criticisms in the wake of COVID-19 [23,24]. For example, in the wake of COVID-19, correlations among countries performance and their GHS score tend to be weak an even inversely. Also using a global index creates a tendency towards a one-size-fits-all framework which may not be adequate. In addition, it has also been criticised that it is biased towards elements of health security deemed important in high-income settings in terms of both its scope and data collection methodology. Also concern was raised on the governance and long term negative impact in terms of values and assumptions involved from such types of rankings. There is also indications that the GHS rankings may have given a sense of complacency to those countries leading the table. Moreover, such reductionist approach into a single figure may disadvantage more qualitative, inductive, approaches to learn best practice and learn from failures in dealing with a pandemic. Nevertheless, in terms of the validity of the GHS as a reliable index, a recent study by [25], concluded that GHS was positively associated with health systems resilience during the pandemic (2020) and the following two years (2021–2022), and that countries' underlying characteristics, including governance quality, bolstered health systems resilience during the pandemic. In addition, a study by [26] that focused on assessing the GHS Index as a predictor of COVID-19 excess mortality, states that the measures within the GHS Index were not intended to serve as a predictive model of how countries will respond in a crisis, but rather as an inventory of the resources and plans available within each country.

On the quality of data reported about COVID-19, it can also be argued that not all countries who have experienced low infection rates and deaths toll so far have managed to capture and report the true figures due to reasons such as their limited capabilities of data collection or other political motivated reasons.

It is appreciated that the intention of such global rankings is to improve the status of countries across the globe, but what can be argued
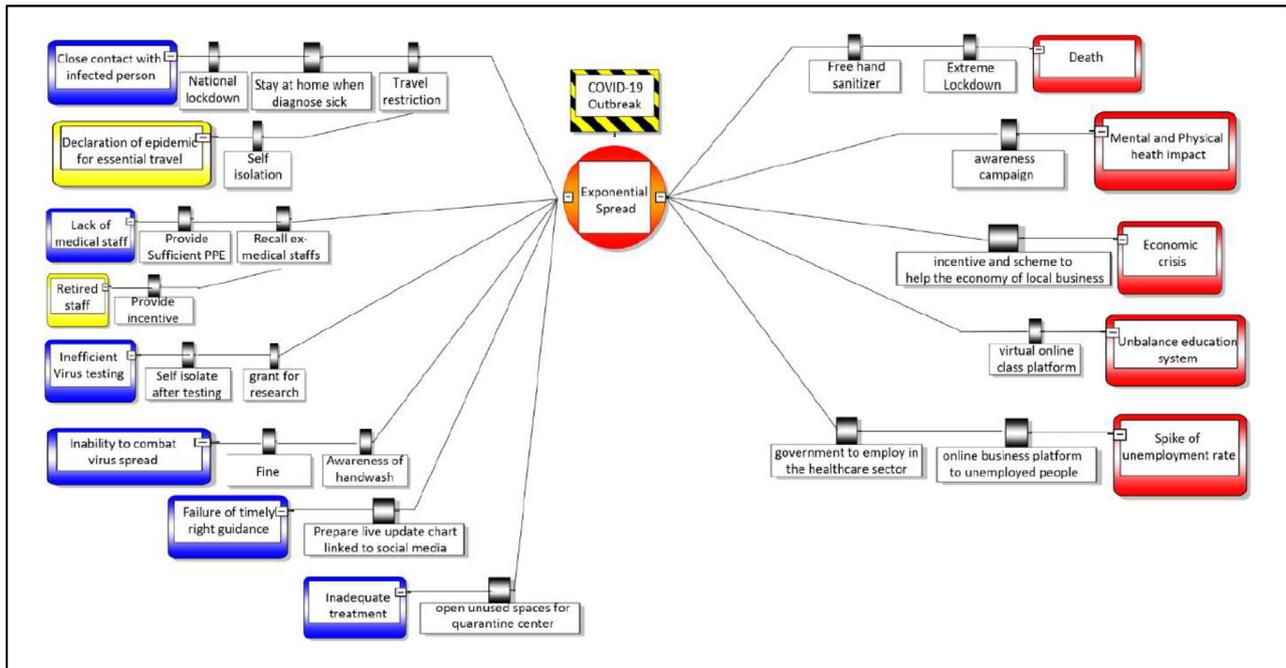
Fig. 4. Example of bowtie model for COVID-19.

