A Complex Systems Approach in Estimating Sustainable System Limits

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Abstract

Sustainability of a system is determined by comparing resource consumption of the system with the limit that the environment can offer. Two famous frameworks used to estimate the limit are reviewed. These global scale estimations of the limit is criticised due to their assumptions leading to low accuracy. Systems approach that breaks down the global system into small pieces of problems is a promising alternative to global approaches. Difference between reductionist approach and systems approach in breaking the whole into parts is discussed. From an observation of a general sustainability principle, a system approach methodology for estimating lower and upper sustainable system limit is proposed.

Introduction: Sustainable Development and Sustainability Issues

The 18th century industrial revolution and 20th century green revolution have drastically increased the pace of development. The exponential increase of per capita productivity in both agricultural and industrial area exerts more and more pressure to the natural environment which is predicted to arrive at major global system collapse (Meadows, 1972). Contemporary macro-economic definition of development is expressed by outward shift of the Production Possibility Frontier (PPF) and this shift is achieved by greater productivity and greater resource utilisation tapped to the production. There is no theoretical limit to the PPF in contemporary economics but in fact there is a physical limit of the nature that bounds the PPF from above (Costanza & International Society for Ecological Economics., 1997).

Realising the urgency of the threat emerging by growing environmental problems, UN General Assembly called upon the Brundtland Commission to actively engage in developing strategy for achieving sustainable development for long-term future by international cooperation. The seminal document in sustainability, *Our Common Future*, often called *the Brundtland Report,* was prepared to call upon the international cooperation as suggested in the strategy in the report. Through wide multidisciplinary consultations with experts and communications, the commission arrived at the definition of the new development paradigm sustainable development; stated as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987). The definition is discussed in context of addressing two foundations of the issue faced: (1) Limits of the Earth, with special emphasis on ecosystem; and (2) Interrelatedness of contemporary environmental-social-economic crisis, which is the basis of the international cooperation.

This document explores the feasibility of evaluating sustainable upper and lower limits of complex interrelated system by decomposing into parts. Traditionally, the complex system is known to lose its emergent property if dissected.

Sustainable Limit

Deriving the operational definition of the sustainable limits of human action with proper scientific justification is very difficult. It is clear that a measure to compare current human activity level and the maximum sustainable limit of human activity is required to assess the sustainability of the human activity. A review of two frameworks, the ecological footprint (EF; Rees, 1992) and the World3 model (Meadows, 1972), to evaluate the global system limits will identify the limitations of those approaches.

The Ecological Footprint has been developed from an original insight captured from an observation that the dense urban population consumes resources supplied from larger rural areas. Most urban system are not self-supporting system but require supplies of resources from many different areas. Rural areas produce food for urban population. Per person, a certain area of land has to be allocated to produce the amount of food consumed by the urban population. There is good correlation between the amount and type of food, the cultivation/production method used, and the area needed to produce it (Gerbens-Leenes, Nonhebel, & Ivens, 2002). Developed further from this insight, the EF framework provides methods to estimate land required for set amount of resource needed. These conversion equations estimates land required to generate energy and material including food, fibre, building material, water and to assimilate wastes into an area unit. This area was then compared with the actual area of the planet. According to Living Planet Report published by World Wildlife Fund (WWF, 2008), the trend of EF is steadily increasing with current value of 1.3 planet area. Although it has served well in increasing public awareness of environmental problems, and carrying capacity of the earth, the scientific foundation of the method is weak. The aggregation of the method uses single data function, for example, MJ of energy converted into m^2 of the land. The conversion does not differentiate land uses, energy sources (e.g. between coal and nuclear) or different dietary consumption ratio of population of different nations (van den Bergh & Verbruggen, 1999). Due to the large coverage, some incomplete data have to be filled in arbitrarily; this results inhomogeneous quality of estimations for different nations (van den Bergh & Verbruggen, 1999).

