System Dynamics and Intervention Design

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Introduction

Interventions are actions designed to change conditions according to desires

Human individuals, organizations and societies keep changing conditions from what they deem undesirable to what they deem desirable. We go to the physician when we feel sick, medical professionals fight viruses when they cause disease, managers restructure organizations when they are not efficient, and militaries fight invaders when their country is under attack. Intervention is the action that people take to change conditions according to their desires. In this work we refer to medical, managerial, or military interventions. Clearly, interventions differ if we look at the surface of observable actions, employed materials, and actors enrolled. However, from Sun Tzu to Clausewitz, classics of strategy sought to inquire beyond the surface to discover regularities that determine success or failure of intervention. Today, complexity research and real-time big data processing offer new opportunities to innovate concepts of intervention.

The aim is to improve prediction of outcomes and designs of interventions

In this article, we transform thoughts from classical strategy and insights from modern complexity science into a novel concept of intervention. In doing so, we pursue two goals: First, to improve the prediction of outcomes, and second, to refine the design of interventions. For the first purpose, we outline approaches to modeling the natural behavior of systems and the effect of interventions. For the second purpose, we propose an idea for the design of interventions. We call the concepts that relate to modeling system behaviors system dynamics, and those that relate to predicting outcomes of interventions intervention dynamics, and we call the concepts that relate to the design of interventions intervention design.

Methods

In the following three steps, we present our approach to system dynamics, intervention dynamics, and intervention design. In the first step, we outline the problem and provide a brief overview of system dynamics and intervention design. In the second step, we present examples from medicine, management, and military strategy to illustrate the concepts of dynamics and design. In the third step, we introduce complexity science as a method for explaining the causal mechanisms of how systems and interventions work. In the discussion, we give the reader some suggestions on how to use system and intervention dynamics to improve intervention design.

1. Overview

Medicine acts on the human body, management on organizations or entire economies, and military on military opponents. The problem of these interventions is their potential to fail, to be inefficient, and to produce undesirable and unforeseen effects. Therefore, we aim at improving the prediction of outcomes and to refine the design of interventions. To this end, we introduce system dynamics, intervention dynamics, and intervention design.

System dynamics

Interventions are designed to change conditions according to the desire of those that intervene. For more accurate analysis, we consider conditions as complex adaptive systems. Such systems tend to lead their own life, or in terms of complexity science, they have the capacity to self-organize, they undergo their own life-cycles, and they respond to internal and external change. We refer to complexity sciences to explain and to model systems and their life as dynamic networks. These networks are composed of functions, that like nodes in a web, connect to interact with each other to maintain or enhance their functioning. In a human body, functions of the innate and the specific human immune system interact to maintain health, in organizations, functions of management and technology interact to maintain industrial outputs, and in an army, functions of command and control, intelligence, logistics, protection, and fires interact to maintain combat force [1].

Intervention dynamics

We distinguish three kinds of causes that drive the behavior of systems: First internal drivers, second external drivers and third, interventions. In a pandemic virus infection acts as external driver, human immune response as internal driver, and vaccination as intervention. In a production crisis shortage of supply acts as external driver, logistic capacities of a company as internal driver, and optimization of supply chains as an intervention. In military defense, enemy attacks and frictions act as external drivers, functions of military personal and material as internal drivers, and active use of combat force as intervention. Systems will respond to their drivers in typical and predictable patterns, which we will illustrate in this article. The key idea of intervention dynamics is that effects of interventions can to be predicted, modelled and designed like internal and external drivers that act on system functions.

Intervention design

We propose to determine the design of interventions from the functions of systems (Table 1). In this work we consider exclusively the specific case of interventions that act on systems that comprise two competing parts that act on each other as external drivers. The first part of such system is the part that we have positive emotions for: It may be us as humans with the desire to stay healthy, it may be a firm that we desire to stay in the market, or it may be the people of a country with a desire to maintain sovereignty. The second part of the system is the part that we tend to have negative emotions for: It can be a virus that threatens our desire to stay healthy, it can be competitors that threaten our firm to be driven out of the market, or it can be an invader who threatens the sovereignty of a country. We call the first part of the system “protagonist”, and the second part of the system “antagonist”.

Desires are the first and most elementary component of intervention design. These desires underlie the objectives of interventions. Interventions on one system with two competing parts tend to root in two kinds of desires: Positive desires for the protagonist, and negative desires for the antagonist. Accordingly, two kinds of desire underlie an intervention: the desire to strengthen the protagonist, and the desire to weaken the antagonist.