is that there is a need to improve the improvement framework. In other words to adopt double loop learning; a term coined by [27]. Therefore, in what follows in this the paper the focus will be on an attempt to improve how we improve the GHS framework. This will be achieved through first going back to basics in defining the concept of resilience modelling, and then attempting to provide an enriched hybrid model that can facilitate learning from COVID-19 to prevent from, and mitigate against, future pandemics.

5.1. Bowtie modelling

Bowtie modelling is a method where its name comes from its shape. Such shape attempts to model causal relationships. These relationships can subsequently lead to a hazardous event (spread of COVID-19). The hazardous event constitutes the 'knot' of the model. Safety barriers are then constructed as way of prevention, and this is placed at the left side of the model. Whereas the consequences of the hazardous event are mitigated against by another set of safety barriers placed on the right side of the model. In other words, on the left side of the bowtie we have prevention, and on the right side there is protection.

Students is a master's course on reliability and asset management where provided with background about resilience modelling. They were also provided with an example from the work of [28]. They were then tasked to design a different bowtie diagram for the hazard of the 'Exponential Spread of COVID-19 (Corona Virus)' and provided the flexibility to alter the components of the fault tree analysis (FTA), if they wish to do so. Since the bowtie diagram starts with a FTA on the left side where the causal factors, and threats, occur, they were asked to extend the opposite right side by constructing an event tree analysis (ETA), where the focus is on consequences and negative outcomes that can lead to escalation of a crisis to become a disaster, for example consequences related to lives (health), or livelihood (economy). A sample of models is shown below in Fig. 4.

However, it is helpful here to discuss the assumptions behind the modelling involved and specifically its assumptions and limitations. In a recent work by [29], such limitations have been identified as follows:

"Although Bowtie modelling is effective in communicating risk and is designed for visual representation, in its current form it does not provide quan-

titative analysis nor prioritisation in terms of order or weights to safety barriers" [29].

In particular, it the bowtie modelling approach does not explicitly capture the temporal 'closeness to hazard'; either before or after the hazard, which is the knot of the bowtie, where such 'closeness' can be in terms of time or space proximity [29]. In addition, the bowtie modelling does not explicitly categorise safety barriers into different types; for example, human, physical, software, and procedures, which can help in diversifications of safety barriers. Finally, although the bowtie modelling classifies barriers into preventative versus reactive, there is no guarantee that they are developed in a balanced portfolio.

5.2. Resilience modelling

The idea of the resilience triangle originated from [30]. Then [31] mathematically modelled it with stages to depict the abilities to plan, absorb, recover and adapt to adverse events.

Although the GHS index attempts to assess resilience capabilities among countries, it does not explicitly employ the described concepts of resilience triangle modelling. In reality straight lines are modelled as curves to depict stages of deterioration and recovery. Therefore in Fig. 5 there is a proposed combined modelling of the resilience triangle and bowtie modelling as originally proposed by [28], which helps to have both a strategic overall and operational views of the analysis. Also in this conceptual model, there is an attempt to map the 6 dimensions (criteria) of the GHS index into both the revised resilience triangle and the bowtie modelling.

It can be observed that the first 4 dimensions of the GHS index can be directly mapped into both the extended resilience triangle and the bowtie models. However, the other two dimensions of Compliance with International Norms and Risk Environment are of overarching generic nature, which can indirectly be placed on either sides of the two models. Hence one can argue that they ought to perhaps carry a slightly less weight compared to the other 4 dimensions.

