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FUTURES

Futures 38 (2006) 74–92

www.elsevier.com/locate/futures

Navigating towards sustainable development: A system dynamics approach

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Available online 10 August 2005

Abstract

Traditional fragmented and mechanistic science is unable to cope with issues about sustainability, as these are often related to complex, self-organizing systems. In the paper, sustainable development is seen as an unending process defined neither by fixed goals nor by specific means of achieving them. It is argued that, in order to understand the sources of and the solutions to modern problems, linear and mechanistic thinking must give way to non-linear and organic thinking, more commonly referred to as systems thinking. System Dynamics, which operates in a whole-system fashion, is put forward as a powerful methodology to deal with issues of sustainability. Examples of successful applications are given.

Any system in which humans are involved is characterized by the following essential system properties: Bounded rationality, limited certainty, limited predictability, indeterminate causality, and evolutionary change. We need to resort to an adaptive approach, where we go through a learning process and modify our decision rules and our mental models of the real world as we go along. This will enable us to improve system performance by setting dynamic improvement goals (moving targets) for it.

Finally, it is demonstrated how causal loop diagrams can be used to find the leverage points of a system.

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doi:10.1016/j.futures.2005.04.005

1. Introduction

We have long believed that science and technology can provide effective solutions to most, if not all, environmental problems facing modern society. However, the validity of this optimistic assumption has become increasingly questioned. The scientific system, thus, faces a crisis of confidence, of legitimacy, and ultimately of power, as there is a growing feeling from many quarters that science is not responding adequately to the challenges of our times, and particularly, those posed by the quest for sustainable development. Issues about sustainability are often related to complex, self-organizing systems, and although there has been a gradual fleshing-out of the meaning of sustainable development, most researchers still find it difficult to grasp the essence of the concept. For instance, most scientists still find it hard to accept that sustainability should not be perceived as a 'project' that has an end point, but as an ongoing process that needs to be regarded as part and parcel of everyday work.

Modern science is characterized by ever-increasing specialization. As a result, it has delivered lots of knowledge but very little understanding. Basically, classical science, be it chemistry, biology, psychology, or the social sciences has focused on isolation of elements of the observed universe. The common belief has been that if we know everything about the parts, we will understand the whole. However, to create understanding, it is not enough to just study parts or processes in isolation. All this knowledge is, thus, in dire need of synthesis through some kind of multilevel and multi-dimensional graph of interconnections. There is a need to accept Leibniz's idea that within an entity of interacting parts, no part can be changed without triggering changes all over the whole. This means that we need to solve the decisive problem of how the order and organization unifying the parts affects the behavior of the whole system.

Likewise, the engineering profession has to learn that arithmetic is a complement to, not a substitute for thought. As several scholars have pointed out, the very power of the computer to simulate complex systems by very high-speed arithmetic has prevented search for those unifying and simplified formulations that are the essence of progressive understanding. The uncertainties related to complex problems will not be resolved by mere growth in our data bases or computing power.

Nonetheless, there is a need to try to bridge the gap between what is known and what is done. To this end, it is essential that research move beyond classical mono-disciplinary and even inter-disciplinary lines to one trans-disciplinary in nature, and fully integrates this approach in its problem solving efforts. There is an emerging understanding that the quality of the decision-making process is absolutely critical for the achievement of an effective product in the decision. This new understanding applies to the scientific aspect of decision-making as much as to any other.

As Meadows et al. [23] point out, the world society is still trying to comprehend the concept of sustainability, a term that remains ambiguous and widely abused even more than one and a half decade after the Brundtland Commission coined it. Therefore, the aim of the present paper is to show how sustainable development can be dealt with by using the system dynamics approach—a feature of systems thinking that considers dynamic relations in a system holistically. Section 2 discusses the concept of sustainable development and some of the efforts made to make the concept operational. Then it goes on to argue that linear cause–effect mechanisms are unable to explain the complexity, which is inherent in issues of sustainability. Section 3 discusses systems thinking and, especially, one of its trans-disciplinary tools i.e. the system dynamics approach. In Section 4, it is stressed that fragmentation in the different branches of science should give way to holism where resources are viewed together, interacting with people and capital as well as interacting with each other. What is important is to understand changes, and to that end, we need to acknowledge the following essential system properties: Bounded rationality, limited certainty, limited predictability, indeterminate causality, and evolutionary change. In Section 5, it is stated that we need to adopt a learning approach to become able to cope with the self-organizing mechanisms active in complex systems. Then, Section 6 shows how system dynamics can be applied to issues of sustainable development. Hereby, it is shown how a system dynamics approach and its causal loop diagrams (CLD) can be used to identify different dynamic structures governing real world ecosystems. By recognizing the dynamic structures, we propose the idea of *viability loops* and describe sustainable development as a matter of keeping those *viability loops* functional. The paper ends with Section 7.

2. Sustainable development

It was the Brundtland Commission [40] that gave momentum to the concept of 'Sustainable Development'. This momentum was further added to by the Rio summit through its 'Agenda 21' in 1992. Joining together the three dimensions of environment, economy and society, sustainable development introduces a process to save basic natural resources from being ruined and emphasizes the forgotten key role of the environmental services in the improvement of livelihoods and incomes. It refers to a process in which the economy, environment and ecosystem of a region change in harmony, and in a way that will improve over time [3]. It calls for an integrated set of policies that maximize human welfare within an inter-temporal framework. The challenge lies in avoiding to do things that, in full accounting of social and natural costs, actually cost more than they are worth [23]. Thus, meeting sustainability objectives will certainly require an increased understanding of the interactions between nature and society.

