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Handling the COVID-19 Crisis: Towards an Agile Model-Based Systems Approach

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April 27, 2020

1 – Introduction

The COVID-19 crisis (see [1], [75] or [66]) took many by surprise. Globally, most of the nations were unprepared. Moreover they reacted in quite different ways as the pandemic unfolded and this can be clearly observed by the rather different dynamics per country in terms of COVID-19 confirmed deaths per million inhabitants (see for instance Figure 1 and [30] or [75]). In this short paper, we argue that one of the root causes of this unpreparedness and this difference of reaction is the lack of conceptual and methodological tools to think about the crisis as a complex system. We advocate that systems engineering is a first-in-class candidate to provide such tools. Namely, we suggest a model-based agile systems engineering approach to crisis management.

Two characteristics of the COVID-19 crisis are striking: first, its extent in space, second its extent in time. This crisis is indeed going to have impact during an unknown, but probably prolonged period of 18 months or longer, affecting all activities on Earth, which makes it a systemic crisis and not only a simple health crisis. The closest analog we have at a global scale is the H1N1 influenza pandemic of 1917-1919 which killed between 17 and 50 million people worldwide (see [12]). Handling the current COVID-19 crisis therefore requires a holistic approach taking into consideration an extremely complex system, i.e. human society as a whole.

Another important aspect of the COVID-19 crisis is that the pandemic propagation is very fast even when considering the ‘epoch of the Internet’ and information exchange at the speed of light, which should enable quick decisions. However, and we think that this is a crucial feature of this crisis, the incubation time of the disease introduces a delay – that has been estimated as being up to 2 weeks according to epidemiologists (see

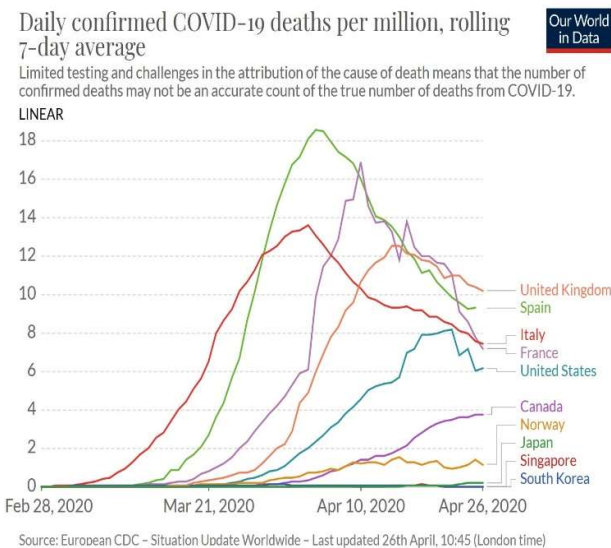


Figure 1 – Statistics at end April 2020 of confirmed deaths per million inhabitants since end Feb. 2020 for some countries

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[67] or [80]) – between the implementation of countermeasures and the observation of their effects. This is compounded by the fact that a significant fraction of the virus carriers appear to be asymptomatic, causing a large difference between the number of *actual* cases and the number of known or confirmed cases (see [18] and [74]). Hence, the problem of monitoring the COVID-19 crisis can be seen as a control theory problem with a delay in the feedback loop used to stabilize the situation in addition to the problem of low or only partial observability of the true system states. We shall elaborate further on this point.

From a system theory perspective, the above characteristics raise at least three difficult problems.

The first one, which is rather expected, regards scalability issues: can our current systems engineering modeling methods (cf. [11], [21], [43], [51], [55], [56], [75] or [67] for instance) be extended to a system, or more exactly a system of systems (SoS), as large and as complex as human society as a whole? What is to abstract away in such a model and what features must be retained in the model and at what level of fidelity? We know that quantitative differences in models induce eventually qualitative differences in action. To which extent does this affect our modeling capacities? These questions are clearly not easy to solve, especially due the fact that they are not answered by the only known models existing in that direction, that is to say the so-called World models, based on generalized Volterra equations, that emerged following the seminal work of J.W. Forrester in the 70s (see [28] and [46]).

The second problem regards the shift from regular operations to crisis management. We know from C. von Clausewitz and Sun Tzu (cf. [57] and [65]) that “war is the continuation of diplomacy with other means”, but it however remains that, at some point, one has to change dramatically and rapidly the management mode, and often also the management teams, when one has to deal with a crisis, especially when it is as complex and systemic as COVID-19. This raises in turn two questions: when and on which basis shall one perform the switch from normal operations to crisis management? And to which extent does this shift of management mode change the needs in terms of models, methods and tools?

The third problem is caused by the emergence of local and partial solutions which is key since the COVID-19 crisis impacts all sectors of society, including the medical, financial, transportation, manufacturing and overall economic systems. On the one hand, society needs fast and innovative solutions in order to mitigate as much as possible the consequences of the crisis, which favors local and partial solutions. On the other hand, society also needs a strong coordination of actors in order to avoid contradictory strategies for addressing the crisis. This is particularly true when it comes to avoiding a second or third wave of the COVID-19 pandemic as was observed during the Spanish flu of 1917-1919 (see [12]). In other words, a central question is how to favor the emergence of bottom-up local actions while, at the same time, ensuring top-down monitoring and coordination of such actions, with very short feedback loops. This calls clearly for an agile approach (see [38] and [67]) of the problems induced by the COVID-19 crisis.

Stating the above problems, we made a clear, although implicit, choice: we do strongly believe in the use of models, and more precisely of systemic models to think through and manage the crisis. Models as we consider them here are however not Platonic ideals, but fundamentally observational models, which rely on the observation of the realness of the COVID-19 crisis, including in particular the effects of the decisions taken based on them. Such models are therefore intended to be working tools that capture the very systemic nature of the crisis in order to achieve a better understanding of the situation and to allow a better communication amongst stakeholders. In that respect, models have two roles: a first, obvious one, which consists in the concrete calculation of key performance indicators (KPIs) to support the decision making process through experiments *in silico*; and a second more metaphorical

one, to help us think better about the dynamic evolution of the systems at stake. We shall discuss here both roles of models.

The remainder of this article is organized as follows. In the next section, we discuss which systemic models may support better management of the COVID-19 crisis. Then, in the third section, we advocate for an agile approach for crisis management. A fourth section concludes the article with several recommendations.