The proposed modelling can help to design simulation exercises, where different scenarios of hazards can be modelled and safety barriers tested. Such exercises are considered as organisational vaccine, since the idea of a vaccine is to inject the body with a mild experience of the virus
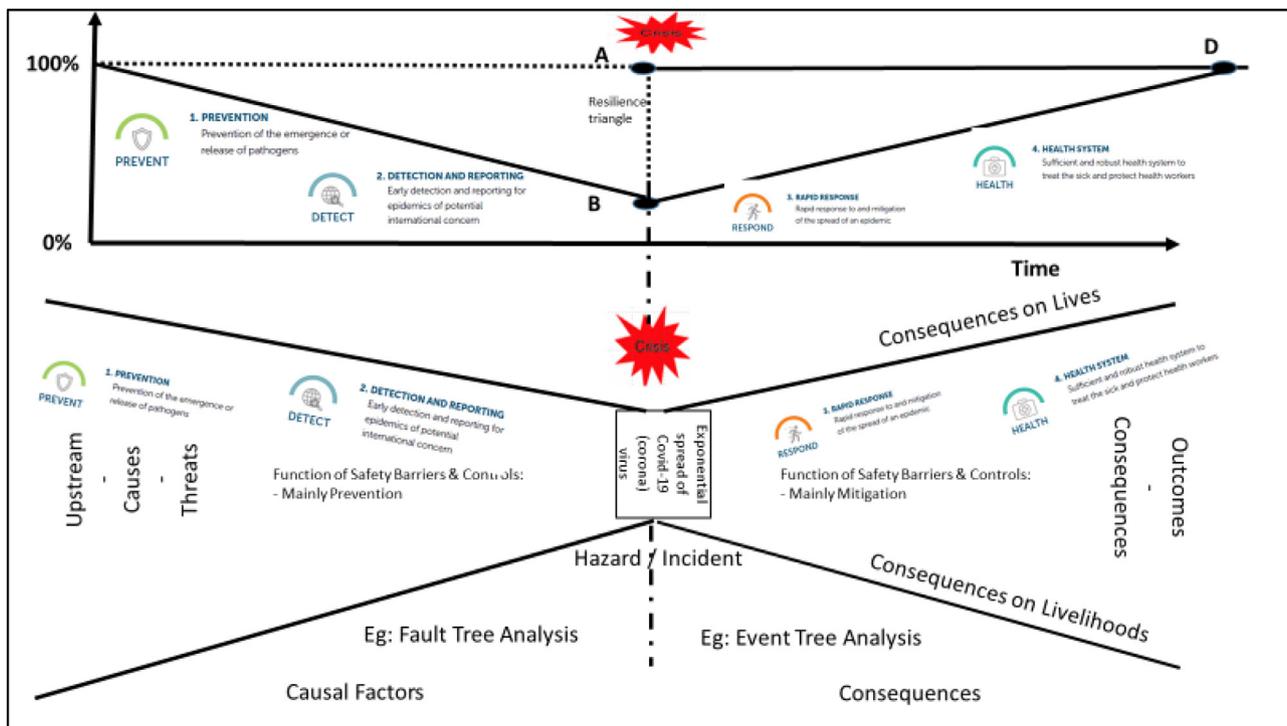
Fig. 5. Incorporation of GHS index dimensions in the hybrid resilience triangle and bowtie diagram - adapted from [28].

intended to be attacked, so that the body can be more resilient. In our case, the body is substituted with an organisation, or a public health organisation of a certain government. Simulations improves ability to model complexities, mimic the real-world dynamics, and predict system behaviour. More specifically, simulation exercises have a multitude of advantages; they help to predict the system performance under different scenarios, encourage creativity by trying different decisions without incurring expensive implementation, avoid disruption by simulating the system behaviour without involving the real system, assess performance through the integration of performance measurements, encourage change by understanding and visualising the results of the change before the implantation, and help to gain knowledge while designing the model and suggest improvements.

6. Conclusion

The main conclusion of the techniques, and arguments, presented in this paper is that pandemics are very complex events, and this calls for consideration of some of the basic principles of resilience modelling. In this paper, it has been shown that resilience modelling is about addressing boundaries of acceptable performance. Hence, resilience modelling in terms of anticipation and learning how to recover, puts in practice the framework of high reliable organisations (HROs), see [32] on its features, and [33] on a method to assess it.