Rationality is the second component of intervention design, that results from the need to determine what exactly we want to achieve to satisfy objectives. Such specification of achievements we call goals. Since the times of Sun Tzu, the first goal of military intervention is “to know yourself and to know your enemy”, which in our terms means to establish proper diagnoses of the antagonist and of the protagonist. In accordance with complexity theory, we identify additional goals of system dynamics: With respect to the protagonist, these goals include to prevent to be attackable, and if getting attacked, to resist, adapt, or to transform the protagonist in response to the antagonist. With respect to the antagonist, these goals include to prevent the antagonist to be able to attack, and if he attacks, to repel, slow down, or eliminate the antagonist.

Targets are the third component of intervention design. Targets as the functions of a system that the interventions are actually intended to affect. Interventionists need to determine on what targets to act on, how to act on them, and what the effects will be. Complexity researchers refer to resilience as the ability of systems to maintain functioning in the face of disturbance. Accordingly, interventions usually have the goal to strengthen functions of resilience in the protagonist, and to weaken functions of resilience in the antagonist.

Table 1. Intervention design

	Intervention	
Guiding question	On the protagonist	On the antagonist
What do we desire (objective)?	Strengthen the protagonist	Weaken the antagonist
What do we want to achieve (goal)?	Diagnose the protagonist; Prevent, resist, adapt, transform the protagonist	Diagnose the antagonist; Prevent, repel, mitigate, eliminate the antagonist
What can we act on, and with which means (target)?	Functions of the protagonist	Functions of the antagonist

2. Examples

In this chapter we introduce basic ideas of natural systems dynamics and intervention dynamics and design, and illustrate these with examples mainly of medicine, management, and military. In this way, we aim at illustrating that most concepts of systems, complexity and interventions are ubiquitous, intuitive, and come to thinkers' minds whenever they start reflecting on the success and failure of interventions.

2.1 System dynamics explain the self-organized life of systems

Natural dynamics explains the self-organization of systems. The capacity of systems to self-organize comprise the ability (i) to remain stable despite internal and external change, (ii) to respond to external change, and (iii) to develop according to their own life-cycles (Figure 1).

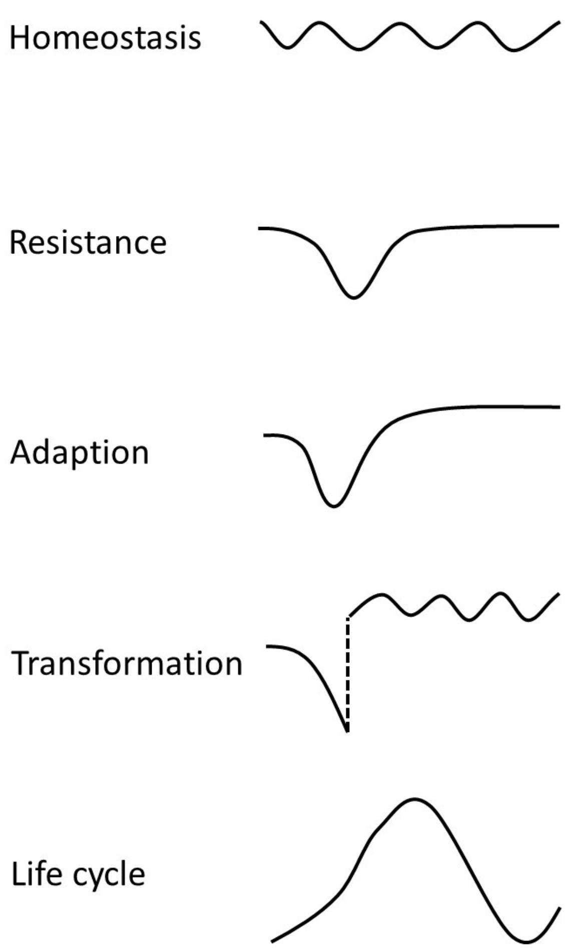

Figure 1. System dynamics

i. Systems maintain their functioning by self-regulation

Systems maintain their functioning while being exposed to internal and external change. Self-regulation is a key feature of complex adaptive systems. For example, homeostasis of human organisms self-regulates functions such as temperature, glucose levels, posture, autonomic balance, blood pressure, and mood. Management theorists describe organizations both, as organisms that are self-regulated by homeostasis, mechanisms of adaption to the organizational environment, and natural selection through economic competition [2], and as brains, where information processing is self-regulated by learning loops [3]. Classical economy describes the functioning of a free market as self-regulation of prices for goods and services by buyers and sellers. Finally, for policy makers, self-regulation has become a crucial governance mechanism for extending political control over professions or state-owned enterprises.