The World3 model is a dynamical numerical model of interactions between population, industrial production rate, agricultural production, pollution, agricultural land, utility, renewable and non-renewable resources (Meadows & Club of Rome., 1972; Meadows, Randers, & Meadows, 2004). The world system is expressed as major single valued aggregate variables: Population, Production, Agricultural Production, Non-renewable, Land, Utility and Pollution. There are auxiliary aggregate variable that mediates between these major variable (e.g. mortality rate, fertiliser, soil degradation, etc). The world industrial production and agricultural production are subject to fixed resources inventory of non-renewable resources and total land, which is the sum of land used for agriculture and future prospect for cultivation, respectively. Causal linkages among the major and mediate variables are made using reasonable theoretical discussions. Pointing out a few interaction formulations, the cost increase of excavating non-renewable resources as the non-renewable reserve gets depleted is modelled out of extrapolation of previous experiences; a similar model is used for cultivating further land for crop productions. The variable, Production is total capital accumulated through industrial production; it has depreciation owing to the aging of machines, etc. A portion of Production is used to build capacity for the variable called Utility. Utility represents produced capital involved in social services including education and health care. The higher the utility, the lower the mortality rate, thus affecting the population growth. As auxiliary variable production rate gets higher, the fertility gets smaller which reflects the trend that wealthier countries have fewer children per household. The model parameters were calibrated with the various time series data provided by FAO Stats. The overall behaviour definitely showed realistic overshoot and collapse pattern of the population and production, which agrees with the common sense. By observing this overshoot and collapse pattern, and by formulating the overall system as interlinked compartments of modules, it was possible to locate which compartment caused the cascade of systemic collapse in several hypothetical future scenarios. It is a highly aggregated model and does not differentiate subtle points resulting in low accuracy. As the author admits, the uncertainty in this model is so great the model can only used to demonstrate qualitative behaviour of the dynamic curves and the exact numerics have little significance.

Detailed Model and Complexity Issue

The essence of the systems approach is in dividing whole system into parts and investigating connections among these parts. The shortcoming of the World3 was the crudeness of its model; if the composition of the model was further refined, it would have shown results with smaller uncertainties, and maybe it could be used as a predictive/indicative tools. At the time of its development, little data was available compared to today, and computational power was weak. With the recent progress in information and computing technology, a much wider range of data, with finer resolution (e.g. GIS and remote sensing), is available. The modelling of the ecosystem in computer simulation right down to very detail dynamics has become common (Chapelle et al., 2000).

The detailed systems model follows from progress in computing technology, but such details come with price; the necessity to scope local areas or specific problem domains. All three seminal sustainability works reviewed above (i.e. Our Common Future, EF and World3) regard sustainability of the global system as multidisciplinary issues, and the holistic view of the system is highlighted. The progress towards such detail is difficult because the size and complexity of the problem has became too large. Instead of taking top-down approach of the initial three works, many sustainability studies started to take a bottom-up approach, by focusing on domain specific sustainability (e.g. sustainable infrastructure, sustainable soil, etc.) The global socio-economic-environmental system is a complex system. Common consensus regarding complex system is that it cannot be dissected without losing its vital characters, owing to emergent property of complex system. In this context, the validity of taking bottom-top approach is questioned.

Can sustainability analysis of local system without reference to global system exist?

In order to resolve this question, we need to look at three areas before going into the analysis of the issue; how formal complex systems analysis have been occurred; how the reductionists approach differs from complex systems approaches, and the hierarchical linkage between sustainability of a system with the sustainability of its subsystems.

The exploration into the peculiar dynamics of non-linear systems such as complex systems dynamics became feasible after computation exploration of patterns that mathematical structures produce. Prior to the computational method, only the analytic method was used to explore non-linear systems, and that exploration was limited to parameter regions where analytical solutions or approximate analytical solution were obtainable. With the computational method, it became possible to explore global parameter regions. The computational method is the prime method that complex system utilises.

One of the earliest complex systems explored is the cellular automata (CA), which demonstrates a set of simple evolution rules repeatedly applied to itself that can generate complex pattern (Langton, 1990). This is a computational complex system formed by stepwise discrete evolution 1D or 2D array of 2-state bins (1 or 0). Centre bin of the array is set to 1 and others 0 as an initial condition. The value of every bin at the next time step is computed based on the value of neighbouring bins directly next to the bin being computed (the size of rules lookup table is as small as 8 for 1D CA). Even this simple set up gives rise to emergence of complex patterns that does not repeat itself. CA is now being used as a simulation framework identifying the emergence of complex spatial dynamics. It has good structural compatibility with raster GIS datasets.

