Catastrophic Shocks Through Complex Socio-Economic Systems: A Pandemic Perspective

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Summary

The globalised economy has become more complex (connectivity, interdependence, and speed), de-localized, with increasing concentration within critical systems. This has made us all more vulnerable to systemic shocks. This paper provides an overview of the effect of a major pandemic on the operation of complex socio-economic systems using some simple models. It discusses the links between initial pandemic absenteeism and supply-chain contagion, and the evolution and rate of shock propagation. It discusses systemic collapse and the difficulties of re-booting socio-economic systems.

1. A New Age of Risk

Consider the following scenarios:

- *A highly contagious pandemic outbreak in South-East Asia (of comparable or greater human impact than the 1918 influenza outbreak) .*
- *A disorderly break-up of the Eurozone and global financial system implosion.*
- *A 'perfect storm'- during a time of major global financial instability - there are terrorist attacks on North African oil installations (partially driven by social unrest arising from record food prices) & a category 5 hurricane hits a major population/ industrial/ oil producing regions of the US east coast.*

These are all examples of potential global shocks, that is hazards that could drive fast and severe cascading impacts mediated through global systems. Global systems include telecommunications networks; financial and banking networks; trade networks; and critical infrastructure networks. These systems are themselves highly interdependent and together form part of the globalised economy. The interest in global shocks and how they manifest themselves has grown in recent years (WEF 2012, 2013; Helbing 2013,; Buldyrev *et. al*. 2010).

First it useful to acknowledge that the hazards referred to in the opening scenarios are increasingly likely. Potentially new pandemic strains are being encouraged by increasing human pressure on the biosphere, while mass global air transport could aid rapid global transmission. Ecological constraints, presently pre-eminent amongst them are food and oil flows and increasingly the effects of climate change are growing. Stresses in the credit backing of our financial and monetary systems are arguably increasing, with the additional vulnerability that such systems are the primary vector through which major ecological constraints in energy and food would be expressed (Korowicz 2011).

One of the primary issues for this paper are, given any significant hazard, how does the impact spread through the globalised economy and in what way are we vulnerable to the failure of interconnected systems. To answer this we need to understand how complex societies are connected and how they have changed over time.

The globalised economy is an example of a complex adaptive system that dynamically links people, goods, factories, services, institutions and commodities across the globe. Such systems can be represented by a 'state' that is not in equilibrium, but defines a set of ordered characteristics that exist within a range of deviations from a mean and persist for a period of time. For example, the state is characterized by exponential growth in Gross World Product of about 3.5% per annum over nearly 200 years within a range of several percentage points. This had correlated with emergent and self-organizing growth in socio-economic complexity which is reflected in the growth of the:

- **Number of interacting parts (nodes)**: This includes exponential population growth; the 50,000+ different items available in Wal-Mart; the 6 billion+ digitally connected devices; the number of cars, factories, power plants, mines an so on.
- **Number of linkages (edges):** This includes the 3 billion passengers traveling between 4000 airports on over 50 million flights each year; the 60,000 cargo ships moving between 5000 ports with about a million ship movements a year; the average number of media channels (internet sites, TV channels, twitter feeds) per person times the population; and the billions of daily financial transactions.
- **Levels of interdependence between nodes**: The growing number of inputs necessary to make a good, service, livelihood, infrastructural output or the function of society as a whole.

- **The speed of processes (or time compression)**:This includes the increasing speed of financial transactions; transportation; digital signaling; and Just-In-Time logistics. If we consider the globalised economy as a form of singular organism, we can understand this process as an increasing metabolic rate.

- **Efficiency:** increasing competition and global trade arbitrage driving down inventories; and globalised economies of scale.

- **Concentration:** The emergence of 'hubs' within the globalised economy- a small number of very highly connected nodes whose function (or loss of function) have a disproportionate role in the operation of the globalised economy . For example, banks are not connected at random to other banks, rather a very small number of large banks are highly connected with lots of other banks, who have few connections to each other. These arrangements are sometimes known as scale-free networks. We can also see concentration in critical infrastructure, and trade networks.

- **De-localization:** The conditions of personal welfare; business or service output; or country's economic output is smeared over the whole globalised economy. The corollary is that if there is a major failure of the systems integration in the globalised economy, a localised community may have extreme difficulties meeting its basic needs.

Economic and complexity growth have in many ways reduced risk. Localized agricultural failure once risked famine in isolated subsistence communities, but now such risk is spread globally. It has made critical infrastructure such as sewage treatment and clean water available and affordable. Global financial markets enable an array of risks, from home insurance and pensions to default risk and export credit insurance, to be dispersed and potential volatility reduced. Indeed, what is remarkable is just how reliable our complex society is given the number of time sensitive inter-connections.