ii. Systems respond to change by resistance, adaptation, or transformation

Systems resist to external change, which means that they prevent, absorb, withstand, or restore in response to changes. In medicine, Hippocrates introduced the idea of preventing disease by leading a healthy life, and the idea of strengthening resilience to maintain health remained popular until these days. Similarly, management theory is currently discovering resilience as an important capacity of organizations to survive in challenging environments. Clausewitz' moral factors, principal moral elements, and military virtues of the army to overcome adversities exemplify the idea of resilience in military history [4]. Alternatively, systems may adapt rather than only resist to perturbation, which means that they change the way how they operate, but not their principal functions. Accommodation and incremental adjustments are ubiquitous in complex systems. For example, skeletal muscles respond to repetitive stress by hypertrophy, i.e., the growth of existing muscles. Similarly, Charles Lindblom's "science of muddling through," Karl Popper's "piecemeal engineering," and Herbert A. Simon's idea of "satisficing " illustrate the belief in the superiority of incremental measures to change complex systems such as business, economics, or politics over turning entire systems upside down in a single stroke. In contrast, systems can transform or collapse in response to perturbations, which means that established system functions perish, and get replaced by new functions that emerge to create a new kind of system [5]. Such revolutionary transformations are observed in all kinds of complex systems, where climate changes transformed entire ecologies, where the discovery of new therapies such as antibiotics revolutionized medicine, or where invention of new weapons and tactics transformed warfare. Especially in economics, ideas of “creative destruction”, and “disruptive innovation” are celebrated as the need to destroy existing markets and technologies and to create new ones [6].

iii. Systems drive their endogenous change by growth, conservation, collapse and renewal

Systems drive their own development in a pattern that has been described as cycles. Developmental biologists keep describing the process of the development by which animals and plants are born, grow, develop, mature and die. Starting with Jean-Jacques Rousseau’s (1712-1778) Emile, developmental psychologists describe stages of psychological development. Economic scientists keep using Kondratiev super-cycles to describe the growth and decline of world economy, and live-cycles of technologies, products, consumption, or enterprises. Similarly, since ancient times, political scientists describe anacyclosis as cyclical development of constitutional forms, or the rise and fall of sovereign power in patterns of birth, growth, maturity, and death [7].

2.2 Intervention dynamics

Intervention dynamics describe systems change in response to intervention. We distinguish three types of responses of systems to interventions: The (i) spontaneous type identifies the natural dynamics of systems, where the spontaneous behavior of systems is usually considered most desirable option of development. Conversely, the two other types of intervention target functions within systems to steer these into more desirable directions. Here, the presumed spontaneous direction of system development is usually considered undesirable. Two different responses of systems correspond to two types of intervention trajectories: In the (ii) upward type system response is desirable directly after initiation of intervention, and in the (iii) downward type, system response is undesirable after initiation of intervention and only later on turn into desirable response (Figure 2).

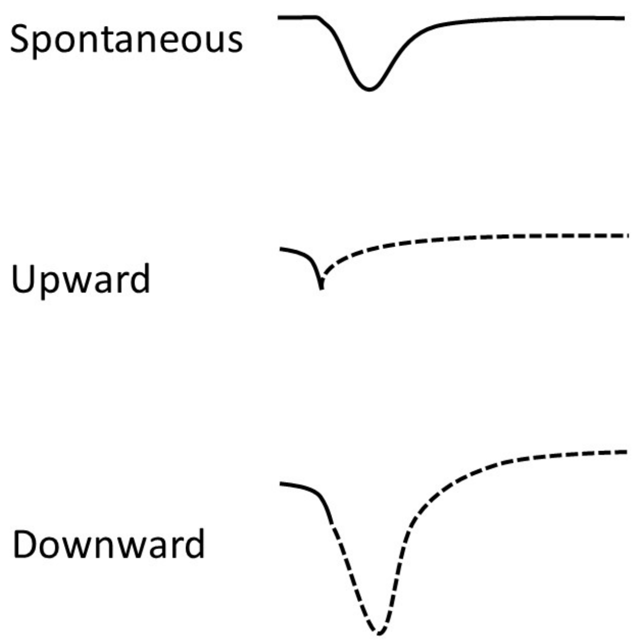

Figure 2. Intervention dynamics

i. Spontaneous trajectory type

This type of trajectory results from the unchanged natural dynamics of systems. Interventionists who rely on natural dynamics alone believe that “things will get worse as soon as we change them”, and their recommendation for intervention is “not to act against the natural course of things”. For example, from Hippocrates (460-370 BC) to the advent of modern medicine physicians adhered to the principle: "natura sanat, medicus curat". They felt that nature had the power to heal, and that physicians only could help by not disturbing its course [8]. Similarly, in Western economy, the doctrine of free market “laissez faire” follows the principle of not disturbing the course of nature. Its major pioneer, Adam Smith (1723 – 1790), based “laissez faire” on three believes: First, that natural laws govern the order of the universe. Second, that the world was governed by a good god, where every event promotes the happiness of the whole. Third, that deliberate action on natural systems does more harm than good [9]. In current Chinese military, the old Daoist idea of non-action or effortless action and Sun Tzu’s (544 – 496 BC) concept to “win without fighting” remain central to Chinese military strategy [10].