Issues about sustainability are not merely complicated; they involve subsystems at a variety of scale levels, and there is no single privileged point of view for their measurement and analysis. Such problems can neither be captured nor solved by sciences that assume that the relevant systems are simple. If something really is complex, it cannot be described by means of a simple theory, and a major problem seems to be that our technologies have become more powerful than our theories.

'Sustainability' is increasingly cited as ideals or goals of development efforts. These ideals should be perceived as desired ends that one, it is hoped, approaches indefinitely even if one can never achieve them completely [25]. This concept makes sustainability a moving target which is continuously getting enhanced as our understanding of the system improves.

Sustainable development must, then, be seen as an unending process defined neither by fixed goals nor the specific means of achieving them, but by an approach to create change

[26]. The necessity for change can be diagnosed by tracing trends and going through a learning process regarding the system under study and its environment.

Many attempts have been made to define sustainable development as a practical concept. Solow defines sustainability as a matter of preserving the production capacity for a long future [35]. Pearce et al. consider development as a vector of desired social goals, which the society tries to maximize by working on its components. The components of the vector are: increase in real per capita income, improvement in hygiene and nutrition, educational successes, access to resources, equitable distribution of wealth, and increase in liberty. Sustainable development is a condition in which the vector of development does not decrease [29]. Fuwa [11] defines biophysical sustainability as preserving or improving the integrity of the life supporting systems on the earth. Klauer considers the common idea of different definitions of sustainability to be preserving a condition. For instance in Solow's definition it is about preserving the production capacity, in Pearce's et al. definition preserving the characteristics of a social system, and in Fuwa's definition preserving the life supporting system on earth. In Brundtland's definition, sustainability is defined as preserving the ability of humans to meet their needs [15]. Odum provided another way to define sustainability. According to his definition "the real world is observed to pulse and oscillate. There are oscillating steady states…If the oscillating pattern is the normal one, then sustainability concerns managing, and adapting to the frequencies of oscillation of natural capital that perform best. Sustainability may not be the level steady-state of the classical sigmoid curve but the process of adapting to oscillation" [28]. For more definitions of sustainable development the reader may look at: Brown et al. [6]; Turner [38]; Lowrance [19]; Shearman [34]; Daly [7]; Svedin [37]; Heinen [12]; Pelt et al. [30]; Munasinghe and Shearer [27]; Bossel [4,5]; and Mebratu [24].

Although those definitions are difficult to put into operational practice, it can be induced that a primary consequence of sustainable development is that the single or multi-purpose approach to projects needs to be changed to a holistic and integrated approach regarding inter-disciplinary and regional problems. So the concept of sustainable development cannot be applied in a single-project scale. In other words, it is not possible to sustain a single part of a system such as a dam; however, caring for a whole system to develop in a sustainable manner is achievable.

3. A shift in thinking paradigms

3.1. Event oriented thinking

Human conventional thinking model is based on a mechanical image of the world and a linear causality to explain the phenomena. This linear causal thinking, which is the basis of our knowledge of nature and our understanding of major scientific laws, assumes that certain causes are acting together linearly to result in an event. The outcome of an event is assumed not to affect input (Fig. 1). For instance, if one wishes to control the event D, one has to manipulate the causing events A and B. This linear causal thinking paradigm leads to an event-oriented view of the world (Fig. 2), where decisions are based on a perceived gap between desired goals and the actual situation of system.

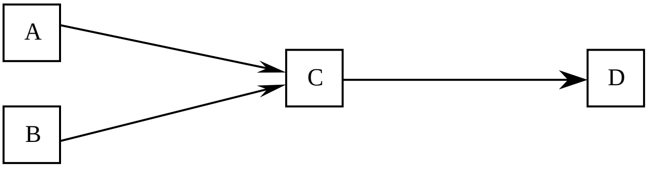

Fig. 1. Linear casual thinking.

The way the linear causal thinking—or as Holling and Meffe [13] called it *command and control*—solves problems is either through control of the processes that lead to the problem (e.g. good hygiene to prevent diseases) or through amelioration of the problem after it occurs. This paradigm implicitly assumes that the problem is well bounded, clearly defined, relatively simple and linear with respect to cause and effect. Dealing with natural resources, the linear causal thinking makes us perceive the varying and highly complex natural systems as engineered structures susceptible to manipulations with predictable and well controlled results.

However, the real world is much too complicated to be predicted and controlled as we wish. It is good to listen to Ackoff as he says: "In an environment in which complexity was also growing at an increasing rate, the ability to forecast and predict deteriorated in an alarming way. As a result, the one thing that is certain about almost any prediction beyond the immediate future is that it will turn out to be wrong. Thus, any method of planning that was critically dependent on the accuracy of forecasting was doomed to failure. Furthermore, there were contexts within which we had found very good alternatives to forecasting. …Planning should be about controlling, creating a desired future, not preparing for one that has been predicted. This led to the realization that one could deal with the future through assumptions rather than predictions. …Assumptions are about possibilities; predictions and forecasts are about probabilities. With multiple assumptions, we can do contingency planning. We can control much of the future and prepare for what we can't control" [1].

Managing the future is a 'wicked' problem, meaning that it has no definitive formulation and no conclusively 'best' solutions and, furthermore, that the problem is constantly shifting. Obviously, however, one cannot even begin to purposefully shape the future without social goals. As we know from "Alice in Wonderland": If you dont know where you are going, it does not matter what road you choose.

The past is the only guide we have for constructing believable stories about the future. Although the past will never repeat itself, there is a sense in which everything yet to happen will be like something from the past at some level of detail. However, not in a predictable way, and we must beware of making sharp predictions.