Another way of saying all this is that our society is very resilient, within certain bounds, to a huge range interruptions in the flow of goods and services. Within those bounds our society is self-stabilizing. For example supply-chain shocks from the Japanese tsunami in 2011, the eruption of the Icelandic Eyjafjallajokull volcano in 2010 or the UK fuel blockades in 2000 all had severe localised effects in addition to shutting down some factories across the world as supply-chains were interrupted. However the impacts did not spread and amplify, and normal functioning of the local economy quickly resumed.

But we know from many complex systems in nature and society that a system can rapidly shift from one state to another as a threshold is crossed (Scheffer 2009). One way a state shift can occur is when a shock drives the system out of its stability bounds. The form of those stability bounds can increase or decrease resilience to shocks depending upon whether the system is already stressed prior to the shock.

The commonalities of global integration mean that diverse hazards may lead to common shock consequences. The systems that transmit shocks are also the systems we depend upon for our welfare and the operation of businesses, institutions and society, so to borrow Marshal McLuhan's phrase, the medium is the message. One of the primary consequences of a generic shock is an interruption in the flow of goods and services in the economy. This has diverse and profound implications - including food security crises', business shut-downs, critical infrastructure risks and social crises. This can in turn quickly destroy forward-looking confidence in an economy with major consequences for financial and monetary stability which depend ultimately on the collateral of real economic production. More generally it can entail multi-network and de-localised cascading failure leading to a collapse in societal complexity.

Previously the dynamics of such a scenario was studied when the initial shock was caused by a systemic banking collapse and monetary shock. This coupled the exchange of goods and services causing financial system supply-chain cross contagion and a re-enforcing cascade of de-localizing multi-system risk (Korowicz 2012).

In this paper a similar methodology is used to look at the socio-economic implications of a major pandemic. After a very brief review of other researchers work (section 2), some real life examples of partial systems failure are reviewed (section 3). This allows us to make make some estimates of shock spreading rates. In section 4 the links between pandemic absenteeism and supply-chain contagion is discussed and related to societal complexity. In section 5 we look at how contagion spreads, the rate, and the relationship to complexity. In section 6 we look at some of the multi-system interactions. In 7, we look at why after a major collapse, the pre-shock socio-economic state may not be recoverable. Finally there is a short conclusion. This paper aims to broadly outline how very simple models can shed light on catastrophic shocks in complex socio-economic systems. A significantly more detailed discussion on several issues may be found here,(Korowicz 2012).

2. Socio-economic Impact of a Major Pandemic

We are interested in the socio-economic implications of a major influenza pandemic whose initial impact would be direct absenteeism from illness and death, and absenteeism for family and prophylactic reasons. The pandemic wave (we will only consider one) lasts 10-15 weeks. We assume this causes an absenteeism rate of 20% or 40% over the peak period of 2-4 weeks, and a rate above 20% for 4-8 weeks when the peak is 40%. This represents our initial impact. Our question is then what happens next.

There are two general perspectives to studying such impacts. The first focusses on the impact on a specific industry or service, often with a view to Business Continuity Planning (BCP). Unsurprisingly, the question of how a health service would manage a pandemic when its own operation is compromised is of recurrent interest (Bartlett and Hayden 2005; Itzwerth *et al*. 2006). Or for example the effect of worker absenteeism on the movement of freight in a coupled US port-rail system (Jones *et al*. 2008). This analysis is important for local preparations however it suffers from having to isolate the system under consideration from the environment to avoid the analysis becoming too open and complex.

The alternative track is to use macroeconomic modeling to look at the impact on an economy as a whole. This type of modeling might be useful for low impact pandemics where the economy remains in its historical range of conditions, for example the impact of the 2003 SARS outbreak (Knapp *et al.* 2004; Keogh-Brown and Smith 2008).

However when considering major pandemics (McKibbin and Sidorenko 2006; Keogh-Brown *et al.* 2010) it is highly questionable if such conventional macroeconomic modeling works, or would be very mis-leading. This is firstly because such models are built out of, and parameterized within the context of long run macroeconomic stability. A major pandemic could be highly de-stabilising, causing, as we shall see, cascading systemic disruption and failure.

Secondly, such models are blind to the issue of rising complexity and the speed of processes, which we argue here are essential for understanding major shocks. Finally, they have little to say about the dynamics of the impact, how it spreads through time and cascading failure. This is of most interest to actual risk management.

3. Vulnerability Revealed

One way to understand and even parameterize the structure and behavior of complex socio-economic systems is to empirically study occasions when there has been some systemic failure.