ii. Upward trajectory type

In this type of trajectory, system response is desirable directly after initiation of intervention. Interventionists who predict this kind to trajectory believe that “things will get better right from the beginning”. In medicine, antibiotics start killing pathogenic bacteria and fever and other symptoms of infection diminish soon. According to economic innovation theory, fundamental technological innovations can create new industrial or commercial sectors and immediate economic growth. In warfare, a single attack at the center of gravity would throw an enemy off-balance or even cause the entire system or structure to collapse [11].

iii. Downward trajectory type

In this type of trajectory, system response is undesirable after the intervention begins, and the desired effects occur later in the course of the intervention. Interventionists who predict this kind to trajectory believe that “things will get worse before they get better”. In medicine, surgery or chemotherapy for malignant tumors worsens the patient's health before the tumor is removed and the patient's health slowly improves. The technological and managerial transformation of a commercial enterprise can lead to its crisis before commercial success occurs. According to Clausewitz, even with victorious battles, the attacker's combat power diminishes as the attack progresses, and therefore the attacker requires a final victory before a culmination point is passed [12].

2.3 Intervention design

Of note, the three types of trajectories, spontaneous, upward, and downward, are part of system responses to interventions and not part of the intervention design. Historically, Clausewitz, as a military theorist, misapprehended this distinction by asserting that attack is the weaker and defence the stronger form of war, implying that combat actions are part of their nature and not the result of empirical interactions within a system of two competing parts [13]. The following section explains the objectives, goals, and targets as part of the intervention design based on the COVID-19 pandemic as example (Figure 3).

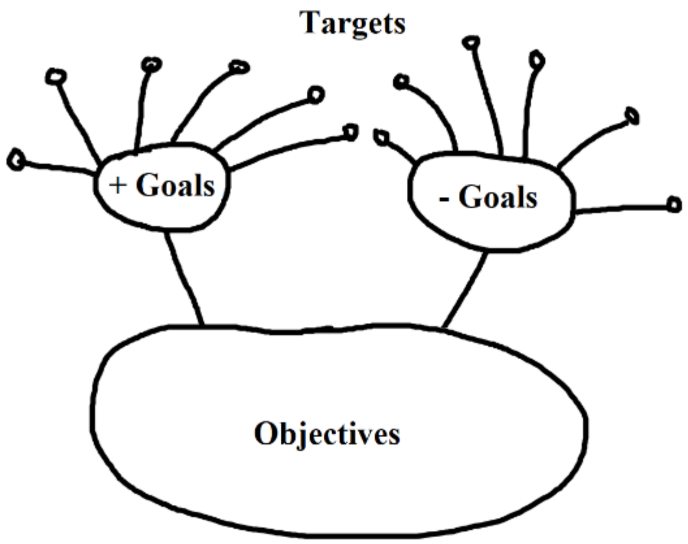

Figure 3. Intervention design

i. Objectives determine desirable and undesirable states of a system

Objectives correspond to the desire to strengthen the protagonist, and to the desire to weaken the antagonist. For example, during the COVID-19 pandemic, virologists and epidemiologists sought to weaken the antagonist by slowing the spread of the SARS-CoV-2 virus whereas scientist from other disciplines sought to strengthen the protagonist by strengthening functions of human resilience, including mental health, social equity, health care, economy, civil liberties, state power, and spending policies.

ii. Goals determine the specific state that a system should achieve

During the COVID-19 pandemic, diagnostic goals comprised diagnostics of virus and diagnostics of human resilience. Diagnostics of virus comprised laboratory tests to rule in or rule out presence of SARS-CoV-2 or to predict the course of infection, and measures to monitor and evaluate the epidemiological state of the pandemic, the implementation of interventions, the effects of interventions, and their options of improvement. Diagnostics of resilience comprise antibody testing for immunity to SARS-CoV-2, monitoring humans with infections, predicting severe courses of disease, assessing risk factors of isolation in vulnerable groups, assessing response to treatment on a micro level, and measure capacities, performance and safety of health systems on a macro-level. Therapeutic goals to weaken functions of SARS-CoV-2 included physical distancing, respiratory-, and hand hygiene, face masks, and gloves to prevent human-to-human transmission, pharmacologic therapies, environmental cleaning, room ventilation measures, and shielding vulnerable populations. Management goals aimed at strengthening humans, including intensive care, mechanical ventilation, or rehabilitation, training of physical and psychological resistance, vaccination for immunological adaption to SARS-CoV-2, sleep, rest, nutrition, and exercises to adapt to exhaustion, peer support to adapt to fear, anxiety and anger, self-efficacy activities to adapt to panic, and crisis teams to adapt to increased and altered organizational workloads. On a societal level, management goals comprised strengthening health care systems with enforcement of moral thinking, social cooperation, leadership, trust and compliance, identity leadership, and shared social identity, or transformation, for example by shifting to digital communication or to new population health approaches.

