Systems Dynamics, Sustainability and Construction Complexity

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ABSTRACT

This paper analyzes the work of Forrester and Sterman (J. W. Forrester Chair at MIT) to establish that these reliable studies address sustainability challenges such as emissions generation. However, these studies do not fully address whether the proposed required reductions in ecological impact can be realized to tame the observed growth rates. The Systems Dynamics models are based on algorithms with chaotic assumptions. In other words: there are no available system representations of complex systems that can serve as the basis for studying long-term sustainability through the twenty-first century.

This lack of realistic systems representation of ‘wicked’ complex problems is the major constraint, not the number crunching capabilities of technology. Behind the lack of realistic systems representation is a deficient worldview that informs the philosophical and scientific constructs used to generate the modelling processes.

This paper proposes a new model for analyzing complexity, using as a basis the reasoning of vectorial calculus.

Keywords: Systems Dynamics, Construction Complexity, Vectorial Calculus, Worldview

1.1 INTRODUCTION

This paper focuses on the ‘complexity’ of the natural and artificial environments, revealing how previous models address complexity and how the state of the art has evolved to understand the characteristics of complexity. This study found that scientific models are primarily algorithmic in nature. The deeper meaning behind this statement is that although the model lends itself to computing techniques well, it does not capture
complexity well, primarily because of the worldview representations and because of the model innate limitations.

We live in a post-Forrester era in which hard dynamic systems are no longer accepted as adequate representations to study the dynamics of complex systems¹ such as economies and large industry sectors. Theories of Complexity (TOC) informs us that uncertainties, capacity for self-organization, adaptability, inventions, economic conditions, the role of regulations, and entrepreneurship call for ‘types of thinking’ that are not based on reductionism, but analyzes complexity to its full extent.

2.1 CRITIQUE OF SYSTEMS DYNAMICS

“Systems Dynamics” is a term specified in a very particular area of study of systems, especially concerned with temporal feedback (Davidz et al. 2006). This is the program of study originally promoted by Jay Forrester (MIT) and now championed by John Sterman (MIT) and followers.

According to Chu et al (2003), (i) there is no generally accepted definition of complexity, (ii) there is a search for a universal and unifying theory of complexity (TOC) that remains ideal in most scientific disciplines, and (iii) there is no simple universal criterion or litmus test to decide if a theory is scientific or not, due to the range of varied domains that comprise science! On the other hand, there are grounded criteria that the aim of scientific theory should address which are discussed in this chapter.

“Complexity is connected by a net of intense interactions and mutual dependencies (contextuality) in a radically open system,” a statement acknowledged by the scientists in question, but that fall short in actual practice, probably due to bias in the inherited paradigms.

An example of the inherited paradigm (that is bias our view of the issues surrounding sustainability) is that ultimately ‘sustainable action’ must take one of the following forms: increased efficiency through high-performance practices, limiting and augmenting that which can be grown organically (i.e. forest woods, ethanol – grain alcohol) or obtained from an indefinite supply from nature (i.e. solar, wind, nuclear, hydrogen), limiting or reducing energy requirements through technological advances, limiting or decreasing consumption (the ecological footprint, Wackernagel et al., 1997, 2002; Van Vuuren and Bouwman 2005), increasing reusability of what exists (i.e. recycling), decreasing the inherent waste in current processes and systems, and others (dematerialization, green design, collocation, and more efficient practices).

Individual and collective actions are supposed to somehow achieve some degree of sustainability, but there are three problems that need to be addressed: (i) There are no metrics of what is needed and how the

¹ “System” defined as a set of different elements so connected or related to perform a unique function not performable by the elements alone.
aggregation of these complex actions achieves their intent; (ii) There is a serious doubt that this shotgun, cafeteria approach, (even if all the instruments for sustainability are performed at their highest level of possible efficiency and effectiveness and at a global scale) can significantly meet exponentialoid growth demands; (iii) Where can the burden be placed for changing a global paradigm (cultural, social, economic, etc)? Economists such as Pearce (1989, 2003, 2006), Pearce and Turner (1990), Pearce et al. (1989, 1993) and Chichilnisky (1997) seek a global economic system to attribute the cost of pollution to common sinks such as the atmosphere and the oceans.

The current Carbon Trading program, influenced by Pearce’s work, is an attempt to account and proportion some cost for excess carbon emissions. Pearce (2006) states that “the world as a whole seeks to convert the atmosphere from an ‘open access’ resource (one in which there are no owners at all), to a ‘common property’ resource, one in which there is a communal interest in avoiding depreciation. Moreover, policy instruments such as carbon taxes and tradable emissions permits are assets embodying permission to emit harmful gases” in exchange for some other form of capital benefit.