In September 2000 truckers in the United Kingdom, angry at rising diesel duties, blockaded refineries and fuel distribution outlets (Public Safety and Emergency Preparedness Canada 2005; McKinnon 2006; Peck 2006). The petrol stations reliance on Just-In-Time re-supply meant the impact was rapid. Within 2 days of the blockade starting approximately half of the UK's petrol stations had run out of fuel and supplies to industry and utilities had begun to be severely affected. The initial impact was on transport - people couldn't get to work and businesses could not be re-supplied. This then began to have a systemic impact.

The protest finished after 5 days at which point: supermarkets had begun to empty of stock, large parts of the manufacturing sector were about to shut down, hospitals had begun to offer 'emergency only' care; automatic cash machines could not be re-supplied and the postal service was severely affected. There was panic buying at supermarkets and petrol stations. It was estimated that after the first day an average 10% of national output was lost. Surprisingly, at the height of the disruption, commercial truck traffic on the UK road network was only 10-12% below average values.

There were clear indications that had the fuel blockades gone on just a few days longer large parts of UK manufacturing including the automotive, defense and steel industries would have had to shut down.
In the end this was a point hazard with systemic impacts, so once government became aware of the systemic risks they forced the truckers' hands and they desisted. Still the event concentrated minds. The UK was within days of a severe food security crisis and widespread socio-economic breakdown.

Lest one think this is an issue for only the most complex societies -a week-long truckers strike in September 2012 in South Africa again saw emptying petrol station and ATM machines within a week of the disruption. And hospitals reliant on burning coal for power had to fall back on reserve stocks (Boesler 2012).

While the UK fuel blockade was probably the most dramatic and well-documented example of supply-chain failure, we also got glimpses of what can happen the following Icelandic volcano eruption in 2010, and the tragic events surrounding the Japanese tsunami and Thai flooding in 2011. From these examples we see that failure of production or supply from one area can shut down factories on the other side of the world within days of the initial interruption. A report from the think-tank Chatham House on the impacts of the Icelandic volcano and subsequent interviews with businesses about its impact and their preparedness came to the general conclusion (Lee et. al. 2012) :

"*One week seems to be the maximum tolerance of a Just-In-Time economy*"…..before major shut-downs in business and industries would occur.

Further, after such a disruption, things would not just return to normal. Again, from the Chatham House study:

"*... many [of the businesses surveyed] said that had the disruption continued just a few days longer, it would have taken at least a month for companies to recover*"

And a quote from a desk study on the impact of a one week long absence of (just) trucks in the UK economy, things would not just return to normal (McKinnon 2006):

"..*After a week, the country would be plunged into a deep social and economic crisis. It would take several weeks for most production and distribution systems to recover*"

So the indications for the UK are that over the first week of the disruption, contagion across supply-chains and businesses rises relatively slowly. But very soon after that socio-economic disruption rapidly become very severe. And then even if the primary cause can return to normal, the economy takes weeks to recover. The studies do not consider what would happen if the primary disruption were to continue for many weeks.

4. Interdependence, Liebig's law, and Cascading

One of the defining features of rising complexity is growing interdependence. That is, the output of a person, a service provider, a factory, a piece of critical infrastructure, or a complex society as a whole depends upon ever more inputs, be they tools, intermediate products, consumables, specialist skills and knowledge or collective societal infrastructures. And those outputs in turn become further inputs through the dispersed networks of the globalised economy.

Some of these inputs may not be necessary to the output of a factory, a service or economy. However, there will also be more critical inputs that the output cannot proceed without. Some of these are easily substitutable through other replacements, suppliers, people or stores that are easily accessed. What we are left with are critical inputs with low substitutability. This is shown in figure:1. We can also see that some of the least substitutable critical inputs are labeled hubs. Hubs are things like electricity, fuel, water, and financial system functionality - things generally referred to as critical infrastructure. They are societal services and functions upon which all society depends. This is represented by the dotted line.