2 – From the Crisis of Models to the Models of Crisis

2.1 – Beyond the COVID-19 Crisis: a Crisis of Models

The general impression which emerges from the huge and rapidly expanding literature dedicated to the COVID-19 crisis is that this crisis was first and foremost analyzed as a health crisis (see for instance [74] or [66]). Economic impacts of the crisis were of course quickly understood everywhere, but, as far as we can observe, they were rather considered as an inevitable consequence of the health crisis that has to be managed independently (see [39]). In this matter, most of the countries did not publicly communicate – to the best of our knowledge – any analysis trying to rationally discuss what could be the best trade-off for jointly minimizing both the health impact and the economic impact of the COVID-19 crisis. It can indeed be expected that thanks to aggressive mitigation measures in many countries only a relatively small number of people according to the existing statistics (see [17], [41] or [75]) will be affected, when however there will be and already is a global economic impact on all of society (see [39] or [60]). But, as one can easily guess, public policies and associated effects that could result from such a trade-off approach would of course be quite different from either an only health-preservation policy (such as promoted in [1]), or conversely an only economic-preservation policy. Perhaps the biggest ethical issue around such model-driven tradeoffs is that it would require placing an explicit economic value on human lives, which is something that, to our knowledge, no national or regional government in the world has been willing to do.

Moreover, one can also probably challenge the assumption that the COVID-19 crisis will be quickly over: what would indeed happen and what shall one do if the health crisis remains endemic in the near future? This may indeed be a possible scenario due to the space and time magnitude of this crisis and the fact that we are still lacking a robust and widely shared medical treatment. As one can see, the way of thinking about the crisis from a global perspective rather than purely a health crisis changes deeply the way of addressing the crisis and its consequences.

This situation is probably the consequence of the fact that the crisis is mainly observed on a daily basis, through for instance the daily COVID-19 reports provided by the World Health Organization [75], by other institutions [17] and by each local government, leading to a rather short-term vision of the crisis. However, changing the time scale of observation gives us immediately another and totally different perspective on the COVID-19 crisis. If we are for instance observing at the time scale of a quarter of a year (3 months), the crisis becomes instantaneous and can be considered as an event – in the classical meaning of synchronous modeling (see for instance [48]) – without any duration. Thus, the choice of time step and sampling frequency is critical as it is in all control systems. The perspective⁷ changes in particular radically since it obliges us to think what could be the next state of the system under observation, that is to say human society, which may be on its way towards a deep economic crisis, at least in the Western countries. Continuing the analysis at the same high-level time scale, a possible

⁷ This remark motivates hierarchical control of the COVID-19 crisis with a meta controller at system level using a weekly monthly or quarterly time step and local controllers using daily time steps (see section 3.2).

catastrophic evolution scenario would be a financial crisis resulting from the economic crisis with some delay, generating thus the specter of a deep and prolonged recession, as pointed out for instance by some economists in recent economic analyses (see [49] or [60]). This, moreover, could then also lead to more classical health crises in the future (see Figure 2) due to the two-sided coupled interaction between the public health system and the economic system.

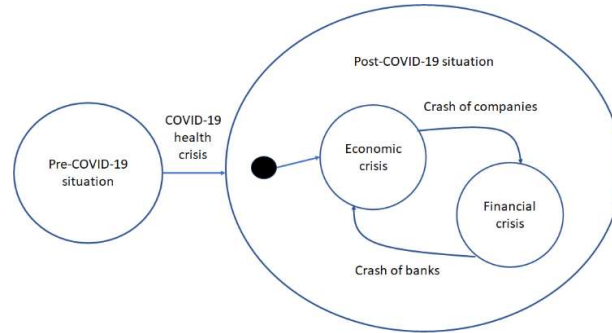


Figure 2 – A possible catastrophic scenario that could result from the COVID-19 health crisis

In such a catastrophic future scenario, extending the duration of people’s confinement in western countries in order to minimize the short term health impact during the initial crisis would for instance result in deeply debilitating the health of more or less the same population in the mid- to long term future (months to years). Such a possible paradox is typical of the classical fact in optimal control theory that the optimal trajectory of any non-linear system can never be obtained through local optimizations alone (see [11]). In order to take into account and to avoid such paradoxical consequences, one must choose a systems approach to analyze the COVID-19 crisis, integrating all existing domains of knowledge into a common understanding of the crisis, since this is the only approach that provides us a global vision, both in space and time and at different possible observation scales, and that gives us a chance to find the global optimum for human society as a whole.

We can thus see that there is another crisis, hidden within the COVID-19 crisis, which is a *crisis of models*. By focusing on the short term, the crisis indeed appears only as a health crisis which is obviously not the case as soon as we are addressing it with a long-term perspective. Therefore, it clearly happens that we are not currently using the right models – which for us are fundamentally integrated systemic models – to analyze and act “optimally” with respect to the crisis.

In this matter, let us first recall that a model is just an abstraction of reality (in the meaning of abstract interpretation theory [20]), but is not reality itself. A model can be useful to act on reality when it reflects well reality, as expressed by the famous assertion “A map *is not* the territory it represents, but, if correct, it has a *similar structure* to the territory, which accounts for its usefulness”, popularized by A. Korzybski [41] or the well-known “*All models are wrong, some are useful.*” by G. Box [15]. As one can easily deduce from that definition, models which are not reflecting well reality may have negative impacts on reality since they will lead to wrong decisions, i.e. control actions. These negative impacts can of course be amplified in the context of a systemic crisis such as COVID-19.

This being recalled, our point of view is clearly supported by an analysis of the 2020 scientific literature. A search of the keyword “COVID-19” on Google Scholar (cf. [33]) on April 13, 2020, revealed that, at this moment of time, only 10 papers – i.e. around 1 % – of the first 900 most cited papers on COVID-19 were *not* discussing of health issues (health covering here biology, epidemiology, medicine and health policy and management), but rather focusing on the societal and economic consequences of the crisis. Moreover, in terms of citations, most of these 10 papers were poorly cited: 2 were cited

around 20 times, 3 around 10 times and the remaining ones less than 5 times, when the average number of citations per paper was 15 in our sample. One can also notice that only very few health-oriented papers, such as [36], are discussing mixed strategies involving economy or psychological considerations to fight the coronavirus. It seems therefore that the majority of the scientific effort is focused on the short-term, without taking into account what might be the mid and long-term societal consequences of the COVID-19 crisis.