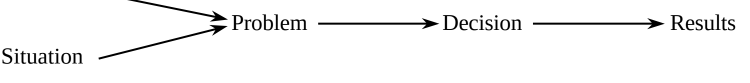

Fig. 2. Event-oriented view of the world.

To do a good planning it is essential to find a way to formulate reality as a system rather than as a set of independent problems. A system is recognized by the integrity and interaction of its components. To improve a system it is no use improving each part separately, rather the whole should be looked at.

A dynamic system model does not predict the future! Its task is to give a valid description of possible system behavior under a given range of conditions (scenarios). It can therefore be used for finding acceptable management solutions.

3.2. Systems thinking

Humankind has succeeded over time in conquering the physical world and in developing scientific knowledge by adopting an analytical method to understand problems. This method involves breaking a problem into components, studying each part in isolation, and then drawing conclusions about the whole. This sort of linear and mechanistic thinking is becoming increasingly ineffective to address modern problems [16]. This is because, today, most important issues are interrelated in ways that defy linear causation. Consequently, humanity is already in unsustainable territory. But the general awareness of this predicament is hopelessly limited [23].

Alternatively, circular causation—where a variable is both the cause and effect of another—has become the norm, rather than the exception. The world has become increasingly interconnected, and endogenous feedback causal loops now dominate the behavior of the important variables in our social and economic systems. Thus, fragmentation is now a distinctive cultural dysfunction of society [16].

In order to understand the source and the solutions to modern problems, linear and mechanistic thinking must give way to non-linear and organic thinking, more commonly referred to as systems thinking—a way of thinking where the primacy of the whole is acknowledged. Richmond gives the following definition of “Systems Thinking”: “Systems Thinking is the art and science of linking structure to performance, and performance to structure—often for purposes of changing structure (relationships) so as to improve performance [33].

It represents a way of understanding reality that emphasizes the relationships among a system’s parts, rather than the properties of the parts themselves. Apart from a powerful perspective, systems thinking offers a specialized language, and a set of tools that one can use to address the most stubborn problems in one’s everyday life and work.

It not only erases the boundaries between the points of view that define the sciences and professions, but also erases the boundary between science and the humanities. Science and the humanities are the head and tail of reality, viewable separately, but not separable [2]. In addition, systems thinking is important since it enables us to understand complexity and not be overwhelmed by it. It helps us see the ‘structures’, ‘patterns’, and ‘events’ that underlie complex situations. The rules of a system define its scope, its boundaries, and its degrees of freedom. Power over rules is real power.

Richmond suggests that “doing good systems thinking means operating on at least seven thinking tracks simultaneously.”. These tracks are: *dynamic thinking*, *closed-loop-thinking*, *generic thinking*, *structural thinking*, *operational thinking*, *continuum thinking* and *scientific thinking* [32].

The field of systems thinking has generated a broad array of tools that let one (1) graphically depict one's understanding of a particular system's structure and behavior, (2) communicate with others about this understanding, and (3) design high-leverage interventions for problematic system behavior.

By adopting a systems approach, the West Sussex County Council managed to improve the qualities of service delivery while lowering costs. Their starting point was that the answer to their problem lay in the system and how the organization thinks [31].

In systems language, 'changing structure' has a precise meaning that has nothing to do with throwing people out, tearing things down, or spending money. In fact, doing any of those things without *real* changes in structure clearly will just result in different people spending as much or more money in a new system that produces the same old results.

In systems terms, changing structure means changing of the *information* links in a system: the content and timeliness of the data that actors in the system have to work with, and the goals, incentives, costs, and feedbacks that motivate or constrain behavior. The same combination of people, institutions, and physical structures can behave completely differently, if its actors can see a good reason for doing so, and if they have freedom to change.

By stating that the analysis was not about people, but about the design of the system, it was made clear that no-one was looking for scapegoats. The interesting thing about this was that change was seen as less threatening because it focused on the causes in the system. In addition, managers quickly learnt that sub-optimal system design was not unique to their organization. It is a consequence of traditional thinking.

An important observation was that there is considerable risk that the introduction of IT before systems thinking will make the system worse.

Among other successful applications of systems thinking are air quality management in Santiago de Chile, based on a social systems methodology [39] and community development in Northern Mexico [14]. These applications were based on an understanding that quality depends on open dialogue between all those affected, and that participatory impact assessments should be recognized as an important tool for improving policy planning and, ultimately, moving towards a system of adaptive management, which means continuously revising targets and the means used to reach them.

3.3. System dynamics

One branch of systems thinking is called System Dynamics (SD), which operates in a whole-system fashion while largely avoiding jargon and convoluted explanations. It combines the theory, methods, and philosophy needed to analyze the behavior of systems not only in management, but also in other fields such as environmental change, politics, economic behavior, medicine, and engineering. It draws on a wide variety of disciplines to provide a common foundation for understanding and influencing how things change over time.

SD is a thinking model and simulation methodology that was specifically developed to support the study of dynamic behavior in complex systems. The methodology, developed by Forrester [8] and refined over the last decades, was initially applied in industrial and business systems management. The scope and uses of system dynamics have since been expanded to a diversity of problems such as pressures on sustaining quality improvement efforts in corporations, diabetes in man, the savings and loan crisis, and river basin resource planning [17,36].

SD and its principles of feedback and secondary effects has also helped many managers to think through how a strategy might or might not work, and what kind of consequences—intended or unintended—emerge.