iii. Targets are those functions of a system that are to be changed

Targets are the functions of a system that interventions are actually intended to affect. Therefore, targets comprise functions of the antagonist, which was SARS-CoV-2, and functions of the protagonist, which were humans and societies. Molecular and epidemiologic functions of SARS-CoV-2 include virus size, genome, nucleocapsid, envelope, surface proteins, functions of viral cycle, cytopathic effects, and mechanisms of virus evasion of host immunity. Epidemiologic functions of SARS-CoV-2 include functions of virulence, pathogenicity, case fatality rates, virus reservoirs, mode of transmission, and basic reproduction number (R0). Human resilience to SARS-CoV-2 is determined by functions such as age, sex, blood pressure, chronic medical conditions, nutrition, housing, and income as physical or material functions, educational levels, coping styles, history of mental disorder as predictors of psychological functions, and long-term impairments, homelessness, occupation, couple and family factors as social functions of resilience. On a societal level, demographic and activity patterns of populations, information, financing, medical products, service delivery, leadership, governance, and health workforce of health systems, and production, level of income and inequality of economies were societal functions of resilience, transparent communication, self-help, sense of coherence, trust, credibility of leadership, community pride, and social support were psychological functions, and democratic institutions, succession mechanisms to replace diseased members of the political elite, checks and balances, open media, and political opposition to check on bureaucratic hierarchy qualified as political functions of resilience against COVID-19 pandemic. It is obvious that the choice of targets, including their proper mix, is an important factor in the success or failure of the intervention.

3. Complexity science

In this third step, we introduce complexity science to provide causal explanations for how systems function, including their ability to resist change, adapt or transform in response to change, and undergo life cycles, including growth, maintenance, collapse, and renewal.

3.1. System dynamics

To predict system behavior, complexity research suggests modeling systems as networks of functions connected by causal loops with positive or negative feedback (Figure 4).

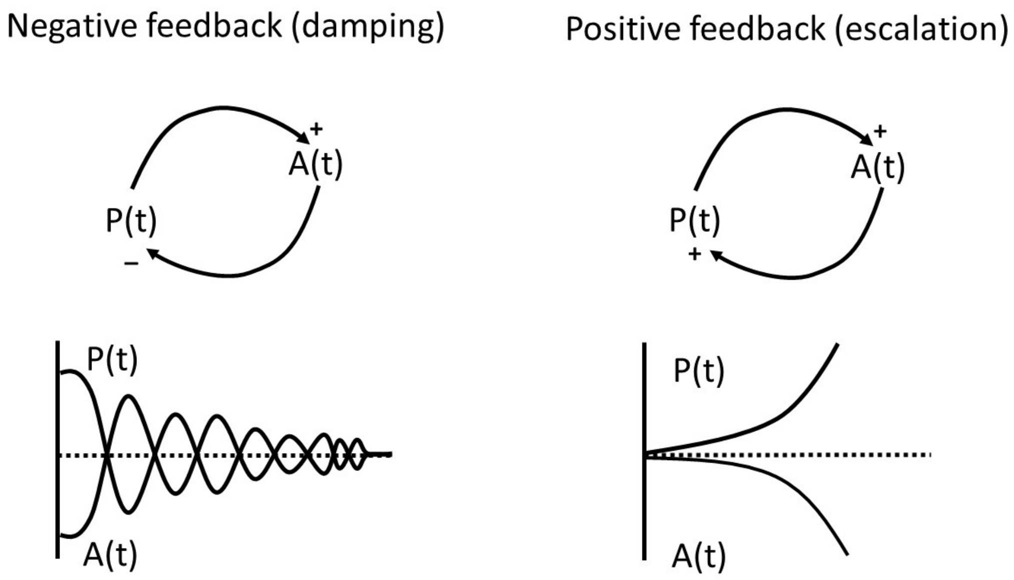

Figure 4. Feedback loops

i. Negative feedback loops

To predict system behavior, complexity research suggests modeling systems as networks of functions, with feedback between these functions [14]. Feedback is the process by which changes in the state of functions feed back to their inputs. Negative feedback is the mechanism by which systems dampen change to keep functions such as body temperature, blood sugar levels, posture, autonomic balance, blood pressure, and mood in a steady state.