Another complex system framework is agent-based systems. This formed another simulation paradigm; complementary to CA. States of individual components called agents, evolves according to predefined algorithms. Rather than the agents being fixed in a lattice formation, these agents are free to move. The usual aim of the agent-based approach is to identify key individual behaviour, which gives rise to the emergence of overall order; e.g. forming of a fish school (Mikhailov & Calenbuhr, 2002) identifies that only three key algorithms of individual fish are need to give rise to various complex patterns in a swarm of fish. Only two instances of the many complex systems classes were presented, but in general, the method of analysing complex systems started with (1) formulating a hypothesis on the individual behaviour (or local evolution rule for CA) in terms of well-characterised evolution equations; then (2) a computational model of ensemble of these agents was constructed on a global scale based on these hypotheses; and finally (3) the global pattern emerging from the holistic computational model was compared with the real system of interest, thus verifying if the interaction hypotheses indeed governed the emergence of a system wide order. From this observation, the very first step in the complex system analysis involves characterising the behaviour of parts.

This raises another question. What is the difference between taking systems apart in reductionism and complex systems analysis? Disassembling a system for in-depth investigation then reassembling for learning overall has been regarded as a key activity in the traditional reductionists approach.

The first difference is the aim of the scientific methodologies used. Reductionist methods are aimed at establishing causal relationships between certain measurable variables in the system. The aim of complex systems analysis is to identify the role of certain algorithm of constituents in overall systemic organisation. In both methods, the analysis of systems must proceed with disassembly of the whole into parts. The distinction of complex systems analysis disassembly from reductionist disassembly is that the system is physically disassembled to observe individual behaviour empirically; i.e. it is a conceptual dissection of the system; not physical dissection. Being a conceptual dissection of the system, the components can function in connection with other components of the system. The component under consideration can be looked at as an open system with on-going interactions with its environment (figure 1). Contrast this to conceptual disassembly; the reductionist approach tries to verify the functioning hypothesis of parts by physically disassembling the system and measuring the required variables. This process of physical disassembly loses on-going interactions of the part with its environment. Therefore, it is important not to take destructive measurement for the part that would lose system integrity of the part that is of interest. If transactions of the on-going input/output fluxes are recorded and processed without significant physical disturbances onto the system, the detailed investigation of the part is possible without loss of the overall essential emergent property. This forms the basis of the philosophy of hierarchical relation of the sustainability assessments of the parts and the whole in the next section.

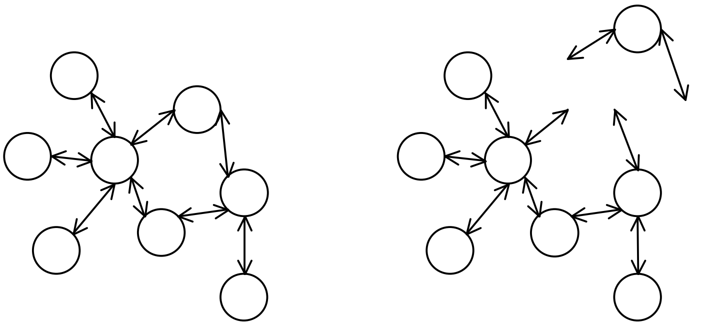

Figure 1 Conceptual disassembly of a system into parts. The top-right element of the network has been disassembled. While doing so, the record of all dynamical activities (input/output) with neighbouring components must be accounted for without intervention. For example, suppose the disassembled part was soil contained in a 1m x 1m x 1m cubic space 3m below ground. The various in/out fluxes of water, nutrients, chemicals, micro-organisms with neighbouring soil portions must be kept on the record all the time. Although accounting of these in/out fluxes are possible on worksheets, empirical measurement by physically taking soil sample out of the ground would ruin the in/out flux connectivity with neighbouring components of the system. Options for empirical work would be using non-destructive measurements techniques (e.g. sonar) or inference from indirect measurements.