One may also point out that there is probably another crisis that can be observed along with the COVID-19 crisis, that is to say an epistemological crisis internal to the medical domain, which itself can be seen as another crisis of models, speaking here of course of medical models. This other crisis is concentrated around the merits of hydroxychloroquine and azithromycin as a possible treatment of COVID-19, as proposed by D. Raoult and his team (see [31]). In this matter, the key question that methodologists are discussing seems to be whether the studies made by D. Raoult are rigorous or not from a statistical perspective due to the fact that they did not use any randomization protocol or control group (see for instance [22]). This last question can however be itself challenged since D. Raoult's team is in fact not proposing a medication, but a medical protocol – consisting of testing people, identifying the infected ones, curing them – and if one wants to be rigorous, one must analyze the complete protocol, not only the medicine involved in it. Moreover medical statistical methodology – as widely used around the world (see for instance [11] for a simple introduction to this domain) – is also clearly questionable from a mathematical point of view: the frequency-based models used in methodological medicine cannot indeed usually have any probabilistic interpretation due to the lack of large series of experiments which are required to be able to apply the law of large numbers [29]; as a consequence, such frequency-based models can only find correlations between proposed medications and observed effects on structurally limited series⁸ due to the very high cost of clinical studies [28]. But any student of probability theory knows that correlation is not causation [67]! Hence, without any understanding of the underlying biological mechanisms, it is just not possible to scientifically deduce anything from such studies, as soon as we agree on the fact that science deals with causal explanations. In this analysis, the debate around the rigor of the pragmatic approach followed by D. Raoult may just be a new classical Popperian debate [52], focusing on what shall be the most suitable medical models to manage a deep infectious health crisis, similar to the debates that existed in physics around Aristotelian theory in the 16th century [43] or ether theory in the 19th century [67], which – as history told us – were respectively destroyed by Galileo's and Michelson's experiments.

To end this initial discussion on the crisis of models, we would just like to point out that if the scenario that we highlighted in Figure 2 comes true, we may also eventually be obliged to deal with another crisis of models, namely the crisis of mathematical models used in finance. These “models” are indeed not models in the observational meaning that we are using in this paper since they suffer of many well-known issues such as reflexivity [33], which refers to the fact that mathematical financial models are essentially observing other mathematical financial models, which is not really the purpose of a “good”

⁸ Note that other problems of mathematical rigor do also appear in clinical experiences of large scale. In this matter, a typical example is Framingham study in cardiology [23] which was made on more than 5,000 people among several decades. This study led to a risk equation (see [32] or [72]) which is widely used in cardiology among the globe in order to see if somebody has a “risk” of dying of some cardiovascular disease depending on a number of clinical parameters. The point is that most medical clinicians do not know at all that this quite famous “risk” equation was obtained through an hybrid statistical modeling process, mixing cohort observation data and socio-professional mortality data (see [32]), which at least shall oblige to consider it with care. Due to the chosen modeling process, it is of course quite impossible to interpret it in a probabilistic manner. As a consequence, the term “risk”, classically used here in the related medical literature, is highly misleading since that terminology cannot have a probabilistic meaning – that is to say a mathematical expectation of some feared event – but just the usual non scientific meaning of the word “risk”, which is terribly confusing for any rigorous mind ...

modeling of reality, or more deeply the lack of evidence for the market equilibrium hypothesis [70], which is at the hearth of the probabilistic framework used in mathematical finance, but which is in fact rarely observed in practice (see for instance [1] or [19]), especially in a financial crisis situation where the market is of course highly unbalanced and therefore out of equilibrium, as pointed out by several researchers.

The COVID-19 crisis is thus forcing us to open our eyes and to look for the right models to use for effectively managing human society. It will indeed become key to use models that are effectively capturing the reality as it is and not as we would like it to be, if we want to take the right decisions in face of a crisis of such magnitude and have a chance to tackle it.

2.2 – Towards a System Model of the COVID-19 Crisis

As stated above, there is therefore a crucial need of constructing a realistic observational model of the COVID-19 crisis, which is exactly the purpose of system theory. We shall now present the main ingredients of such a realistic system model in the forthcoming sections.

2.2.1 – Ingredient 1: Constructing a Systemic Framework for Modeling the Crisis

Taking a systems approach leads us naturally to construct first a systemic framework for modeling the COVID-19 crisis. The first step towards that objective is of course to understand what are the key systems⁹ involved or impacted in the crisis. In that respect, the following ones are quite obvious:

- the natural environment, from which the coronavirus which initiated the crisis is coming,
- the social system, which contains the population that is or can be infected by the coronavirus,
- the health system which attempts to cure the people infected by the coronavirus,
- the governance system which has to choose the optimal health policy to face the pandemic,
- the economic system which may be indirectly impacted by the COVID-19 crisis.

Note that the impact of the COVID-19 crisis on the economic system depends of course on the health policy chosen by the governance system. If a local health policy recommends or forces for instance – as done in many cases (see [75]) – a large fraction of its population to stay home, it indeed creates mechanically a double shock (see [60] for more details), first on the supply side (economic actors which are lacking a work force must indeed reduce their production) and secondly on the demand side (people who are not working anymore are usually paid less or not at all and thus are consuming less).

We can now sketch the first element of our generic COVID-19 systemic framework which is the high-level *environment* (cf. [17]) that we modeled in Figure 3. This first system view exposes the key quantities flowing through the system

which are matter, people, information and

Figure 3 – High-level COVID-19 environment

money – plus coronavirus in our context. These are the exchanges and interactions, existing between the various systems involved in the COVID-19 crisis that we mentioned above. Note that the overall system taken into account here, i.e. human society as a whole, including its natural environment, is a closed system on our home planet Earth. As a consequence, the only levers to solve the crisis are internal to this global system.

The static view of Figure 3 provides us however only the space in which the COVID-19 crisis takes place. But this is not enough to model a system: we also need to consider its time evolution to get a complete picture from both a spatial and temporal perspective [17]. This leads us to the second element of our

⁹ The term “system” is of course taken here and throughout all this paper in the meaning of system theory. We refer for instance to [17] for a mathematical definition of the notion of system.

generic COVID-19 systemic framework which deals with the *lifecycle* of our system of interest, human society, where we depict its different states over time. In this matter, we now need to understand what could be the possible future(s) of human society after the COVID-19 crisis, which leads us to think in terms of lifecycle scenarios, since our future is by nature uncertain. Each such global lifecycle scenario can typically be obtained in a standard way through a synchronized product [7] of the domain-specific lifecycle scenarios that are modeling the evolution of each of the key systems involved in the COVID-19 environment.

Using that technique, the point is thus to be able to construct realistic domain-specific lifecycle scenarios for each system involved in the COVID-19 environment. We first focus only on the social and economic systems, since we are considering here the situation that occurs after the end of the COVID-19 health crisis (see Figure 2). We can then see that:

- the lifecycle of the social system can be analyzed to first order in terms of wealth and health, where these features can be respectively derived from the economic system lifecycle and from a post health crisis epidemic propagation model (see next subsection),
- the lifecycle of the economic system can be analyzed from an economical perspective using classical impact analysis techniques (see for instance [49] or [60]).