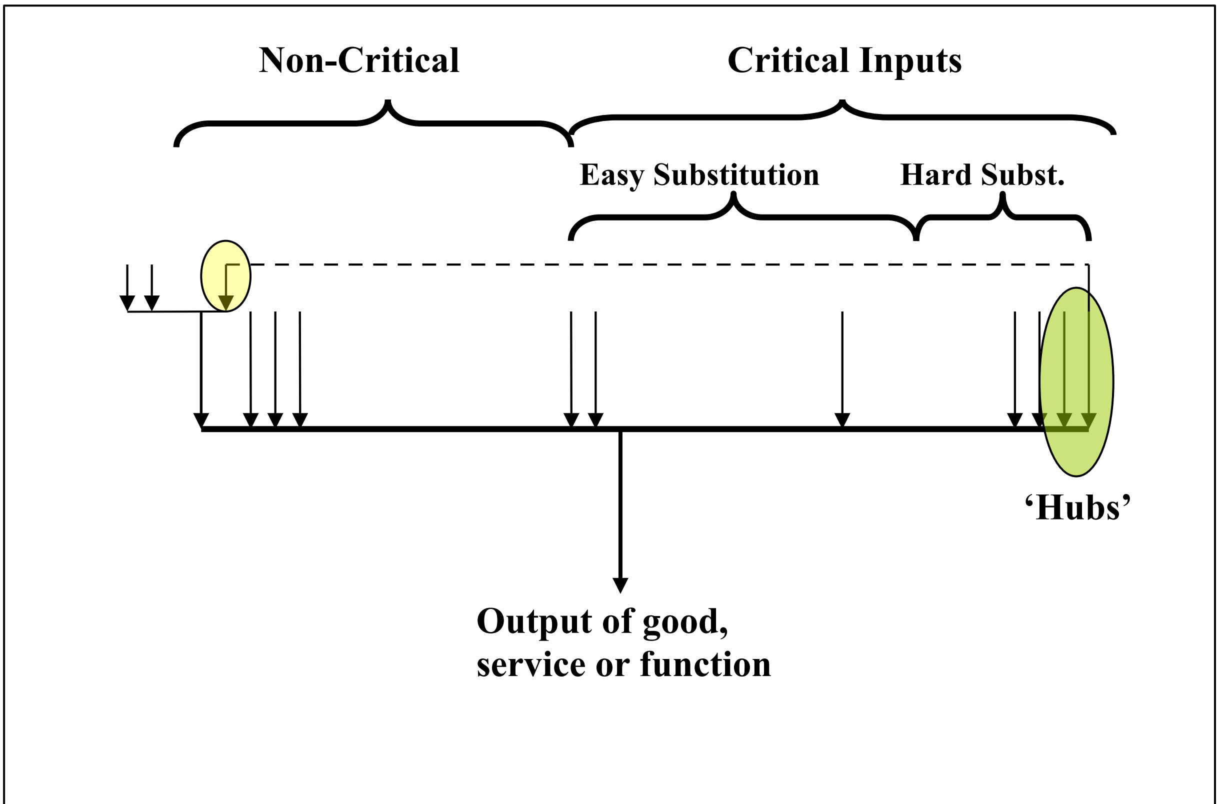

Figure 1 : *For a business, service or even society, increasing inputs are required to produce and output. Some fraction of those will be 'critical' without which an output cannot proceed, and some of those will be hard or impossible to substitute. Some of the hardest to substitute are 'hubs' such as critical infrastructure-shared by very many functions in society, see dotted line.*

A simple but important principle, Liebig's Law of the Minimum, says that the production is constrained by the scarcest critical input. So even if you have ample supplies of all but one critical input, your production fails. That is, production fails on the weakest link.

This explains why the most exposed businesses to supply-chain failure are the most complex businesses. Firstly; they have some of the most inputs (making a car can mean assembling up to 15,000 components). Secondly, they have more inputs are very complex and specialized, and so cannot be easily substituted. Alternative production lines might not be available or take months to re-engineer or specialist skills may be in limited supply. Thus, auto and electronic manufacturers were some of the most affected by the Icelandic volcano, the Japanese tsunami and the Thai flooding in 2011.

What Liebig's law shows is that you do not need to lose everything to stop a business, service or function or society - just the right bit. This helps to explain why a loss of only 10-12% of commercial vehicles had such a big impact during the fuel blockades.

As our economies have become more complex we have been, on average, adding more inputs into our lives, into goods and services, into the functioning of our societies. Secondly more of those are critical with low substitutability.

Let us now apply Liebig's law to pandemic absenteeism. The people affected by a pandemic are part of the supply of inputs to any system's function. There may be many people contributing to one output of a business, service or function. We assume that most employees are either unnecessary for the period of the pandemic, can telecommute, or are easily substituted. But there is a smaller number of sub-functional roles occupied most likely by those with specialist skills who are critical with low substitutability. If any one of them is unavailable, the sub-functional role fails and with that, the output of the whole organization/ function. We can then say that the complexity of the output is the number of specialist, low substitutability sub-functions, this we can take as a measure of complexity *C.*

We are interested in the probability that the output fails, *Pf*. Let 0   1 be the absentee rate, and r be the redundancy where one specialist plus one spare is r==2, or 100% redundancy. For each specialist role, the chance that it can produce a successful output is 1- ^{r}. If there are *C* distinct specialist roles then:

Eqn:1

$$P_f = 1 - (1 - \alpha^r)^C$$

In figure:2 we see a simple model of absenteeism as might happen in a pandemic situation. It is shown for absenteeism rates of 20% and 40%. It also shows where there is no staff redundancy, and where every specialist has a 'spare'.