Much of the art of SD modeling is about discovering and representing the feedback processes, which—along with stock and flow structures, time delays, and nonlinearities—determine the dynamics of a system [36]. The understanding of these processes is then used to draw causal loop diagrams (CLDs). CLD is a powerful graphic tool to see the relationships among a system's parts and their interactions with each other.

SD is also a method to enhance learning in complex systems [36], another important aspect of SD. Attempting to draw CLDs is a useful process for gaining a better understanding of a system's mechanisms and feedback links. Going through a learning process will help us to modify our decision rules and our mental models of the real world. As we get updated in a learning process, we will be able to set dynamic improving goals (moving targets) for the system under study. This will enable us to improve system performance.

There are two loops in a learning process (Fig. 3). In the first learning loop, decisions are influenced by information feedbacks from the real world; however, they are deeply influenced by strategies and decision rules, which are formed by our mental models of the real world. In the second learning loop, the information feedbacks modify the structure of our mental models which will prompt us to update the decision rules.

Another important feature of SD lies in its applicability in building and running simulation models to analyze system performance under different scenarios. In most cases, it is enough to identify a system by means of its CLDs. However, one may go further

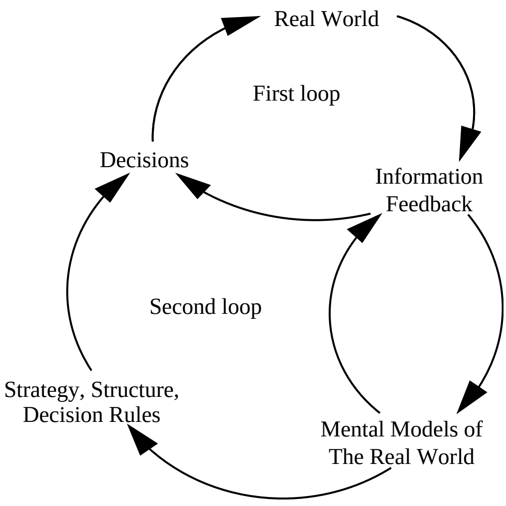

Fig. 3. Learning process.

and build up a simulation model and run it in a virtual environment to see how the basic reference modes of the system vary through time. It is also useful to evaluate different scenarios by adding or omitting some links or by changing some system parameters. Such analyses offer a good decision support tool for choice of appropriate strategies or policies for a system.

One feature that is common to all systems is that a system's structure determines the system's behavior. System dynamics links the behavior of a system to its underlying structure. System structures can generally be characterized by means of a set of elementary archetypes. All archetypes are combinations of simple *Reinforcing* and *Balancing* loops. A reinforcing loop enhances everlasting growth or decline; while or decline a balancing loop has an attenuating effect and, thus, generates a goal seeking behavior.

The most common archetypes acting in dynamic systems are: *Limits to growth*, *Shifting the burden*, *Eroding goals*, *Escalation*, *Success to the successful*, *Tragedy of the commons*, *Fixes that backfire*, *Growth and underinvestment*, *Accidental adversaries*, *Attractiveness principle*.

4. From fragmentation to holism

Almost all human concerns relate to how the past led to the present, and how today's actions determine the future. Therefore, it is important to understand how an organization's traditions determine its decision-making and its future. Our old mental models and decision habits are deeply ingrained; they do not change just because of logical argument. Any theory of decision-making will, thus, be pretty empty unless we can specify ways in which the inputs of the past determine the present images of the future. This implies that, to cope with change, we need to develop some purposefully organized system structures that can bring together expectations of diverse actors about possible development paths to formulate strategic views about the future, taking the broad social and economic development into account. Such an effort would imply a greater consideration of the centrality of man in the construction of his own future and represent a holistic approach that at the same time considers the interaction between technological, social, economic, political, and cultural variables.

To make such an effort successful, there is a need for an analysis of the way in which organizational structure affects the flow of information. In the most extreme case, we can imagine a role structure and communication network of an organization that determines the inputs to each role so completely that there is virtually no freedom of decision at all, and no matter who is the role occupant, the decisions will be much the same.

Water management is one of the truly 'wicked' problems where people talk past each other, and justify their ideas on very different reasons. Water can mean very different things to different people, but few, if any, of these meanings of water are captured by traditional, physical science methods of hydrologic modeling or water quality sampling. This diversity in perceptions of the essential qualities of water cries out for methodologies that are holistic and conceptually heterodox.

In studies of any systems in which humans are involved, it is necessary to account for the specific characteristics of living organisms, that they are open systems endowed with abilities to react to their environment. In these systems, the elements have purposes of their own, which they may attempt to achieve regardless of stated system purposes. Thus, studies of such systems must be based on a humanistic conception of human nature, as opposed to the prevailing mechanistic, robot conception, that fails to do justice to the spontaneous and self-motivated activity of mind and body.

Our current development mode, with all its inequity and indifference, has left many people alienated, sociopathic and malicious. Those people and their children are likely to use whatever means that are available to them to struggle for recognition and justice or for revenge.

By using World3, a system dynamics model, Meadows et al. managed to show how various policy assumptions produced a range of outcomes from collapse to sustainability [22]. In the foreword of the book, Jan Tinbergen, a Nobel Laureate in Economics, claims that the great merit of the book is that it shows us where and when we may reach the frontiers of the possible, and thus clarifies the conditions under which sustainable development, a clean environment, and equitable incomes can be organized.

Twenty years before, the authors wrote *The Limits to Growth*, a book that created a furor because people did not understand the difference between systems thinking and traditional, reductionist thinking [21]. The book was interpreted by many as a prediction of doom, but it was not a prediction at all. It was not about a preordained future. It was about a choice. It contained a warning, to be sure, but also a message of promise.