Current action is limited to the above plethora of solution scenarios. The FT (10/20/06) states that all alternative energy sources, everything from solar and wind to waves and waste, with the double digit growth in energy demand, are not forecast to make up more than 2% of the total energy mix by 2030. The current mix, projected to remain into the 2030’s is a third from oil, a fourth from coal, a fifth from gas and one fifteenth from nuclear, with approximately 2% from all other. The center of the problem then is a worldview that does not understand the type and magnitude of required actions, but understands the dynamics of growth mainly in terms of algorithmic equations, and does not take into consideration the complex forces behind the reality that creates the problems. Forrester’s (1968, 1971), Sterman’s (2002), Pearce’s (2006) and Chichilnisky’s (1997) approaches to the issues are limited by a deficient worldview.

2.1.1 Forrester’s approach

Forrester (1968) makes three general points: The world is a system, exponential growth can’t continue, and a comprehensive approach is necessary. The intent of the following analysis is not to bash a 40 year old model and its descendants, but to open the discussion to new ideas.

This model was created as state of the art technology and heuristics in practice at that time and has served to bring global attention through publication and as the foundation for future work. Since this model informs

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2 Algorithm is defined as a computer program with a fixed sequence of deterministic steps to follow.
about current strategies to the problems, the worldview, the model and its internal mechanisms are of interest if we want to understand what was done, and how and why to find a new way of approaching a worldview, model and mechanisms.

2.1.1.1 The world is a system

Viewing the world as a system is Forrester’s cornerstone for identifying a structure and creating a systems model to represent it. Forrester (1968), in *The Principles of Systems*, establishes the principle of ‘structure’ as fundamental for framing the principles of dynamic behavior. Forrester acknowledges the complexity (Waldrop 1992, Lucas 2000, 2004, 2005; Kauffman 1993, 1995) of social systems (Tavistock, 1996) that need to be understood in terms of ‘principles to structure knowledge’ so that they can be modeled in a system of dynamic behavior.

Specifically, Forrester uses the closed system of feedbacks that is influenced by past behavior and controls predictions. Feedback, in his model, can be positive or negative, where negative feedback seeks a goal and responds as a consequence of failing to achieve the goal. Positive feedback generates growth processes whereby action builds a result that generates still greater action. Forrester’s (1968, 1971) models treat the world as a closed continuous system and represent the identified ‘important parameter’ in the system.

Forrester created several models: The first model, named ‘World 1’ was the result of the meeting of the *Club of Rome* in 1970. Later on ‘World 2’ and ‘World 3’ were created with over 120 interdependent variables calibrated to historical trends. Variables which measure levels, sometimes known as ‘state variables’, are: population (P), natural resources (NR), capital investment (CI), pollution (POL) and the fraction of capital devoted to agriculture (CIAF). Each of these ‘state variables’ affects the change of the other variables through a set of relationships. It is the definition of these relationships, which reflects both the accuracy of the model and its actions. Small changes in a relationship between two states could cause vast changes in the forecasting action of the model.

The model was originally written in Dynamo and by now in other formats. This model was an important breakthrough in developing subsequent work. Forrester’s 1968 and 1971 are interplay models between demographic, industrial, and agricultural sub-systems, designed to study the rapidly growing stresses within our largest social system, the world community. These models, as indicated, are based on “Systems Dynamics” developed at the Massachusetts Institute of Technology. Forrester saw models as the policy solution and felt that models could serve policy purposes even without good data (emphasis added).

The bounded and apparently self-closed Forrester model has both strengths and limitations. One limitation is the difficulty of identifying and
measuring all the necessary and sufficient “generators of complexity”. It also fails in a proper understanding of their dynamic inter-connections. These limitations are inherent to the very idea of a model itself where a relatively small number of elements of a system are deemed to be relevant by the modeler when informed by a particular worldview. The formalization of the elements into mathematical equations (algorithms) constitutes a contribution of the Forrester model, although to some, Forrester’s real contribution is bringing the problem to the forefront through publication. This selective representation of parameters (Chu et al. 2003) creates an ‘impoveryed’ model when compared to reality, (with the caveat made by Chu, “this statement is true for any model”).

Reality, in a universal definition of a System of Interest (SoI), partitions the world into the system and its ambiance (or environment). The idealization process of modeling not only involves a simplification of the internal dynamics of the SoI but also the idealization of the system-ambiance (environment) interaction through a manifested worldview. This partition highlights the problems of radical openness and contextuality.

Radical openness

Modeling either ignores the system-ambience interactions (such as in laboratory tests) or models them in terms of sinks (outputs) and sources (input) such as in Forrester’s (1971) model. Chu et al. (2003) observe that no equivalent of ambience as-it-actually-is can be present in the model because if it were, it would simply become an extra element of the system of interest, with an enlarged boundary but deficient in capturing the larger meta-system, the new ambiance. Therefore, although systems such as Forrester’s are nearly closed, they remain open in a real-world context, a condition termed as “radical openness” and thus open to added complexity-additional unknown variables.