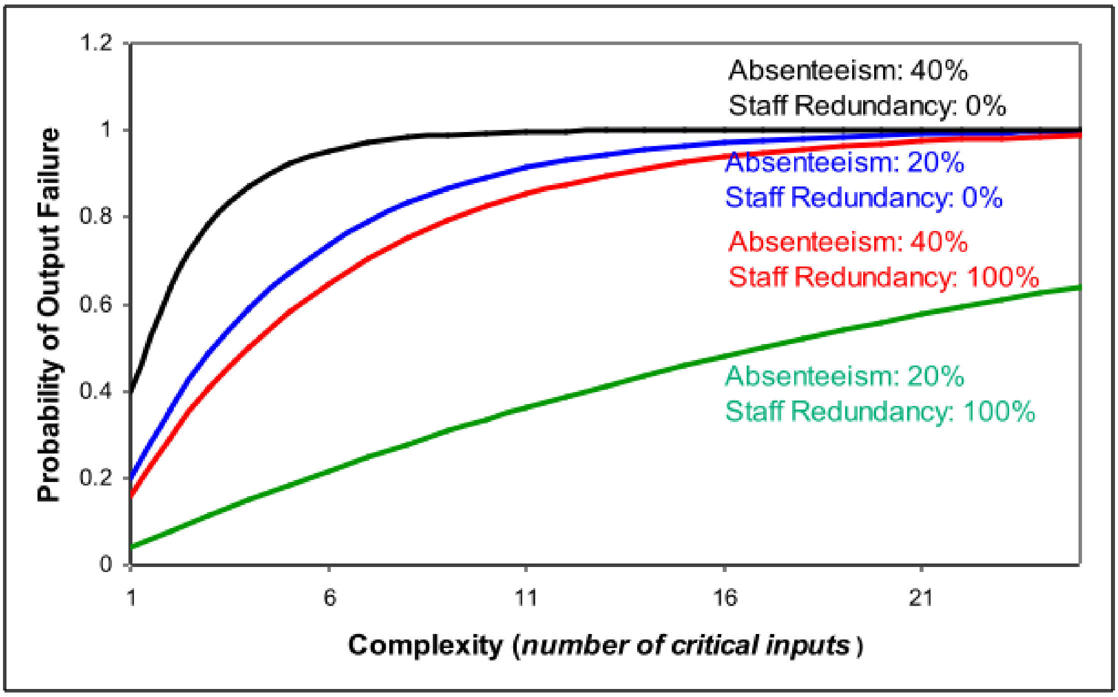

Figure 2: *As the number of hard to substitute critical inputs increases, in this case people with specialist skills/ knowledge serving critical sub-functions, then the probability of a failure in the output of a business, service or society increases. This probability is shown for different pandemic absentee rates, and the level of redundancy in those specialist roles.*

Clearly, higher absenteeism rates and no staff redundancy increase the chance of a system failure. We can imagine a factory or service with hundreds of employees including 6 independent but critical specialist roles, with 100% redundancy, upon which the whole factory depends. But even with a 20% absenteeism rate, there is still a 20% probability that the factory or service goes down because one critical specialist and their spare is absent. Once this happens, all the other hundreds of employees might as well go home. These become the indirect absentees.

Firstly, with the loss of this output good or service (especially if it is critical with low substitutability) other businesses and services may be affected potentially causing cascading affects through complex socio-economic networks as a whole. The dual absenteeism-output cascade is shown in figure:3.

Secondly we can see the effective absenteeism in society is the initial absenteeism due to the pandemic plus the sum of indirect cascading absenteeism. Further the lack of inputs stopping production would add further indirect absenteeism. This positive feedback means the number of economically inactive people in the society is potentially far greater than the absenteeism rate. This tends not to be reflected in macroeconomic modeling which is blind to complexity risk and cascading affects.