The major conclusion was that the growth trends of the 1970s would lead to a collapse within 100 years, but that it was possible to alter those growth trends and to establish a condition of ecological and economic stability that is sustainable far into the future.

It needs to be understood that diversity and possible conflict is not an unfortunate accident that could be eliminated by better natural or social science. Environmental policy cannot be shaped around an idealized linear path of gathering and subsequent application of scientific knowledge.

A complex system is characterized by emergent behavior resulting from the interaction among its parts, and for that reason cannot be fragmented without losing its identity and purposefulness. For such a system, short-term predictability may be possible, but long-term planning is impossible. Nonetheless, current knowledge allows us to rule out a range of futures as unrealistic [23].

Thus, in the first decade of the 21st century, the main branches of the empirical sciences face a paradigm shift as deep as that which occurred at the beginning of the 20th century, when classical physics gave way to relativity and subsequently to quantum physics [18].

Since its very beginnings, science has been trying to describe the world in terms of formulas and theories that reduce, simplify and generalize. Now, however, we find such theories increasingly incomplete. Many phenomena have been found to be much more complex and unpredictable than traditional, reductionist theories can account for.

Issues about sustainable development are not about resources seen separately, but about resources viewed together, interacting with people and capital, which are in turn interacting with each other. To address such issues, we need to move on from a static, one-factor-at-the-time analysis to a dynamic whole-system analysis.

A one-factor-at-the-time approach fails to appreciate the dynamic complexity of species and ecosystems and human interactions with them, where the system is as a whole is more than the sum of its constituent parts. Moreover, it cannot be used to devise strategies that are robust in the face of uncertainty and surprise and capable of adaptation, both to the dynamic complexity of the underlying system and to the changes in people's perceptions, needs, and aspirations. Consequently, policies of environmental management and sustainability have failed to address the core problem. Progress made towards one objective has often resulted in unacceptable costs for other objectives. Small wonder then that, during the last few decades, our capabilities for efficient problem recognition have often shown discouraging results. Consequently, we face the unpleasant risk of decline in societal welfare if societies do not prepare sufficiently well for the future [23].

5. Self-organizing systems and the learning society

Basically, linear systems, as seen in the industrial assembly lines, thrive on order, top-down command and control management based on distinct hierarchical structures. The end product is known and knowable. Given causes lead to predictable results, each and every time. However, systems involving humans cannot be considered sensibly unless and until the nature of cooperation and participation in the processes involved has been determined. Here, we have a family of systems involving numerous components that interact with each other and the whole system in a manner that cannot be discerned by observing the activities of the internal elements themselves. Due to a complex web of feedback mechanisms, change and cause and effect are not due to a single one-way sequential line of events, but reflect interactive influence through feedback loops from all over the system, including its environment. Such systems can produce completely unexpected results, even if we have advanced understanding of the original system conditions. Forrester used the word *counterintuitive* to characterize such systems [9]. Other words used to highlight particular aspects of their behavior are *non-linear*, *complex*, *dynamical*, or *dissipative*.

A basic notion is that of a *dynamic* and not mechanical order—dynamic order is an order where the components are organized by system-wide correlation that replaces randomness with a stable and dependable pattern.

As Meadows et al. point out, the depths of human ignorance are much more profound than most humans are willing to admit [22]. Especially at a time when the global society is coming together as a more integrated whole than it has ever been before, when that society is pressing against the dynamic limits of a wondrously complex planet, and when wholly new ways of thinking are called for, no one really knows enough. Thus, we have to resort to experiments, and use our action, whatever it is, to learn.

In common with other complex systems, human systems have a tendency to stagnate and fail to adapt to external and internal change. Change is never-ending and even an apparently stagnant society is bubbling away underneath. Failure to adapt will eventually lead towards the thresholds of crises, where change will boil over. To mitigate such problems, we need to encourage reflection, learning and personal choice. Thus, we need to learn how to learn; learn how to manage social change and how to increase the pace of social learning and become a learning society. How to achieve that is a truly difficult problem that science is only just beginning to address.

As making big plans and implementing demanding programs requires more time and knowledge than we will ever have, we must recognize the importance of taking an experimental approach to social learning about complex system behavior. But, to get people onboard, they need to know what story they are part of.

One cannot learn without making mistakes, telling the truth about them, and move on. Learning means exploring a new path with vigor and courage, being open to other peoples' explorations of other paths, and being willing to switch paths if new evidence suggests that another one leads more efficiently or directly to the goal.

Unfortunately, however, our leaders have lost both the habit of learning and the freedom to learn. Somehow, a cultural system has evolved that assigns most people to the role of followers, who expect leaders to have all the answers. Like Meadows et al. [23], we fear that humanity will pursue short-term goals of increased consumption, employment, and financial security, ignoring the increasingly clear and strong signals until it is too late.

Thanks to systems theory and hierarchy theory, ecologists have become well aware of the interconnections and coherences within the web of life and with its total environment. Non-linear dynamics and non-equilibrium thermodynamics have provided us with efficient tools to broaden these relations to social systems and to recognize their common patterns of organization as self-organizing networks [18].

In such systems, it is often possible to find 'leverage points', places within a complex system (a corporation, an economy, a living body, a city, an ecosystem) where a small shift in one thing can produce big changes in everything [20].

This idea is not unique to systems analysis. We are all familiar with the idea about the 'silver bullet' or magic cure that will make all ills go away. Ackoff uses the word *panacea*, and claims that managers and organization consultants tend to be far too panacea-prone.