Sustainable Limits: Systems Approach

Back to sustainable limit evaluation, a necessary condition for upper sustainable limits of a given system was already mentioned in rudimentary terms in the Brundtland report; "Living standards that go beyond the basic minimum are sustainable only if consumption standards everywhere have regard for long-term sustainability." (Brundtland, 1987; p.44). This is a corollary from the interrelatedness of subsystems in the global world system and resource competitions among them. The global socio-economic-environmental system consists of many compartmental systems. Among these subsystems, any physical systems require resources to operate and maintain its functions, and many systems share common resources (e.g. water for urban water supply vs ecological system). This means increase in activity in one system usually means the degraded environmental conditions, including resource availability, for other connected systems. If a given system is known to operate above minimum sustainable limit, it is required to define the upper sustainable limit to safeguard all other connected systems preventing them from getting low of resources and environmental condition below a certain threshold (called minimum need). This was the underlying theme that supports the Brundtland definition of sustainable development. If all subsystems are operating above their minimum sustainable requirements, it can be said that a necessary condition for global sustainability has been fulfilled.

By being a necessary condition, this sustainability criterion does not guarantee the systemic sustainability of the global socio-economic-environmental system. It is only one of many constraints that engineering/policy designers must consider in practical applications, or designs, in regard to sustainability. Not meeting this requirement rules out any possibility of the global system being sustainable. Subsequent sustainability criteria must be identified, and added, until sufficient and necessary conditions as set for sustainability are found. There are still other conditions to discover, but this paper will focus on this condition; meeting minimum requirement of every subsystem.

A hypothetical scenario is constructed to explain how upper sustainable limits can be evaluated when the lower sustainable limits are found to provide for all subsystems (figure 2). The hypothetical global system consists of 4 components (note the earth system contains millions of components). It is assumed that the sustainable minimum requirements have already been identified for all subsystems (a general methodology for sustainable minimum requirements of the subsystem is presented at the next section). This figure shows the feasible region of operation of hypothetical subsystem A; the dimension of the decision space is arbitrarily chosen to be 2. This is the same feasible region used in linear programming. The interested object in sustainability is the feasible region boundary, and the methods how these boundaries are determined. Given the sustainable minimum requirement condition for every subsystem ABCD, the first boundary, absolute baseline A is the minimum condition of A without modification.

The minimum conditions of BCD must be translated to evaluate the upper sustainable bound for subsystem A. This translation requires an understanding of dynamic linkages between subsystems, namely A-B, A-C and A-D. Usually subsystems are related with resource competition regime and this is reflected as upper limits as in figure 2. Increasing y_A to the point exceeding upper limit bound by system B (see figure 2) will result in not enough resources being available for subsystem B and B will fail. In hatched regions, at least one of the subsystem fails, thus, at these operation decision parameter set, the overall system is not sustainable.