ii. Positive feedback

In contrast, positive feedback self-enforces change of functions and deviation from steady states [15, 16]. Positive feedback is the mechanism of enforcing rather than dumping change. Resilience research predicts non-linear responses in systems with functional nodes that can flip between alternative states [14]. Human systems can adapt to a pandemic, which means that they change the states of their existing functions while maintaining the established system. Alternatively, human systems can transform in response to a pandemic, which means that established system functions perish, and get replaced by new functions with new networks of feedback loops that emerge to create a new kind of system [5]. For example, in a pandemic, functions of human systems flip between the state of having or not having infections, panicking or not, losing and not losing a job, or being alive or dead. Therefore, resilience research is likely to predict non-linear responses of human systems to a virus pandemic. During a virus pandemic, non-linear responses of human systems may reach a tipping point, beyond where minor triggers can invoke domino effects with synchronous shift of high numbers of functions that lead to quick collapse of the entire system. Negative feedback drives resistance with apparent stability before the tipping point, and positive feedback drives domino-effects and rapid collapse after the tipping point [14] [16]. Resilience research identifies critical slowing down of central functions as an early warning sign of critical transition, where systems become increasingly slow in recovering from small perturbations [14, 17].

iii. Adaptive cycles

Mechanisms of self-organization also drive the adaptive cycles of complex systems [18]. The schematic cycle consists of four phases, but the movement of systems through these phases is not predetermined. Systems are usually in a phase of exploitation or a phase of conservation. In the phase of exploitation systems tend to remain stable. As the system moves from the phase of exploitation into the conservation phase, system potential and connectedness of functions increase within the system, and resilience decreases because the high connectedness makes the system vulnerable to cascading disturbances. In the phase of release and in the phase of reorganization, dynamics are rapid as the system transitions into a new phase of exploitation [19].

3.2 Intervention dynamics

We identified interventions as external drivers of system change, where intervention dynamics describes systems change in response to intervention (Figure 5). In the following we provide complexity science-based mechanisms of intervention dynamics, where we refer to the COVID-19 pandemic as example.

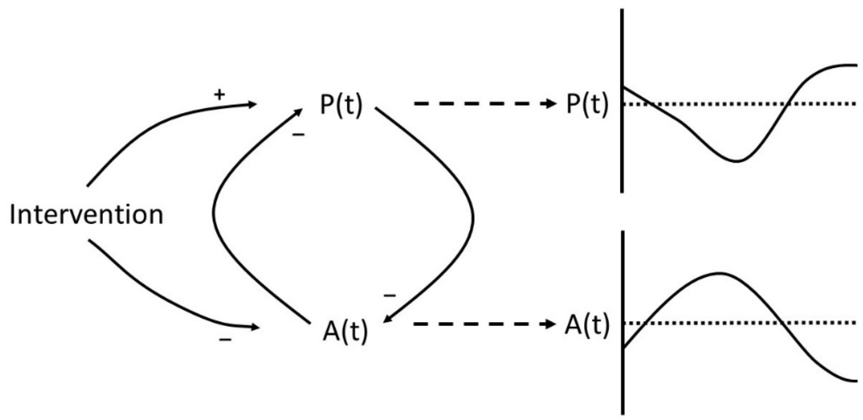

Figure 5. Intervention mechanics

i. Spontaneous dynamics

Pandemics will always come and go regardless of human intervention [20]. The spontaneous course of pandemics follows its own laws of growth, stationary phase and decline. In terms of complexity research, these spontaneous courses exhibit nonlinear dynamics. At the molecular level, the functions of SARS-CoV-2 enable viral infection of and growth in human cells. Molecular functions of viruses are also responsible for their virulence, pathogenicity and rate of spread in human populations. The dynamics of virus growth and spread follow nonlinear functions known as growth curves in cells and waves of virus spread in populations. The interaction of viral functions ($P_{(t)}$) with human functions ($A_{(t)}$) determines the spontaneous courses of pandemics. For example, SARS-CoV-2 grows in cells of the human respiratory tract because the virus can bind its S protein to human angiotensin converting enzyme II receptor proteins expressed on the surface of human respiratory cells. The human functions not only enable SARS-CoV-2 to infect and destroy human cells. Human resilience functions are able to resist and adapt to SARS-CoV-2. Human resilience functions enable maintenance of homeostasis despite viral infection, and memory B cell formation enables long-lasting protective immunity against SARS-CoV-2. Complexity science models the human ability to maintain homeostasis with negative feedback loops that maintain functioning, and it models the adaptation of the human immune response as a positive feedback loop in which stronger immunity of one patient leads to stronger elimination of SARS-CoV-2, and herd immunity of entire human populations leads to a decline in the waves of virus spread. Thus, the spontaneous dynamics of SARS-CoV-2 will begin with growth and then transition to decline, and the spontaneous response of human resilience will begin with decline and then transition to growth. Eventually, an equilibrium will emerge between the virus and humans, which together form an interactive system. This system will face new virus variants and new waves of spread, but the viruses will "learn" that it pays not to kill the host on which they live.