In a systems approach, we will thus have to construct the different possible global lifecycle scenarios that can be achieved in this way (see Figure 4 for an illustration of this classical process), to evaluate their probabilities and to define means to mitigate the worst consequences. To obtain more detailed models, we shall moreover refine them both in terms of space, to capture the geographic dimension of human society, and time, to be able to maintain both a short and long-term vision of the COVID-19 crisis which is key for making optimal trade-off decisions. Note also that these lifecycle scenarios are of course highly country dependent due to the key role of the governance system in the resolution of the COVID-19 crisis, as well as the susceptibility of the population which is an initial condition. This is why we did not develop them here and just focus on a generic process to obtain them.

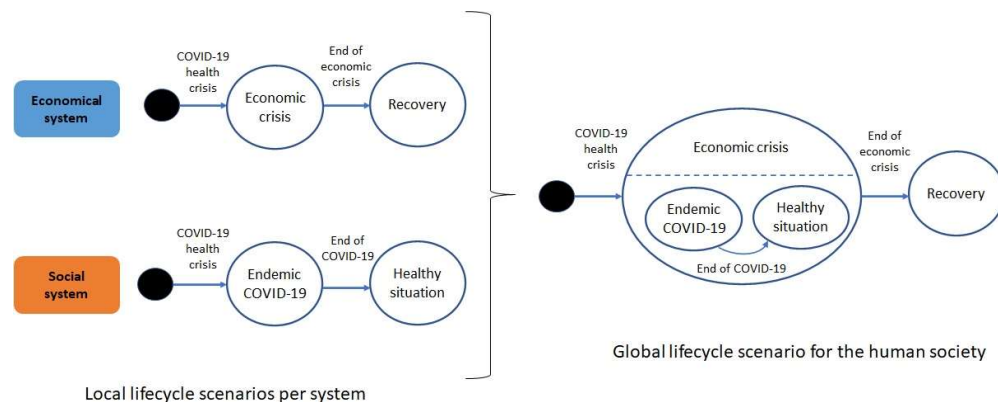


Figure 4 – Illustration of the standard process for constructing a COVID-19 global lifecycle scenario

The last element of our COVID-19 systemic framework is finally a *mission* statement [17], i.e. the core high level requirement regarding human society which expresses the objective that the governance system wants to fulfill. One can indeed understand that the behavior of our system of interest – human society – will be totally different depending whether one wants to minimize the impact of the COVID-19 crisis on the social system, health system or economical system or to find the best balance between the impacts on these three systems. This is essentially a multi-objective optimization problem. It is therefore of high importance – as system theory tells us (see [17] or [55]) – to be able to clearly define the mission to achieve.

Taking a systems approach to the COVID-19 crisis consists therefore of instantiating our systemic framework per country, as soon as one wants to use it to understand a given situation. This is due to the central importance of the social and governance systems in the COVID-19 crisis as it can clearly be seen in Figure 3. Each country has its particular specificities, associated with its own historical and political culture, that one must of course take into account in a systems approach: for instance, Chinese traditional medicine and rigorous group behaviors are specific to China, while a centralized governance system and poorly followed health rules are specific to France, while a heterogeneous health system that favors more affluent consumers and differentiated laws and policies per state are specific to the United States of America (USA)

2.2.2 – Ingredient 2: Modeling the Epidemic Propagation in a Realistic Way

Another key ingredient of our systems approach consists in understanding the dynamics of the human population when stressed by the coronavirus. The dynamics of all other systems involved in the COVID-19 environment (see previous subsection) are indeed highly governed by that dynamic: the spatial scope, duration time and lethality of the COVID-19 pandemics are for instance typically of key importance for the health system and the economic system, as one can easily understand.

In this matter, epidemiology provides us so-called compartmental models that are all originated from the seminal work of W.O. Kermack and A.G. McKendrick [41] that goes back to 1927. The main idea of these models is to decompose a population subject to an epidemic into a number of discrete compartments, such as for instance S (for susceptible people), I (for infected people), R (for recovered people) and D (for deceased people), and to model the propagation of an epidemic as a continuous Markov process controlled by Lotka-Volterra-like evolution equations (see [16], [44], [63] and [64]).

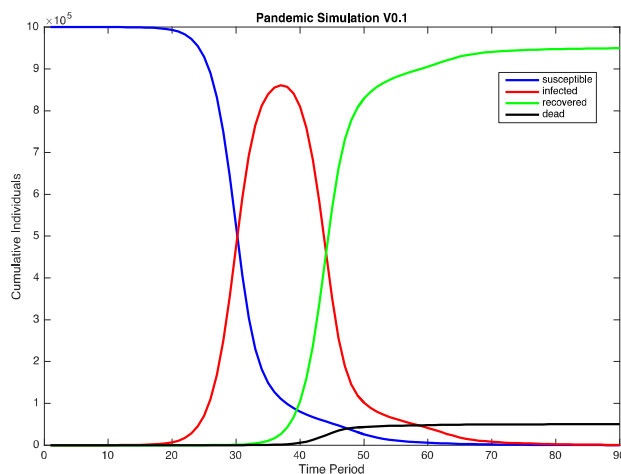


Figure 5 – SIRD simulation with 10 average daily contacts, 10 % propagation probability, 14 days of disease duration, 5 % lethality and no countermeasures

Figure 5 shows a generic SIRD-type simulation with a human population of 1 million. It can be observed that it takes 20 days from patient 1 until the infection curve (in red) and its geometric growth become macroscopically visible. Within another 10 days half the population is infected. Deaths appear with delay around day 40. Finally, there is a long tail due to late infections requiring nearly 90 days for the whole pandemic to run its course.

This kind of models have an important modeling limitation since they only consider the human population in a macroscopic way, reacting globally in a uniform manner to an epidemic, which is not the case in reality. Furthermore, in a classic SIRD model such as the one in Figure 5 eventually 100 % of the population is infected which is unlikely. In the COVID-19 pandemic, one can for instance observe clusters where the epidemic recursively focuses (see for instance [8] or [18]), which rather suggests a fractal epidemic propagation as already mentioned by H.K. Jansse et al. in 1999 [40]. Such a fractal behavior is however not at all captured by the classical SIRD-like compartmental models in epidemiology. Note also that, quite surprisingly, we did not find significant scientific papers studying

the geometric multi-scale structure of the geography of the COVID-19 pandemic, which also suggests that this dimension has not yet been analyzed in depth.