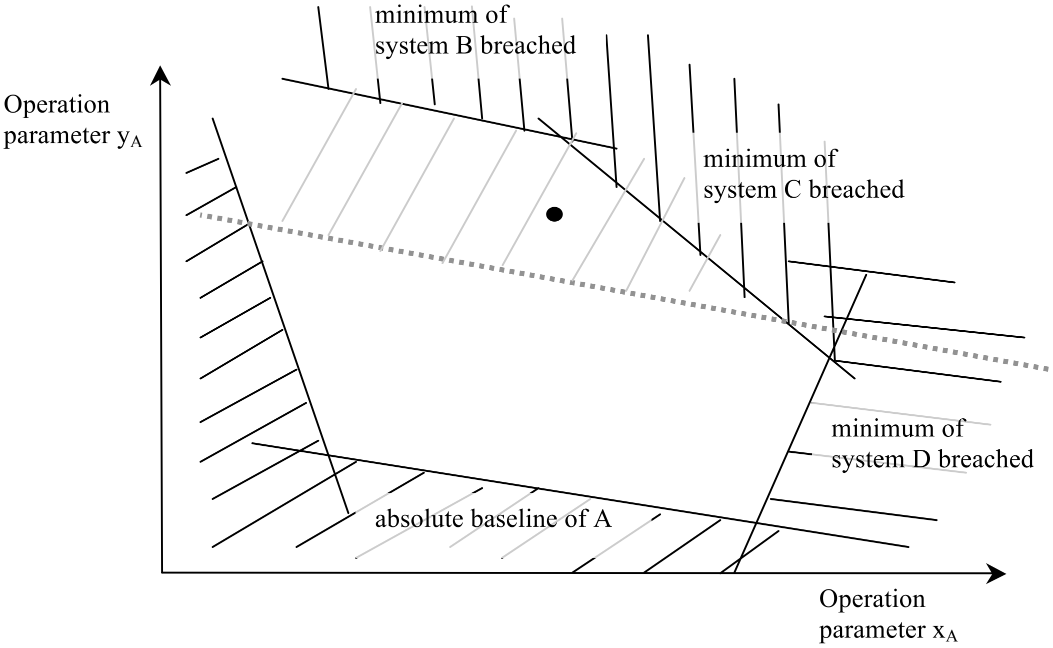

Figure 2 Feasible region by minimum limit constraints. Upper sustainable bounds of a subsystem can be evaluated one by one from lower sustainable limits conditions of other subsystems.

Although the resource competition is usually expected between subsystems, some systems may not be related by resource competition. For example, an increase in a subsystem may benefit system function (symbiotic, see figure 3). Many environmental impact studies aim to quantify the degree of benefits/harms caused by change in activity level of a subsystem in the immersed environmental system; see for example (Chapelle et al., 2000). It will be feasible to use these impact studies to aid the evaluation of sustainable upper limits.

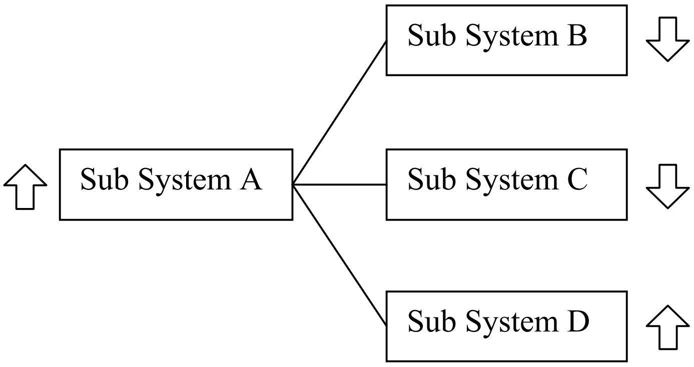

Figure 3 Causal relations between activity levels of subsystems. Some relations may not be competitive. Subsystem A and subsystem D in this hypothetical scenario is in symbiotic relation, where increase in system activity in A benefits the activity of system D.

Sustainable minimum limit of subsystems

The absolute baseline or sustainable minimum requirement of a given subsystem can be obtained from domain specific modelling, and analysis of the system. This minimum requirement of the system is obtained by the set of requirements posed by survivability of its constituents and the maintenance of the processes in the system, with a buffering capacity included. For example, consider the determination of the minimum requirement of a hypothetical population of small freshwater fish. Suppose the fish feed on benthic algae of river habitat and are predated by various species nearby. The only operation decision parameter here is the population density. For the survivability of the fish population, the set of environmental parameters such as temperature, pH, dissolved O_2 concentration (DO), nutrition density (i.e. algae density) required within habitable range for individual fish must be considered. A process maintaining continuation of fish population is fertilisation, as there must be sufficient male-female encounters during the mating season. The population density must be above zero to keep the fertility rate sufficiently high to compensate for loss rate during the period between mating seasons. This poses another minimum requirement to keep the existence of the population indefinitely.