ii. Upward dynamics

Interventions target SARS-CoV-2 functions or human resilience functions, with the goal of weakening virus functions or strengthening human resilience functions, or both. An intervention that weakens SARS-CoV-2 functions without weakening human functions may result in upward dynamics of human resilience. Remdesivir is an example of an antiviral drug that reduces SARS-CoV-2 RNA production by interfering with viral RNA-dependent RNA polymerase functions. This intervention allows faster recovery from SARS-CoV-2 infection with little or no adverse effects in humans. From a complexity research perspective, weakening SARS-CoV-2 functions triggers positive feedback loops. Weakening of SARS-CoV-2 replication enables strengthening of human resilience functions with further weakening of the virus and strengthened human health recovery. Therefore, if no undesirable mechanisms disturb this intervention, an effective anti-viral drug therapy can result in an upward dynamic.

iii. Downward dynamics

Conversely, an intervention that weakens both SARS-CoV-2 and human functions is likely to result in a downward dynamic in which human resilience declines immediately after the intervention begins. Lockdowns are an example of interventions that tend to develop downward dynamics as they weaken both the spread of SARS-CoV-2 and the physical, economic, psychological, and political functions of individuals and societies. Lockdowns are effective only when initiated at a very early stage of the COVID-19 pandemic. Thus, in the initial phase of lockdowns, it seems inevitable that the resilience functions of individuals and societies will decline long before they slow the spread of SARS-CoV-2.

3.3 Intervention design

The complexity science-based perspective suggests that interventions target functions of systems to strengthen the protagonist and weaken the antagonist. Identifying causal loops between the key functions of both parts of the system enables prediction of the spontaneous course of systems and their upward or downward dynamics in response to interventions. In what follows, we describe the contribution of system dynamics and intervention dynamics to the design of interventions. Again, we use the COVID-19 pandemic as an example.

i. Objectives

Objectives determine desired and undesired states of a system and thus charge the entire system and its courses with positive and negative values. Intervention theorists tend to view objectives as uniform. However, in the reality of larger scale interventions, there are many people and many desires. Therefore, objectives are the most important and the most fragile part of intervention. In the COVID-19 pandemic, it became clear that some people in some countries were lacking the desire to support interventions, and governments tended to resort to "public relations" to unify the desires of their people [21]. An important part of intervention design is to balance the two seemingly opposing emotions: the positive emotions for the protagonist and the negative emotions evoked by the antagonist. In the COVID-19 pandemic, interventionists recommended a mix of heroization of pandemic fighters and fighting of public panic [22] [23]. A complexity research-based view suggests avoiding interventional overreach or underreach by misjudging collective desires and emotions. Thus, functions of collective emotions, public opinion, and community psychology are key functions of resilience with pivotal relevance for interventions [24]. Interventionists tend to ignore this seemingly trivial insight. The history of the use of the "winning minds and hearts" strategy may illustrate the problem. The strategy emerged only after the lack of public support for intervention had been long ignored or only half-heartedly pursued, and often both were the case.

ii. Goals

The principal goal of the interventions is to weaken the functions of the antagonist and to strengthen the function of the protagonist. An upward intervention with a single attack on an antagonist's center of gravity with its immediate and complete elimination always seems a tempting option. However, especially with the emergence of new antagonists such as SARS-CoV-2, such a panacea is usually not available. The next intuition of many interventionists is then to devote all strengths to a downward intervention aimed solely at weakening the antagonist. Some countries expanded gigantic resources on lockdown measures that came too late to slow the spread of SARS-CoV-2 but were critical enough to weaken major functions of people and societies. Therefore, we propose to consider antagonist and protagonist as two parts of one system, where interventionists should always pursue two goals, that of weakening the antagonist and that of strengthening the protagonist. Complexity research has shown that crossing a tipping point poses a great risk of downward dynamics of intervention that can lead to the collapse of the entire system. Therefore, an intervention should not be planned in advance and then followed through at any cost. On the contrary, intervention design should be dynamic, with continuous monitoring during the intervention allowing prediction of intervention dynamics with rapid adjustments and shifts in the weighting of the two main goals.

iii. Targets

The ability of complex systems to resist, adapt, transform, and undergo life cycles results from the interplay of functions, many of which provide potential targets for intervention. Such targets exist at different system levels, ranging from molecular-level functions to societal- and political-level functions; they exhibit different types of functions, ranging from virus replication to governance functions; and they involve different ecologies, such as humans, viruses, and the environment. Causal loop diagrams can be used to show how components of systems interact with each other and to predict how the state of systems will change in response to changes in individual functions [25]. Evaluation of system properties such as connectivity and homogeneity enables prediction of system behavior, such as critical transitions [14]. Network analysis can be used to identify critical functions within systems, and measurements of early warning signs such as critical slowdowns or flickering indicate that systems are approaching a tipping point where there is a risk of collapse [17]. The increasing availability of high-performance big data processing techniques will increasingly enable real-time modeling and prediction of the outcomes of alternative tactics for combining targets during intervention.