There are two problems related to leverage points: First, people often manage to find them by intuition, but generally try very hard to push them in the wrong direction [10]. Economic growth is a case in point. Every government strives to boost economic growth in order to increase welfare. However, economic growth requires costly adjustments. Thus, there is more leverage in slowing down the growth so technologies and prices can keep up with it. Secondly, even if you push in the right direction, there is often a need for an essential complementary activity. Forrester showed that subsidized low-income housing is a leverage point—the less there is of it, the better off the city is [9]. That is because subsidized housing—without equivalent efforts at job creation for the inhabitants—severely disrupts a city's employment/housing ratio, effectively increasing unemployment and welfare costs and despair.

A complex system usually has numerous negative feedback loops that help it self-correct under different conditions and impacts. One of the big mistakes we make is to strip away these 'emergency' response mechanisms because they are not used often and they appear to be costly. In the short run, we see no effect from doing this. In the long term, we drastically narrow the range of conditions over which the system can survive [20].

Positive feedback loops are sources of growth or decline. A system with an unchecked positive loop will ultimately destroy itself. For example, the more the soil erodes, the less vegetation it can support and, the fewer roots and leaves to soften rain and runoff, the more soil erodes.

Information structure is an important feedback mechanism with high-leverage. If you make information go to places it did not go before, it may well cause people to behave differently.

Missing feedback is one of the most common causes of system malfunction. As Meadows points out, we humans have a systematic tendency to avoid accountability for our own decisions and that is why so many feedback loops are missing [20]. Thus, adding or restoring information can be a powerful intervention, usually much easier and cheaper than rebuilding physical infrastructure.

6. Sustainable development in terms of system dynamics

Based on the traditional, linear thinking, scientists tend to assume that society and social institutions have an ‘end-state’ towards which they are evolving. Thus, they posit that nation-states, societies, and even individuals can be positioned along a developmental pathway, and policies can be devised to help them towards the next level.

Sustainability is neither a state of the system to be increased or decreased, nor is it a static goal or target to be achieved. But sustainable development is a process in which, in terms of system dynamics, the destroying reinforcing loops are controlled by means of some balancing mechanisms and where these balancing loops are allowed to act normally, as they must do in order to guarantee the system to work everlastingly. There are key loops in the real world, which are responsible for the viability of all ecosystems including human based ecosystems. We call these loops *Viability Loops*. Thus, sustainable development is a process in which the viability loops can remain intact. Planning for sustainable development is therefore to identify the viability loops and to keep them functional.

Fig. 4 shows the viability loops which generally exist in the real world and how they are interconnected to each other. Several viability loops can be recognized in that figure. One loop is associated to meeting human needs. It begins with *Human Needs* which causes the *Demand for Economic Support* to be increased. This in turn leads to increase in *Expenditures and Depreciation* to be able to more *Supply Human Needs* in order to make it decrease. This balancing loop is extracted from the main diagram and is depicted separately in Fig. 5 to better see the circulation. The other loop which is associated to the economy, begins with *Economic Capital*. This is reduced due to *Expenditures and Depreciation*, so its decrease will result in increase in *Demand for Economic Utilization*. This demand will in turn cause the exploitation of resources to be raised up. So *Exploitation of Renewable Resources* as well as *Exploitation of Non Renewable Resources* will be increased resulting in more *Economic Utilization*. This will enhance *Economic Growth* which will increase the *Economic Income* leading to more *Economic Capital*. The economic loop—which is a balancing loop—is depicted in Fig. 6. The third loop which is associated to environment starts with *Renewable Resources* as well as *Non Renewable Resources*. They account for both *Exploitation of Renewable Resources* and *Exploitation of Non Renewable Resources* which support *Economic Utilization*. The increase in *Economic Utilization* results in more *Waste Generation* and consequently more *Waste*. The *Waste* is returned back to *Renewable Resources* through the *Degradation* process. But on the other side, more *Waste* causes more *Pollution* which reduces *Life Supporting*