There is another mechanism that may be relevant in determining a sustainable ecosystem limit – the self-organising character of ecosystems (Folke et al., 2004). The ecosystem is a dynamic system that shows chaotic trajectory of evolution known as a strange attractor. A strange attractor is a sink in a phase space of dynamical systems with dimension greater or equal to 1 (not a point sink, the shape is usually a loop or similar). The state of the ecosystem represented as a point in phase space is drawn towards the attractor and undergoes cyclic oscillation near the attractor with inherent chaotic fluctuation. Regardless of the small-scale chaotic fluctuation, the overall oscillation dynamics remains. The resistance to chaotic perturbation is called dynamical stability in phase space, which is in place by a ‘dynamical restoring force’ towards the attractor loop cycle. By this mechanism, the overall quality of ecosystem dynamics remains similar every year. It turns out many ecosystems have multiple numbers of attractors in phase space, meaning a multiple number of stable operation modes. Present human impact on ecosystem is getting greater, and resulting dynamics is a gradual shift in ecosystem condition. With the stability provided by the dynamical attraction towards current attractor, the qualitative pattern of ecosystem dynamics remains intact, but if the ecosystem is pushed beyond a threshold point, called basin boundary, then ecosystem dynamics will follow another attractor and the quality of ecosystem dynamics will be completely different from the current one. The existence of an ecological threshold, called the basin boundary, is another source of minimum ecological constraints that sustainability must consider.

Summary and Future Direction

Any assessment of sustainability of a given system makes sense only after the justified estimation method of the system limit is developed. Initial top-down approaches in estimating the system limit suffered severe inaccuracy through extensive aggregation. Due to the large number of components involved, a top-down approach of refining global model cannot succeed. Instead, a methodology derived from a systems approach that looks into sustainable minimum limits of subsystems to build up capacity for defining upper limits of subsystems and, hence, overall systemic sustainability, has been attempted. Although the precise, necessary, and sufficient condition for overall sustainability cannot be guaranteed, at least a necessary condition for global sustainability can be constructed from scientifically based data and analysis. Detailed case studies to demonstrate this methodology are needed for future direction, but the determination of the limit depends on studying the dynamical properties of ecosystems. The use of current environmental impact studies to estimate upper/lower sustainable limits looks very promising.

References

Brundtland, G. H. (1987). *Our common future*. Oxford ; New York: Oxford University Press.

Chapelle, A., Menesguen, A., Deslous-Paoli, J. M., Souchu, P., Mazouni, N., Vaquer, A., et al. (2000). Modelling nitrogen, primary production and oxygen in a Mediterranean lagoon. Impact of oysters farming and inputs from the watershed. *Ecological Modelling, 127*(2-3), 161-181.

Costanza, R., & International Society for Ecological Economics. (1997). *An Introduction to ecological economics*. Boca Raton, Fla.

[s.l.]: St. Lucie Press ;

International Society for Ecological Economics.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., et al. (2004). Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology Evolution and Systematics, 35*, 557-581.

Gerbens-Leenes, P. W., Nonhebel, S., & Ivens, W. (2002). A method to determine land requirements relating to food consumption patterns. *Agriculture Ecosystems & Environment, 90*(1), 47-58.

Langton, C. G. (1990). COMPUTATION AT THE EDGE OF CHAOS - PHASE-TRANSITIONS AND EMERGENT COMPUTATION. *Physica D, 42*(1-3), 12-37.

Meadows, D. H. (1972). *The Limits to growth; a report for the Club of Rome's project on the predicament of mankind*. New York,: Universe Books.

Meadows, D. H., & Club of Rome. (1972). *The Limits to growth; a report for the Club of Rome's project on the predicament of mankind*. New York,: Universe Books.

Meadows, D. H., Randers, J., & Meadows, D. L. (2004). *Limits to growth : the 30-year update*. White River Junction, Vt: Chelsea Green Publishing Company.

Mikhailov, A. S., & Calenbuhr, V. (2002). *From cells to societies : models of complex coherent action*. New York: Springer.

Rees, W. E. (1992). Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environment and Urbanization, 4*(2), 121-130.

van den Bergh, J., & Verbruggen, H. (1999). Spatial sustainability, trade and indicators: an evaluation of the 'ecological footprint'. *Ecological Economics, 29*(1), 61-72.

WWF. (2008). *Living Planet Report*: World Wildlife Fund.