It has been constructed to help understand the hazard in terms of its top event, threats, and consequences. It has also helped to improve the knowledge gained from the assessment of safety barriers (controls) and helped us to identify the need for new, improved, or diversified ones.

Highly critical situations resulted from severe accidents such as COVID-19 pandemic are regarded as ones what can be referred to as post normal science [34], where novelties emerge successively, uncertainty deepens over time, and emergent complexity between individuals and systems comes in Unfortunately, these cannot be controlled by relying on past statistics.

It is also clear that more research is needed into the design and effectiveness of crisis simulation exercises in general, and in partic-

ular those related to public health outbreaks. In conclusion, the paper combines empirical insights with conceptual modelling, offering a multi-component and layered perspective on resilience. Hence, it can be claimed that one of the strengths of this work is its empirical grounding, where the use of multiple data sources adds credibility to the findings. Moreover, it demonstrates the real-world applicability of the proposed resilience strategies. Also, such approach can be replicated by different entities that wants to use it, which can realise its impact. It is therefore hoped that suggestions in this paper will lead to a right direction for future research.

Relevance to resilience

The paper uses the Resilience Triangle Model as a tool for investigation. It also applies the resilience capabilities and utilises a set of integrated tools for resilience modelling.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Ashraf Labib: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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References

[1] Labib A, Harris MJ. Learning how to learn from failures: the Fukushima nuclear disaster. Eng Fail Anal 2015;47:117–28.

[2] Labib A. Learning (and unlearning) from failures: 30 years on from Bhopal to Fukushima an analysis through reliability engineering techniques. Process Saf Environ Prot 2015;97:80–90.

[3] Baker, S.R., Bloom, N., Davis, S.J., and Terry, S.J. 2020. COVID induced economic uncertainty, NBER Working paper, no 26983.

[4] GHS (Global Health Security) index (2019): https://www.ghsindex.org/wp-content/uploads/2019/10/2019-Global-Health-Security-Index.pdf (accessed 20/12/2020).

[5] Wang Z, Duan Y, Jin Y, Zheng ZJ. Coronavirus disease 2019 (COVID-19) pandemic: how countries should build more resilient health systems for preparedness and response. Glob Health J 2020;4:139–45.

[6] Chang CL, McAleer M. Alternative global health security indexes for risk analysis of COVID-19. Int J Environ Res Public Health 2020;17(9):3161.

[7] Dahlin KB, Chuang YT, Roulet TJ. Opportunity, motivation, and ability to learn from failures and errors: review, synthesis, and ways to move forward. Acad Manag Ann 2018;12(1):252–77.

[8] Chowdhury AZ, Jomo KS. Responding to the COVID-19 pandemic in developing countries: lessons from selected countries of the Global South. Development 2020;63:162–71.

[9] BBC Parliament, 2020, Select committee, lessons learned from COVID-19, with Matt Hancock, health and social care secretary, 24th November. https://www.bbc.co.uk/iplayer/episode/m000qv96/select-committees-COVID19-committee.

[10] Nuki, P., and Gardner, B., Exercise Cygnus uncovered: the pandemic warnings buried by the government, The Telegraph, 28 March 2020. (https://www.telegraph.co.uk/news/2020/03/28/exercise-cygnus-uncovered-pandemicwarnings-buried-government/) (accessed 2nd August 2020).

[11] Vaughan D. The challenger launch decision: risky technology, culture, and deviance at NASA. Chicago: University of Chicago Press; 1996.

[12] Kim JY, Miner AS. Vicarious learning from the failures and near-failures of others: evidence from the US commercial banking industry. Acad Manag J 2007;50(3):687–714.

[13] Labib A, Read M. Not just rearranging the deckchairs on the Titanic: learning from failures through risk and reliability analysis. Saf Sci 2013;51(1):397–413.