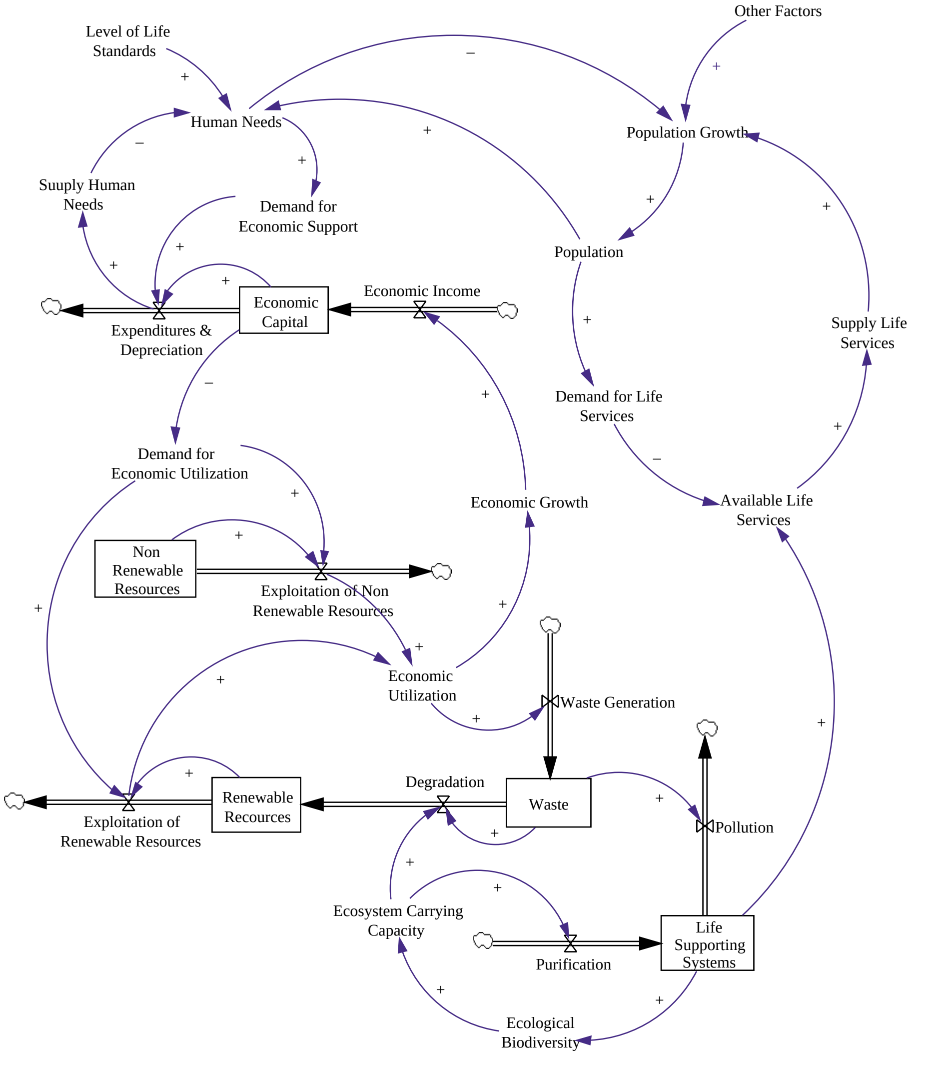

Fig. 4. Interaction of viability loops in the real world.

Systems. This results in less *Ecological Biodiversity* which will cause the *Ecosystem Carrying Capacity* to decrease. The more the *Ecosystem Carrying Capacity* is, the more will be *Degradation* as well as *Purification* which support *Waste* reduction and enhancing *Life Supporting Systems*, respectively. The environmental loop is depicted in Fig. 7. As it is seen the environmental loop is not closed back to the *Non Renewable Resources*. This must be considered as an alarming signal to reduce the dependency of real life structures on the *Non Renewable Resources*. This environmental loop is linked to another loop which affords for life services to the man. This loop starts with *Available Life Services* which support to *Supply Life Services*. This in turn enhances *Population Growth* which results in

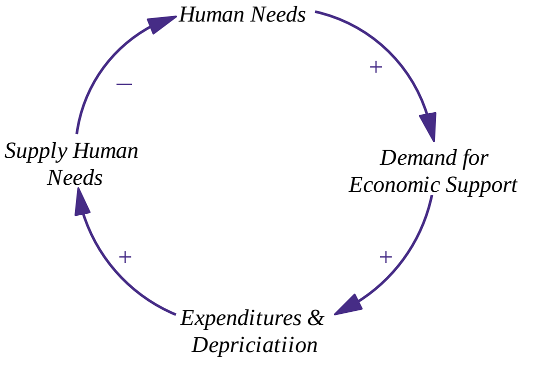

Fig. 5. Human needs structure.

more *Population*. The increasing *Population* leads to more *Demand for Life Services*. This will reduce *Available Life Services*. The life services loop is depicted in Fig. 8.

As it is seen, the viability loops are balancing structures tending to control the state of the system and maintain it at a balanced level. Thus, the system would be sustainable when the viability loops function properly and support an everlasting flow of matter and energy as well as its fair distribution in the system and among its components. However, some exogenous changes may cause devastating changes to those loops and make them go into a destroying mode. Therefore, it is important to identify and eliminate or counteract such threats to the system.

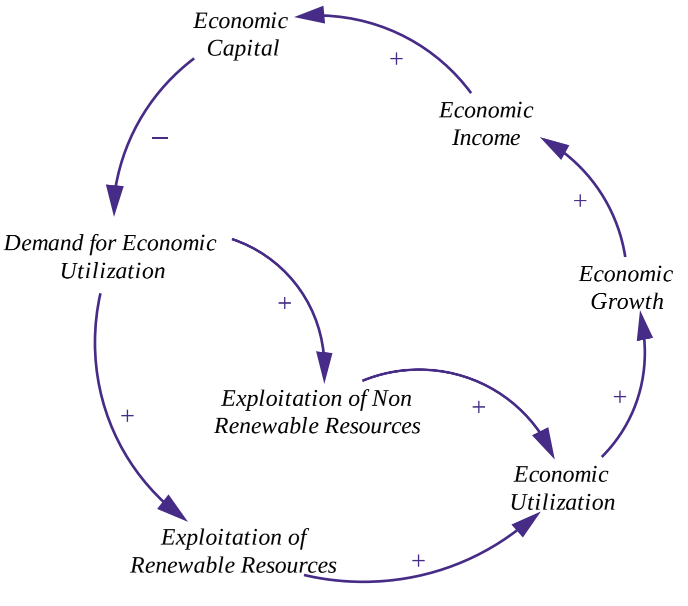

Fig. 6. Economic structure.