Discussion

In the part, we discuss our approach to system dynamics, intervention dynamics, and intervention design in terms of three questions: what was previously known and what is new about this approach, how can the new approach be used, and what are the limitations of this approach.

What was already known and what is new?

Our approach is the unification of many previously established elements from numerous sciences and traditions of thought into a novel approach to intervention. In particular, we have adopted concepts of system dynamics primarily from complexity science and modern ecology, concepts of intervention dynamics from Clausewitz's concept of culmination and nonlinear dynamics including mathematical approaches from complexity science, biology, and economics, design thinking from Herbert A. Simon, and objectives and goals as part of intervention design from classical strategy. The strength of this unification lies in combining classical concepts from medicine, management, and military strategy with concepts from the natural sciences to improve the certainty of evidence, the precision of predictions, and the effectiveness of interventions.

How to make use of the new approach?

This work offers insights that readers can use to develop their understanding and ways of using it. Below, we outline some of the key insights and uses that we had in mind when writing the manuscript.

i. System dynamics

Medicine, economics and military strategy intervene in systems that follow their own dynamics and take their own course in response to changes and developments. A scientifically sound study of these dynamics enables prediction of future system states, including their responses to change. Only by understanding the dynamics of systems can one properly assess the nature and prospects of possible interventions. Future strategists must study system dynamics as part of their education.

ii. Intervention dynamics

Interventions in complex systems lead to nonlinear responses of these systems that can be very surprising to those who do not properly understand the dynamics of intervention. Perhaps with the exception of classical economists, the decision to let systems follow their own spontaneous evolution seems foreign to many interventionists. Large-scale interventions often lead to downward trajectories. This dynamic requires close monitoring of critical functions and highly dynamic adjustments during the ongoing intervention. Only with complexity science-based prediction of the progression of tipping points and flexible switching between tactics that primarily strengthen the protagonist's functions and those that weaken the antagonist's functions can optimal dynamics and desired outcomes of interventions be achieved. Therefore, intervention dynamics is very useful for selecting strategies during intervention planning, but also for adapting strategies and changing tactics during the intervention.

iii. Intervention design

Intervention design uses insights from system dynamics and intervention dynamics to plan and to adjust interventions. In terms of objectives, interventions, especially those involving many people or requiring a longer period of time and greater effort, may require both qualitative and quantitative estimates and often measures to strengthen the functions of collective emotions, public opinion, and community psychology as integral part of the intervention. In terms of goals, interventionists, especially those most likely to lead to a downward trajectory, should continue to pursue both types of goals: weakening the adversary and strengthening the protagonist. In terms of targets, complexity science-based modelling of functions of the protagonist and the antagonist can help to predict the natural course of systems and their responses to intervention. Such predictions should be used not only for planning before intervention but also, and possibly most importantly, during the intervention. Intra-interventional predictions with use of real-time data may be the future especially for extensive downward interventions to avoid both underreach with suboptimal or incomplete intervention results and overreach with reaching tipping-points and risking system collapse.

What are the limits of a system dynamics-based approach to intervention?

Systems dynamics, intervention dynamics, and intervention design contribute to the theory of classical strategy by enriching and revising some of its concepts with insights from the natural and computer sciences. Thus, it captures important aspects of strategy better than classical theory. On the other hand, however, it leaves out many other aspects of strategy, such as leadership, maneuver, positioning in markets or territories, structures of organizations or combat forces, and more. Only with a decision about what constitutes a system of interest, including the identification of subsystems and the relevant system levels, does meaningful modelling and prediction become possible. These decisions are part of a broader strategic thinking that we do not address in this approach. Therefore, the approach we present here is of value only for those who know how to use it properly. The approach is a tool of strategy, not a strategy itself. It provides the strategist with important insights into the dynamics of systems and the effects of interventions on systems. An important contribution of this approach to the future of strategy will be powerful and accurate prediction of system behaviours. But again, these predictions will only support and enrich the decision making of future strategists, just as automated ECG curve analyses support physicians today, economic forecasting tools support managers, and satellite-based intelligence data support military commanders.

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