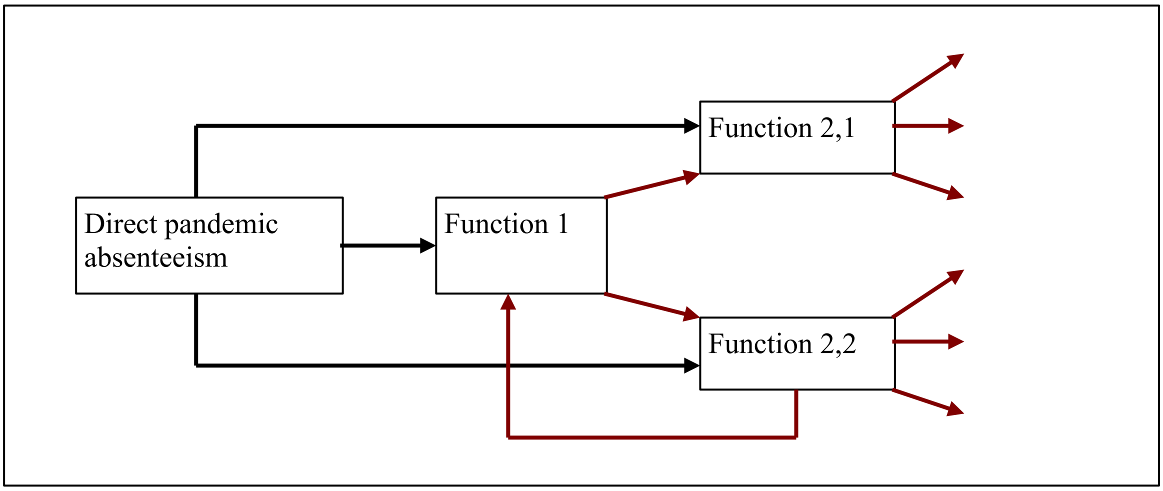

Figure 3: *Cascading failure through functions (factories, services) goes via absenteeism (black lines) and loss of goods/ services outputs (red lines). Together they represent supply-chain contagion. Indirect cascading absenteeism is not included.*

5. *Time and Cascading Failure*

In society there is always a level of absenteeism and a percentage of goods and services that can't be delivered for whatever reason. You do not get the spread of supply-chain contagion as complex societies are efficient at finding alternative suppliers, and some inventories are carried to help when there is a hiatus. Further most factories don't produce very critical things or there is lots of substitutability. One wont miss a brand of toothpaste in the supermarket when there are 20 brands available.

To initiate a cascading failure one first needs appropriate scale, from a major hub failure or large enough absenteeism. Secondly, one requires that what is affected has what is sometimes known as *centrality*, meaning how critically connected it is to other parts of a socio-economic network. Thus the effects of a pandemic or hub failure in a weakly connected country, Mali say, would be unlikely to spread supply-chain failure widely.

Thus we can conclude that there might be point above which supply-chain contagion takes off, and below which the society is still operational and recovery can occur. This point depends upon the initial pandemic absenteeism rate and the society's complexity at the epicenter of the pandemic. This point, in the language of complex systems is a critical transition, I_c ,measured as the initial number of 'infected' supply-chain nodes, which when crossed, causes a positive feedback of supply-chain contagion.

A simple model of supply-chain failure can be based upon the idea that the more supply-chains are disrupted or infected, the greater the chance that further supply-chains will be infected (Korowicz, 2012). This is limited ultimately by the number of connected parties, *L*. This has the form of the logistic equation where we can associate the time constant with the average time a society can operate using its stock inventories, T_i. The number of infected nodes is:

Eqn: 2

$$I(t) = L I_o \frac{e^{\left(\beta \frac{t}{T_i}\right)}}{\left(L + I_o e^{\left(\beta \frac{t}{T_i}\right)} - 1\right)}$$

Where $I_O > I_C$ and   is a constant.