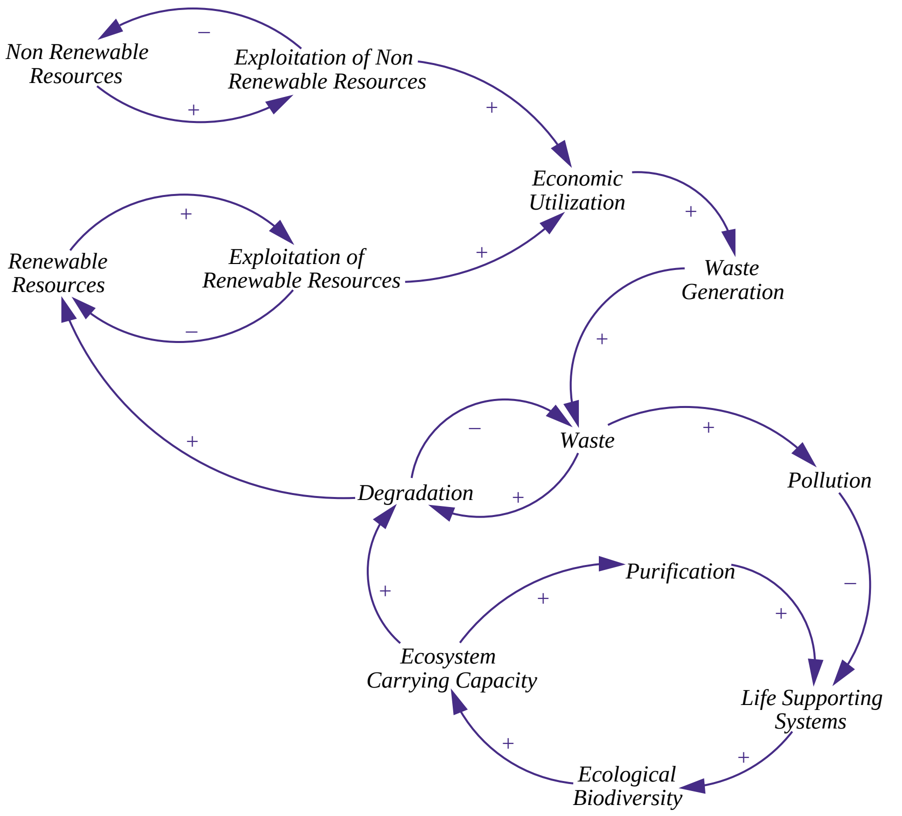

Fig. 7. Environmental structure.

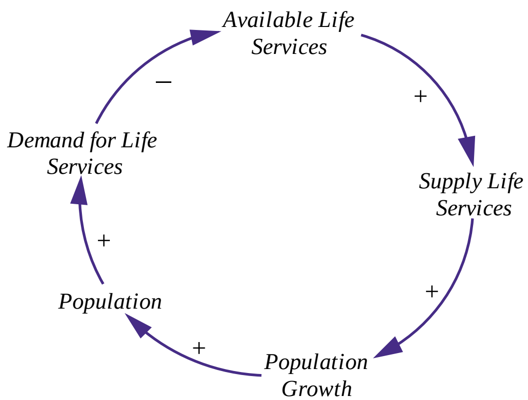

Fig. 8. Life services structure.

7. Conclusion

In spite of its simple definition, sustainable development risks to become a meaningless buzzword since most scientists are stuck in reductionist thinking. Many attempts have been made to put the concept into practice. However, rather than providing practical guidance, these attempts merely show that there are widely different perceptions of the concept of sustainable development.

Many scientists look at sustainable development as a ‘project’ which has an ‘end state’. But it should be noted that sustainability is neither the state of the system nor is it a target to be achieved. Sustainability is an ideal to the system, which as an ongoing process, needs to be regarded as part and parcel of everyday work. It inter-relates different aspects of economy, environment and society.

Classical science solves problems by breaking them down into elements and then focusing on the isolated elements. This paradigm which assumes that problems are limited and well defined is no more useful to face complex systems.

Sustainable development is an issue of complex systems. Dealing with sustainable development requires moves across the boundaries of different branches of science and humanities. A shift of paradigm from fragmentation in science to holism is required. To achieve such a shift, linear and mechanistic thinking must give way to non-linear and organic thinking, more commonly referred to as systems thinking. Systems thinking is a way of understanding reality that emphasizes the relationships among a system’s parts, rather than the parts themselves.

System dynamics—one branch of systems thinking—is a thinking model and simulation methodology that was specifically developed to support the study of dynamic behavior in complex systems. It offers a powerful perspective, a specialized language, and a set of tools that one can use to address the most stubborn problems in one’s everyday life and work. Thus, it provides us with potent tools for coping with sustainable development.

Any natural system is run under the control of some balancing mechanisms, negative feedback loops, or *Viability Loops*, as we call them in this paper. The role of these viability loops is to keep the system working everlastingly. Hampering these balancing loops will result in domination by the reinforcing loops, which will finally destroy the system.

Sustainable development—regarding the terminology of system dynamics approach—is therefore described in this paper as the process in which the viability loops are kept functional. Thus planning for a sustainable development would be to identify the viability loops in the system, and to direct efforts towards keeping these loops in a healthy state.

Thus, if we base our analysis on a holistic vision of human and natural interactions, heterogeneity, and uncertainty, we arrive at the conclusion that, to be able to deal with sustainable development, we need to acknowledge the following essential system properties: Bounded rationality, limited certainty, limited predictability, indeterminate causality, and evolutionary change.

The generic viability loops associated to Human needs, Economic, Environmental, and Life services structures have been shown and discussed using the CLD analysis. Sustainability is seen as an unending process of perceiving changes and keeping those loops active to adapt the system to changes. The System dynamics approach helps us to better understand the dynamic relations in the system and become aware of their changes through a learning process. This perception would be helpful to set moving targets for the system.

Acknowledgements

Financial support from the Swedish Institute is gratefully acknowledged.

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