In order to integrate better geography, which is obviously one of the important features of the human population system, we choose a social-network approach to model the propagation of the epidemic in line with some existing variants of the SIRD-like models (see [59]). In such an approach, the human population is modeled as a network, that is to say a non-directed graph [14], where each node of the network represents an individual or a group of people, e.g. a family, and where each edge represents a connection between people. For the purpose of our study, we used networks randomly generated according to the Barabasi-Albert model [2], which is believed to capture the most important features of real social networks. In this matter, let us recall that the Barabasi-Albert model generates networks by introducing nodes one by one (after an initial step). A degree d is chosen for each new node, which is then connected to d nodes chosen at random among the nodes already in the network. To simulate a social network, the average value of the degree d has to be chosen between 2 and 3. The Barabasi-Albert model produces randomized scale-free networks, i.e. networks in which most of the nodes have a low degree, but some may have a very high degree. In order to understand how an epidemic propagates in a population modeled in that way, we considered networks with 100,000 nodes and an average degree for new nodes of 2.1. With these features, the degree of nodes in a social network modeled in such a way is typically distributed as in Table 1.

Maximum degree	Cumulative proportion of nodes
2	0.05
3	0.43
4	0.62
5	0.73
10	0.91
20	0.975
100	0.999

Table 1 – Example of nodes distribution in a Barabasi-Albert social network

To model the propagation of an epidemic, we discretized a classical SIRD-like model (see [16] and [64]) which leads us to represent the evolution of the state of each node of the social network that models the human population by a stochastic finite automaton whose possible transitions are described in Figure 6. Time is then discretized and all nodes evolve simultaneously at each time step, which represents a day, just like in cellular automata [76].

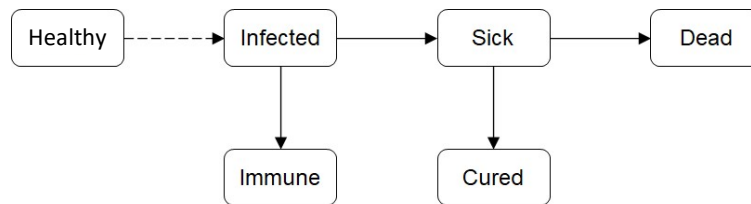


Figure 6 – Stochastic state automaton modeling the possible evolution of a node in a social network

Transition probabilities were chosen as follows in order to be close to some key COVID-19 propagation parameters (see [74]): 1) the incubation time is uniformly distributed between 10 and 20 days, 2) the maximum sickness time is uniformly distributed between 20 and 30 days, 3) the proportion of infected people who get sick is about 20 %, 4) the proportion of sick people who die is about 20 % leading to a net mortality rate of infected people of about 4 %. At each step, a healthy node can be infected by one of its infected neighbors with a certain probability p . A node cannot be infected "spontaneously", but only through its infected neighbors (connected via an edge in the social network). On this basis, we then performed Monte-Carlo simulations to study the possible evolutions of our model. Each trial of the simulation consisted in starting with a network in which all nodes are healthy, but one picked up

at random which is infected (patient 1), then letting the network evolve according to the above stochastic laws until it stabilizes, i.e. when there are no more nodes infected or sick. Note that our model and the computational experiments realized on this model do not aim at all at representing "reality". Our model is conceptual: it helps to think about what might happen in the real world, not to mimic what actually happens in the real world. We however believe that such a model can provide good fundamentals for constructing more realistic models, even if it would require a very significant amount of data collection and fine tuning of the model. The use of contact tracers in health systems is for instance a direct, but laborious, way to reconstruct such social networks to quickly identify infected people and to isolate them before they infect others (see [81]).

At this point, we explored several hypotheses through Monte-Carlo simulations. We shall report here four virtual experiments that are of special interest. For each measure reported below, we give the number of trials that were performed. Monte-Carlo are very time consuming. Consequently, we chose the number of trials so to get stabilized mean values, without making simulations too long.

The first experiment consisted in simulating increasingly virulent epidemics by assuming increasing values of the probability ρ of infecting somebody (1,000 trials were done per value of ρ). The results that we obtained are described in Table 2. They show a remarkably interesting phenomenon: for all values of the probability ρ , only a tiny fraction π of the population is eventually infected in most of the cases (less than 1 out of 1,000 persons in more than 90 % of the cases), or when a significant proportion is, the size of which depends on ρ . In everyday terms, this could be stated as follows: there are a lot of viruses circulating, but only a few of them give rise to epidemic outbreaks. The reasons for which a virus gives rise to an epidemic outbreak are indeed intrinsic to the virus itself (for instance its contagiousness, its dangerousness or its capacity to mutate), but also depend on external factors such as who is infected first, and where. This may explain, at least to some extent, why some countries or regions are more stricken than others, which suggests again a fractal interpretation of the geographic scope of an epidemic, as already mentioned above. This calls also for a multi-scale systems approach of epidemic outbreaks and not only a purely medical one.

ρ	π	τ	π	τ
0.005	$\pi < 0.1\%$	997	$1.7\% < \pi < 2\%$	2
0.010	$\pi < 0.1\%$	983	$21\% < \pi < 23\%$	17
0.015	$\pi < 0.1\%$	959	$43\% < \pi < 47\%$	41
0.020	$\pi < 0.1\%$	945	$58\% < \pi < 62\%$	55
0.025	$\pi < 0.1\%$	908	$70\% < \pi < 74\%$	92

Table 2 – Proportion π of the population that is infected, for different values of the propagation probability ρ .

The second experiment aimed at measuring effects of the incubation time of the disease. We made vary here two parameters *mutatis mutandis*, with the probability ρ of infection set to a fixed value, here 0.015, that is to say the proportion τ of the population that become sick before the epidemic becomes observable and the delay δ (measured in days) before countermeasures, typically confinement, are put in place. Table 3 shows the best-case lethality of the epidemic for different values of τ and δ , i.e. the lethality assuming that the countermeasures are perfect. The worst-case lethality, corresponding to the case of no countermeasure, is 2.10 %. Each measure reported in the table was obtained by means of a Monte-Carlo simulation of 2,000 trials.

$\tau \setminus \delta$	10	15	20	25
0.01 %	0.30 %	0.44 %	0.68 %	0.96 %
0.03 %	0.52 %	0.76 %	1.00 %	1.25 %
0.05 %	0.63 %	0.88 %	1.15 %	1.38 %

Table 3 – Best case lethality of the epidemic for different values of the reaction threshold τ and the delay of intervention δ .

These results illustrate what we said in the introduction: a key and crucial feature of the crisis is the delay introduced by the incubation time of the coronavirus. Even the most drastic countermeasures cannot prevent significant damage if taken too late, i.e. if the course of events has not been anticipated and the health system duly prepared. Again, this motivates a systemic approach to the crisis.