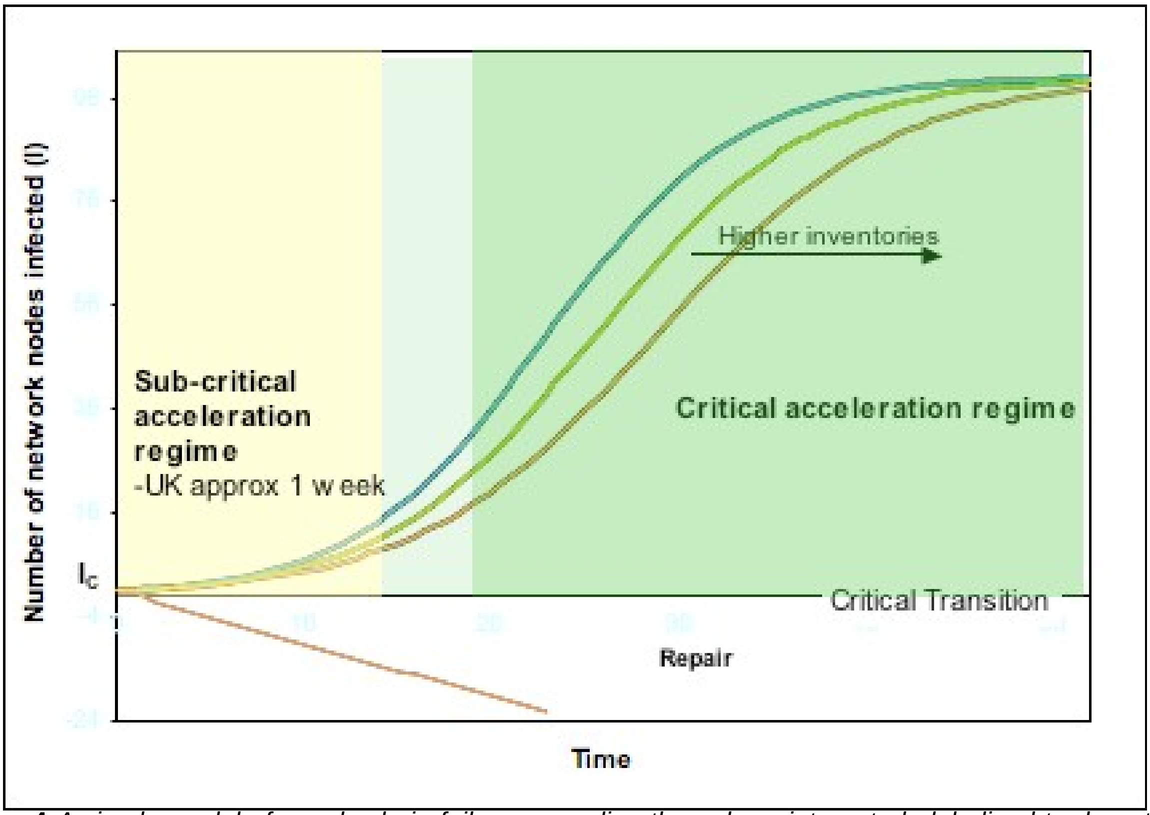

Figure: 4 *A simple model of supply-chain failure cascading through an integrated globalised trade network. A critical transition point marks the boundary between where contagion spreads and where it does not spread, but can be repaired.*

Once contagion begins it rises slowly, but a point comes where it begins to accelerate rapidly. That point is the dividing line between the sub-critical and critical acceleration. We can see that the longer time inventories are held within a society, the longer the time the operation of society can function before the critical acceleration. Clearly then the rising speed of societal processes, in this case, supply-chain re-charging, reduces temporal resilience to shocks.

Even this very simple model reproduces the main features of real events and studies seen in section 3 - the impact on society does not rise linearly with time but starts to accelerate as more inventories are drawn down. From what we have seen, the sub-critical time is about a week for the UK. In section 2 the scenario for a major pandemic would have had greater than 20% initial absenteeism for 4-8 weeks, clearly this would be very deep into the critical acceleration regime. Of course this assumes the initial absenteeism brought the supply-chain failure above the critical transition. There are good grounds for thinking this would be so by considering that a loss of 12% of trucks was already bringing the UK along the sub-critical acceleration curve.

For pandemics in less complex societies we would expect a higher critical transition point, and a longer period before critical acceleration occurs.

6. *External Cross-Network Contagion*

We imagine a pandemic outbreak occurs in South-East Asia, say. The main vectors through which a shock could propagate outside the region are pandemic contagion, financial system contagion, and supply-chain contagion. How they transmit that contagion depends upon the network structure and centrality of the effected region with respect to the external world. We might also assume that the spread would require an initial external impact greater than some critical value for external contagion to occur, this is in correspondence with the critical transition level I_C in section 5. Further we would expect the shock to spread at different rates (banking shock could travel faster than supply-chain contagion because the operational speed of the financial system is greater than the inventory turn-over time). We would also expect different periods for each network before critical acceleration occurs, with the fastest system dominating.

The local spread of the infection would in broad terms spread out in geographical space at the speed of human transport. There would also be the spread through airport linkages. Here the global spread of the pandemic is across a different topological space related to the density of linkages between airports and the shortest paths between any airports (Woolley-Meza *et. al.* 2011).

Some countries' role in trade is far more important to the globalised economy than others. The more important the initially impacted region is, the greater is the likelihood of spreading supply-chain contagion globally. Kali & Reyes (2007) measured countries' influence on global trade, not only by trade volumes, but the influence a country has on the global trading system. They used an *Importance Index* to rank their influence. For example, they find that Thailand, which was at the centre of the 1997-1998 Asian financial crisis ranked 22nd in terms of global trade share, but 11th on their level of importance. In another study, Garas *et. al.* (2010) used an epidemic model to look at the potential any country had to spread a crisis. One of their data sets is based upon international trade in 2007. It uses a measure of *centrality* to identify countries with the power to spread a crisis via their level of trade integration. Like the previous paper, the centrality in the network does not necessarily correspond to those countries with the highest trade volumes. There are 12 inner core countries, which are listed in no particular order are: China, Russia, Japan, Spain, UK, Netherlands, Italy, Germany, Belgium-Luxembourg, USA, and France. The data sets used by both groups combine Belgium and Luxembourg data, both sets of authors have classified them together and separately respectively.