[14] Madsen PM, Desai V. Failing to learn? The effects of failure and success on organizational learning in the global orbital launch vehicle industry. Acad Manag J 2010;53(3):451–76.

[15] Maslach D, Branzei O, Rerup C, Zbaracki MJ. Noise as signal in learning from rare events. Organ Sci 2018;29(2):225–46.

[16] Tversky A, Kahneman D. Judgment under uncertainty: heuristics and biases. Science (1979) 1974;185(4157):1124–31.

[17] Montibeller G, Von Winterfeldt D. Cognitive and motivational biases in decision and risk analysis. Risk Anal 2015;35(7):1230–51.

[18] Kunz, R. (2011). The challenger disaster: making it personal. http://www.asee-se.org/proceedings/ASEE2011/Papers/FP2011kun110_183.PDF.

[19] Bunker D. Who do you trust? The digital destruction of shared situational awareness and the COVID-19 infodemic. Int J Inf Manage 2020;55:102201.

[20] Williams NL, Wassler P, Ferdinand N. Tourism and the COVID-(Mis) infodemic. J Travel Res 2020;61(1):214–18.

[21] Tran TPT, Le TH, Nguyen TNP, Hoang VM. Rapid response to the COVID-19 pandemic: Vietnam government's experience and preliminary success. J Glob Health 2020;10(2):1–14.

[22] Ngoc Su D, Luc Tra D, Thi Huynh HM, Nguyen HHT, O'Mahony B. Enhancing resilience in the COVID-19 crisis: lessons from human resource management practices in Vietnam. Curr Issues Tour 2021;24(22):3189–205.

[23] Baskin, J. COVID-19 and the Global Health Security Index (GHSI): values and value in global governance (2020).

[24] Razavi A, Erondu N, Okereke E. The global health security index: what value does it add? BMJ Glob Health 2020;5(4):e002477.

[25] Headley TY, Kim S, Tozan Y. Countries' progress towards Global Health Security (GHS) increased health systems resilience during the Coronavirus Disease-19 (COVID-19) pandemic: a difference-in-difference study of 191 countries. PLOS Glob Public Health 2025;5(1):e0004051.

[26] Ledesma JR, Isaac CR, Dowell SF, Blazes DL, Essix GV, Budeski K, Bell J, Nuzzo JB. Evaluation of the global health security index as a predictor of COVID-19 excess mortality standardised for under-reporting and age structure. BMJ Glob Health 2023;8(7):e012203.

[27] Argyris C, Schön D. Organizational learning: a theory of action perspective, Reading MA: Addison-Wesley; 1978. (ISBN 0-201-00174-8).

[28] Labib A. Towards a new approach for managing pandemics: hybrid resilience and bowtie modelling. Saf Sci 2021;139:105274.

[29] Labib A, Jones D, Andreassen N, Elvegård R, Cainzos MD. Characterization and modelling of potential seaborne disasters, in the ANA region. Appl Sci 2025;15(782):782 *(Switzerland)*.

[30] Bruneau M, Chang SE, Eguchi RT, Lee GC, O'Rourke TD, Reinhorn AM, Shinozuka M, Tierney K, Wallace WA, vonWinterfeldt D. A framework to quantitatively assess and enhance the seismic resilience of communities. Earthq Spectra 2003;19:733–52.

[31] Tierney K, Bruneau M. Conceptualized and measuring resilience. TR News 2007;250:14–17. http://onlinepubs.trb.org/onlinepubs/trnews/trnews250_p14-17.pdf) Accessed 15th August 2020.

[32] Rochlin GI, La Porte TR, Roberts KH. The self-designing high-reliability organization: aircraft carrier flight operations at sea. Naval War Coll Rev 1987;40(4):76–92.

[33] Agwu AE, Labib A, Hadleigh-Dunn S. Disaster prevention through a harmonized framework for high reliability organisations. Saf Sci 2019;111:298–312.

[34] Funtowicz S, Ravetz J. Emergent complex systems. Futures 1994;26:568–82.