The third experiment aimed at studying the effect of the confinement of the population. Indeed, such a confinement can only be partial as the essential functions of society such as food distribution must be upheld. Moreover, it is impossible to separate children from their parents, patients from the doctors and nurses and so on. The idea in this experiment is to simulate the efficiency of the confinement by reducing the capacity of edges in the network to propagate the disease by a factor $1-\varepsilon$ with $0 \leq \varepsilon \leq 1$. At each step of the simulation, representing one day, an infected node has thus probability $\rho \times (1-\varepsilon)$ to infect an adjacent healthy node. Table 4 shows the resulting lethality that we observed for different values of τ and ε , *mutatis mutandis* (i.e. with $\rho = 0.015$ and $\delta = 20$). Each measure reported in the table was obtained by means of a Monte-Carlo simulation of 2,000 trials. τ corresponds again to the proportion of the population that becomes sick before the epidemic becomes observable.

$\tau \setminus \varepsilon$	0.0	0.5	0.6	0.7	0.8	0.9	1.0
0.01 %	2.10 %	1.21 %	1.07 %	0.89 %	0.82 %	0.75 %	0.68 %
0.03 %	2.10 %	1.43 %	1.28 %	1.22 %	1.12 %	1.06 %	1.00 %
0.05 %	2.10 %	1.49 %	1.40 %	1.32 %	1.25 %	1.18 %	1.15 %

Table 4 – Lethality for different efficiencies ε of the confinement and different reaction thresholds τ .

These results show that confinement (also known as social distancing) is an efficient strategy to reduce deaths caused by the epidemic. Indeed, the earlier and the stricter, the better. In this experiment, we assume however that the whole population is confined until the epidemic extinguishes itself (e.g. see period of 90 days in Figure 5). Given the parameters that we used in our simulation, observing a 1 % lethality means, roughly speaking, that 5 % of the population have been sick and 25 % have been infected. In other words, 75 % of the population have been confined ... while remaining perfectly healthy. Saving lives is priceless, but it has a cost in terms of economic impact.

The fourth and last experiment we shall report on in this section aimed at studying the effects of the de-confinement of the population. We took here the hypothesis that this de-confinement takes place after a certain number of days γ . Values of the lethality reported in Table 4 assumed that γ is as large as necessary, which is clearly not realistic, but gives us the underlying trend, since authorities cannot maintain the confinement too long, for both economic and psychological reasons. Table 5 reports values of the lethality we observed for different values of the reaction threshold τ and numbers of confinement days γ . As previously, $\rho = 0.015$ and $\delta = 20$. Moreover, we took $\varepsilon = 0.66 (= 2/3)$. Each measure reported was obtained by means of a Monte-Carlo simulation of 2,000 trials. τ corresponds

as before to the proportion of the population that became sick before the epidemic became observable.

$\tau \setminus \gamma$	0	30	60	90	120	∞
0.01 %	2.10 %	1.32 %	1.13 %	1.08 %	1.02 %	0.98 %
0.05 %	2.10 %	1.42 %	1.35 %	1.36 %	1.35 %	1.35 %

Table 5 – Lethality for different values of the reaction threshold τ and numbers of days of confinement γ .

As expected, the longer the confinement, the fewer deaths. Note however that, to be fully efficient, the confinement must be rather long, several months in our virtual experiment. The most interesting part of this experiment comes however from the observation of the total duration of the epidemic outbreaks. Table 6 shows these durations for the same values of τ and γ as in Table 5.

$\tau \setminus \gamma$	0	30	60	90	120	∞
0.01 %	243	407	539	361	220	195
0.05 %	243	322	247	192	189	188

Table 6 – Duration of the epidemic for different values of the reaction threshold τ and the number of days of confinement γ .

If the confinement is maintained sufficiently long, not only does the lethality drop significantly, but so does the total duration of the epidemic outbreak. If the confinement is not maintained sufficiently long, it is still effective, in that it reduces the lethality, but it has a quite paradoxical consequence: the epidemic outbreak lasts longer than if no countermeasures were taken. The shorter confinement does not prevent the disease from significantly propagating, it just slows down the propagation and thus the impact on the health system, thus avoiding the sharp peak of infected shown in Figure 5 around day 40, which is its main motivation in order not to overwhelm the capacity of the health care system. For this reason, when the population is de-confined early, the disease is still present (except if we wait sufficiently long). The epidemic can then restart nearly “from scratch” or, to put it differently, the disease remains endemic. Hence the importance of a strict monitoring of the de-confinement process and a global, long term, monitoring of the epidemic.

Another way to look at results of these experiments is to relate the number of days of confinement with lethality. Figure 7 shows the corresponding curves for the values 1/2, 2/3 and 3/4 of confinement efficiency ε . This figure illustrates three important points. First, the more efficient the confinement, the lower the lethality. Second, for each confinement efficiency, there is a duration beyond which it is useless to maintain the confinement: the lethality does not decrease anymore. Third, the decrease of the lethality obtained by means of the confinement should be put in regard with its social, economic and even health consequences: in this matter, there is indeed also a duration, about 50 days in our experiment, beyond

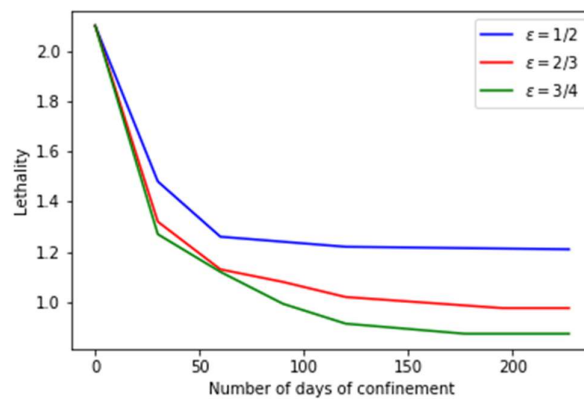


Figure 7. –Number of days of confinement versus lethality

which the confinement has probably more negative than positive effects on the society, even though maintaining it results in decreasing the lethality due to the virus.

As already said, the above experiments do not pretend to fully represent reality. A very significant effort is required to get fully realistic results. It was out of the scope of the present article to perform such a full study (moreover, the authors do not have access to all figures required for such study). However, as pointed out by E. Stattner and N. Vidot in [59], “network models turn out to be a more realistic approach than simple models like compartment or meta-population models, since they are more suited to the complexity of real relationships”. These two authors also point out the difficulty of tuning network models. While we agree with them on both points, we believe that network models can help to think about epidemic scenarios as they capture essential features of reality, as shown by the results of experiments reported in this section. One of the limitations of existing network models is that they do not distinguish between recurring social links with family members and co-workers and casual links based on one-time encounters such as in public transportation or large events. They should therefore be further refined and integrated into a model-based agile approach for crisis management, while taking into account their limitations.