Hidalgo & Hausmann (2009) used international trade data to look at two things - the diversity of products a country produces, and the exclusivity of what they produce. An exclusive product is something made by few other countries. Most countries in the world are non- diversified and make standard products. The most complex countries are diversified and make more exclusive products. More exclusive products have less substitutability. It can also be assumed that even a standard product, bread say, requires many more critical inputs in a complex country than in a less complex one.

Financial system contagion outside the initially impacted region could be through banking networks, the bond market, the shadow banking system, currency volatility and confidence. Again the structure of financial networks and the centrality of the region with respect to financial assets and liabilities would determine the extent of any shock. A additional issue is how vulnerable or resilient the external financial system is at the time of the shock.

If a multi-network failure were to spread globally the ability of the external world to help the initially impacted region would be undermined. In this case there would be global systemic collapse.

*7. **Recovery & Recursion Failure***

We saw indications in the empirical studies of failure in section 3 that once supply-chain failure starts to go critical, the removal of the primary cause does not allow the immediate resumption of socio-economic activity. Why?

The disruption could have pushed companies into bankruptcy, and purchasing power in the economy would be lost as trade collapsed. Failures in critical infrastructure including payment might also occur. More generally there would be an intertwined supply and demand collapse.

More broadly, if an economy was shattered, and its forward looking viability looked both precarious and uncertain one would expect a collapse in the value of a country's currency. Rather than helping exports (which would be very little because the economy's productive capacity had collapsed), it would hinder imports of emergency supplies and make debt in external currencies much more difficult to service. The economic damage and reduced economic prospects may then cause tightened credit conditions, spiraling bond yields and systemic bank failure.

There are also issues that are most pertinent for more complex societies. We imagine that after a pandemic wave people are again available for work. But people cannot however become productive immediately because other inputs are also needed. But those inputs are stalled because they rely upon other inputs and so on. More broadly we may define Recursion failure as: "*the inability of a complex economy to easily resume production and trade after a significant collapse because in a complex and interdependent economy, production and trade must resume in order for production and trade to resume*".

Further even if a government wanted to rebuild, it may be too complex to orchestrate resumption from the top down. This is firstly because the economy has evolved by self-organization, nobody has ever had, nor could they have put its elements together in the first place. Secondly, even if it could be done, the systems of command, control and supply that might do it would be the very systems that had been undermined.

Over time entropy would become an issue as engines rust, reagents become contaminated, and expected maintenance and repairs are left undone. This would all add to the cost and inputs needed for resumption. In a more complex society the degradation rate may be higher for thermodynamic reasons.

Overall, we are saying the longer a socio-economic system spends in the critical regime, the more likely it is to undergo a complete systemic collapse and loss of basic function. In addition, the longer it spends in this state, the more difficult it may be to ever return to its pre-pandemic state.

This is a complex society's equivalent of a heart attack. When a person has a heart attack, there is a brief period during which CPR can revive the person. But beyond a certain point when there has been cascading failure in co-dependent life support systems, the person cannot be revived. This means that the socio-economic system could be changed irretrievably and the job of society and government would be to both manage the crisis and plot a fundamentally different path.

The extent of our contemporary complex global system dependencies, and our habituation to a long period of broadly stable economic and complexity growth means a systemic collapse would present profound and existential challenges.

8. Conclusion

To make the systems we depend upon more resilient ideally we would want more redundancy within critical systems and weaker coupling between them. Localization and de-complexification of basic needs (food, water, waste etc) would provide some societal resilience if systems resilience was lost. We would have more buffering at all levels, that is, larger inventories throughout society.

All this is the very opposite of the direction of economic forces. The reason we have such tight inventories, tight coupling, and concentration in critical infrastructure is they bring efficiency and competitive advantage. Further, in a time of global economic stress there is a drive towards further economic efficiency. For example, during super-storm Sandy, fuel shortages were exacerbated by low inventories that were the direct result of cost cutting arising from the financial crisis (Schneyer & Gebrekidan 2012). In general we are locked into socio-economic processes that are increasing complexity-derived vulnerability.

Increasing vulnerability coupled with increasing hazard mean that the risk of a major socio-economic collapse is rising. The commonalities of catastrophic shock outcomes across a range of hazards suggest common risk and resilience planning is urgently required. Further, because of the possibility that a permanent state shift could occur, planning needs to consider how to deal with non-reversion to pre-shock conditions.

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