3 – Towards an Agile Approach of the Crisis

In the previous section, we identified a deep crisis of models that has been exposed by the Covid-19 crisis and proposed to mitigate this issue by constructing a systemic model of the crisis. In this section, we shall deal with some possible solutions to master the crisis using a systems approach.

3.1 – Stating the Problem to Solve

As well known in any scientific discipline, the solution of a problem highly depends on the clarity and rigor of the way the problem was stated. We will therefore dedicate this short section to the statement of the problem that we need to solve in the context of the COVID-19 crisis.

The first key characteristic of the COVID-19 crisis is its *global impact* on human society. This crisis can therefore be considered as a common cause of failure – in the meaning of system safety theory [54]– for all main systems forming human society. If we are taking a safety approach, which seems quite well adapted to our context, the first key problem to solve is therefore to mitigate the impacts of the crisis on the vulnerable systems forming human society, that is to say the social system, the health system and the economic system, as it results from the system analysis of section 2.2.1.

A second key characteristic of the COVID-19 crisis comes from the need to take into account *strong feedback delays*. In this matter, a first type of delay comes from the fact that it is most of the time too late for deploying mitigation actions to limit the epidemic propagation when significant numbers of infections are observed somewhere, since the effects of these actions will only be observable two weeks later. Moreover, a second–totally different type of delay comes from the fact that focusing on short term health impacts of the crisis may lead to long term issues of an economic nature, which forces to arbitrate between short and long term consequences of a given action.

Finally, a last key characteristic of the COVID-19 crisis is *uncertainty*. Due to the global nature of the crisis and the rather short period of time on which it is concentrated, uncertainty is everywhere. Clinical data about the infection are for instance permanently partial, so difficult to interpret. Understanding of the social system structure, and thus of the key parameters used in its modeling, are ambiguous. The exact nature and size of the impact on the economic system are difficult to evaluate. Precise data on the capabilities on which to rely may be tricky to obtain. Last, but not least, the crisis also results in

a massive, heterogeneous and often contradictory amount of information in which the really interesting signals may be either weak or hidden and have therefore to be found.

Synthesizing these three key features of the crisis, the problem to solve in our context can now be clearly stated: *how to optimally mitigate the short- and long-term consequences of the COVID-19 pandemic on human society, taking into account delays and uncertainties that are specific to this crisis?*

One can notice that this statement is a typical control problem – in the sense of control theory [58]– integrating here delay and uncertainty, which can be addressed by many existing techniques (see [47] and [2]). Consequently, the objective should be to design a new system that will support this controllability objective. Based on a closed-loop control principle which is the only one that allows to achieve a given target behavior along the time axis (see [58] or [68]), such a COVID-19 decision-aid system will therefore have to measure the current state of the key systems forming human society in order to provide relevant feedbacks on the social system through the governance system which is the only one who is legitimized to take decisions and control actions. Figure 8 describes how such a decision-aid system could be integrated in the high-level COVID-19 environment.

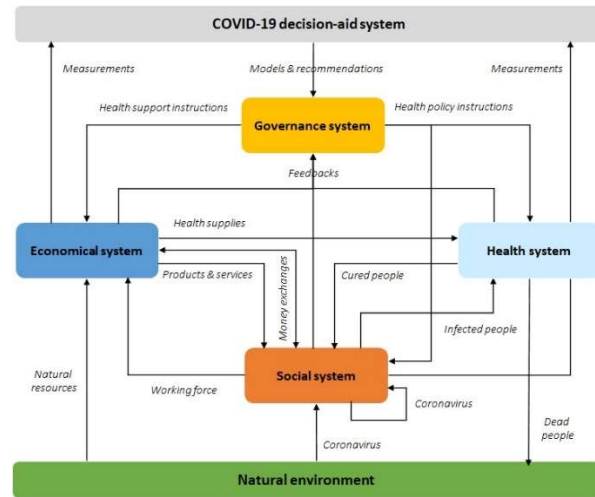


Figure 8 – High-level COVID-19 environment integrating a specific decision-aid system that has to be designed

3.2 – A Possible Answer: an Agile COVID-19 Decision-Aid System

There is at least one domain where making decisions under structural uncertainties on an underlying geographic scope is quite well known since a long time in human history, which is the military domain. Architecting a COVID-19 decision-aid system using the typical architectural pattern of a C4¹⁰ system (see [6] or [62]), used to support network centric warfare approaches in the defense area (see [5] or [73]), seems thus quite a natural idea. This leads us to propose an organization for a COVID-19 decision-aid system based on the following three hierarchical layers, that correspond to three natural levels of abstraction associated with a given geographic scope (that may be either the international, country and local levels, or country, region and city levels in practice), exactly like C4 systems are organized:

1. the *strategic layer* is the place where global situational awareness is required to master the crisis on a given large-scale geographic scope: its mission is to monitor at a high level the crisis and to elaborate strategic decisions based on an overall vision, fed by tactical information,
2. the *tactical layer* is intended to master the crisis on a given medium-scale geographic scope: it is thus a distributed system which has to capture and synthesize operational information and make tactical decisions on their basis in accordance with the strategic decisions coming from the strategic upper layer,
3. the *operational layer* is intended to master the crisis on a local geographic scope: it is thus again a distributed system which has to capture and synthesize field information and make

¹⁰ C4 stands for Computerized, Command, Control and Communications.

operational decisions on their basis in accordance with the tactical decisions coming from the tactical upper layer.

Note that this architecture (see Figure 8) shall be understood as a hierarchical enterprise architecture [71] which defines the way an organizational system, supported by suitable information systems and models, shall be organized and behave.

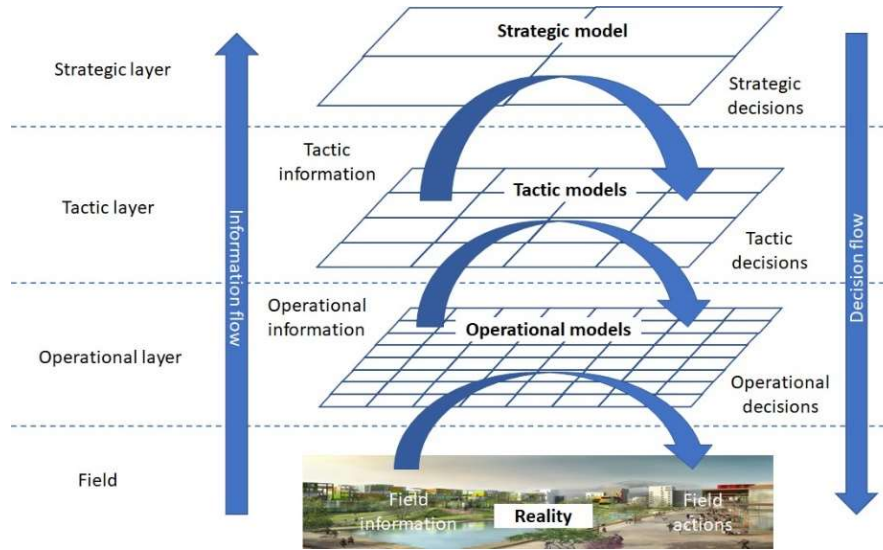


Figure 9 – Proposal of generic systems architecture layers for a COVID-19 decision-aid system

The main idea behind it is a principle of subsidiarity: decisions have to be taken as close as possible to the level that is the most appropriate for their resolution. This principle means in particular that an upper level shall avoid to make decisions that are too intrusive at a lower level in order to let each local level take always the more appropriate actions at their level depending on the real local conditions that it can observe, while following at the same time global orientations when locally relevant. This is key in the military sphere, but even more key in the context of the COVID-19 crisis where speed of decision making is fundamental due to the latency of the epidemic propagation as seen in section 2.

In this approach, each layer has a dual bottom-up and top-down role: its actions shall be of course guided by the general directives which are given by the upper levels, but it shall also capture and coordinate the bottom-up initiatives that may emerge or be promoted in the context of a crisis like the COVID-19 one. This last point is key: field actors are the ones who know the best what happens in their local environment and it is of key importance to let them propose best practices based on their local understanding of the crisis since they will probably be well adapted to the real local issues. This however has to be done in the context of clear rules of engagement in order to avoid situations where local or regional units are working at cross purposes.

Note that it is also key to capture weak signals of systemic importance at each level of the proposed architecture: to illustrate that point, the fact that a police officer is infected in a certain area is for instance a typical weak signal since we may infer from it that there is a certain probability for the police force in the concerned area to be infected, at least in the near future.

Proposing the previous hierarchical architectural pattern is however of course not enough to specify how a COVID-19 decision-aid system shall work. One indeed also has to connect it with the system approach that we proposed previously. In this matter, the first key point is to organize the systemic model that we sketched in section 2.2 according to the hierarchy that we just presented and which is

used to organize the decision-aid system that we are discussing here. This means that such a model is not monolithic, but consists of a series of inter-related models describing human society and epidemic propagation – using the society decomposition and the social network modeling which were presented in the last section – at each level of the geographic decomposition that gives the systems architecture layers of our COVID-19 decision-aid system. These system models shall be complemented by key systemic indicators, also structured according to the same hierarchy, as this will allow decision makers at each level to see at each moment what is the current and possible short-, mid- and long-term future state of the different systems forming human society in their scope of responsibility. Typical examples of such key systemic indicators may be:

- number of tested, infected, hospitalized, and dead people for the human population,
- number of hospitals, beds and ventilators used by COVID-19 patients for the health system,
- number of closed companies, furloughed workers, filed un- or under-employment claims, for the economic system,

Note that these system models do play a fundamental role due to the latency of the COVID-19 crisis as observed in section 2. They shall indeed be used at each level of the decision-aid architecture that we are proposing in order to guide decision makers, by anticipating the consequences of the key decisions that have to be made on the key systemic indicators that were chosen to follow the crisis. Optimal control actions with delay techniques may of course also be used here in order to find what could be the best mitigation strategies at each level (see for instance [13], [34] and [47]). COVID-19 is indeed a totally new phenomenon for which one does not usually have a lot of similar past data: as a consequence, a realistic systems model, permanently fed by field data and permanently recalibrated and modified to capture as well as possible the reality of the crisis, can thus play a key role to support the best possible decisions in a complex and fast changing crisis environment. Note also that we are not the first ones to propose this type of approach. A similar proposal – at least in its core principle – was proposed by Z. Zhan et al, but in the context of a classical epidemic (see [81]).

Last, but not least, the COVID-19 decision-aid system that we sketched here, which is fundamentally an organizational system supported by relevant information, decision and communication systems, shall behave in an agile way, in the meaning of agility in software or industrial development (see [3], [25], [27] or [44]). A pending problem is indeed to have a plan, do, check and act process that can quickly adapt to a quite fast-changing reality. Agility allows to solve that issue by, on the one hand, structuring in a very rigorous way the analysis, decision and action processes and, on the other hand, providing a lot of flexibility to all involved actors, which are two mandatory features for addressing a complex crisis like COVID-19 one. In practice, an agile COVID-19 decision-aid process has typically to be organized around regular agile rituals – managed at different time scale (for instance daily and weekly) and levels of synthesis – where the key scenarios, views and indicators have to be shared and challenged regularly at each level of the chosen decision-aid architecture. The key idea here is to provide regularly a synthesis of the current situation of the crisis to the relevant domain actors in order to allow them to manage their missions with the best possible understanding of the situation and of the consequences of their actions.

4 – Conclusions

In this paper, we draw attention to the core importance of having realistic system models to manage and to mitigate a systemic crisis of the order of magnitude such as the COVID-19 crisis. We also sketched what could be an agile approach to use in this kind of crisis. Our purpose was of course not to propose some definitive solution which is probably impossible due to the very nature of the crisis.

We do however think that the ideas contained in this paper are valuable contributions that may be of interest in the context of the COVID-19 crisis, especially due to the fact the underlying health crisis will probably be endemic for a certain period of time and be coupled with future short term and mid-term economic outcomes.

There are of course many detailed aspects of the proposed COVID-19 decision support system shown in Figure 7 that require further detail and elaboration. We have focused on the issue of delay to the overall control system in this paper, however, as we discover more about the particular nature of this particular coronavirus, the issue of observability of human society may be an even larger one. In order for the measurements to be transmitted from the health system to the decision-aid system, it is for instance necessary to know who in the human population is infected and contagious, even if they are not sick. It indeed appears that many infected people are asymptomatic while infecting others. Thus, the importance of testing not only of sick symptomatic people, but also asymptomatic people who may be healthy or infected is a crucial point that will have to be addressed.

We also believe that systems engineering is probably the only discipline that can enable the necessary collaboration of the various scientific and professional disciplines – such as biology, economics, engineering, epidemiology, finance, geography, health management, immunology, logistics, manufacturing, medicine, safety, sociology, urban systems, etc. – that are all providing a piece of the complex puzzle formed by the COVID-19 crisis.

Moreover, to validate the proposed concept in practice we propose to apply this framework in the future to specific countries such as China, France and the United States of America, among others. The heterogeneity of global responses and outcomes by country provides a natural set of experiments from which the necessary data can be drawn in the future.

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