Radically open systems go beyond what can be represented by ‘sinks’ and ‘sources’ in a model. This radical openness is captured by the concept of meta-systems, previously alluded to, where the whole is less than its parts, and contains absurdities and paradoxes. Radical openness is a direct consequence of the richness of the connections between systems and their ambiance, whereas contextuality captures the complexity of intra systems. The radical openness is reducible if the ambiance interactions can, for specific modeling purposes (especially on a specific spatial and temporal scale), be internalized (sinks and sources) by some choice of system boundaries. Important cases of irreducible radical openness are systems or domains that transform their ambiance and are transformed by it on a relevant temporal scale, such as natural systems or domains in the problem at hand.

Some choices of systems boundaries might be better than others and actually approximate quasi-closed systems on some spatial and temporal
scales. In these cases we may consider the radical openness reducible, an option that Forrester and his followers have taken.

**Contextuality**

Contextuality is conceptually independent from radical openness and is an important concept in understanding Forrester’s model. Contextuality implies that the same natural system may be studied and modeled using a number of different approaches. Accordingly, the models will focus on different aspects of the system-as-it-is and will be motivated by various interests, research programs, problem definition and world-views. Chu et al. (2003) define a system as contextual if it includes one or more elements that also occur in a different system(s), or is in itself a shared element (generator of complexity) between more than one system; in this other system(s) the shared elements take part in causal processes different from those included in the original system.

Contextuality is a property that is a direct consequence of the partitioning of the world into systems and ambience that precedes the modeling work. Contextuality is reducible if the contextual properties of a system can be disregarded for all practical purposes or the contextuality is purely internal (that is, if there are no contextual features with other systems that lie in the ambiance) and there is no causal connection between the phenomena in the SoI and the contextual features of the ambiance. In other words, systems contextuality often manifests itself through elements that play multiple roles, fulfill several functions across the boundaries of the systems, or may be wholly irreducible in the sense that contextuality degenerates to a trivial property as in the case of many laboratory experiments.

Chu et al. (2003) further observe that contextuality in radically open systems (i.e. meta-systems) is a major source of unforeseen and potentially detrimental side effects (i.e. absurdities and paradoxes) of interventions into complex natural systems. Lack of attention to contextuality and the characteristics of radically open systems are examples of a deficient or outdated worldview interpretation.

The worldview, for example, that Forrester frequently uses implies that pollution will cause death and that efforts at population control are “inherently self-defeating”. Forrester interprets crowding as a force that will affect exponential growth, but that has not been the case as urban developments continue to increase in density never before observed, although it is possible that a threshold has not been reached where his postulation becomes a reality. This view has been dispelled by the current drastic Total Fertility Rate reduction, attributed by most to combined efforts of contraceptives, abortions, women’s education and urbanization. The claim that “there may be no realistic hope of the present under-developed countries reaching the standard of living demonstrated by the present industrialized nations” has not materialized, when we consider the
examples of China and India. “From the long view of hundred of years hence, the present efforts of underdeveloped countries to industrialize may be unwise.” The underdeveloped world has answered in the negative and plowed ahead with dramatic increases in living standard by developing countries’ populations.

The methodology employed by Forrester (1971), with closed feedback loops, does not take into account elements of social complexity that have been found to have significant impact in both creating and solving the problem. The feedback loops are structured on two kinds of variables: levels and rates. Levels are the accumulations (integrations) within the system. Rates are the flows that cause the levels to change. Again Forrester’s speculation that “levels are cause to change only by the related rates of flow” stems from a deficient worldview, using only levels and rates in a schema where all systems change through time.

Also, the levels chosen as the cornerstones on which to build the system structure, if not the underlying assumptions of the modes of behavior of interest and their interactions are suspect. The pollution loops, population controlled by crowding, pollution, and natural resources loops are suspect. The following “Proven Resource” loop (see Figure 472.1) is an early version used in the Forrester model.

In Forrester’s (1971) own words, a computer model embodies a theory of systems structure (see Figure 472.1). “The model is only as good as the theory which lies behind it. A good computer model is distinguished from a poor one because it captures more of the essence of the social system that it presumes to represent.” We may add that his computer model captures

![Figure 472.1 Forrester partial model of resource consumption](image)

the understanding of the social system workings at that time, but not the mature magnitude of the exponentialoid force confronting his worldview of (artificial) sustainability, henceforth being the model’s Achilles heel.

Forrester’s (1968) “System Dynamics” model is based on the previously mentioned ‘classical control theories’. A classical control theory premise is that the knowledge of the state of a closed system (at least a
modeling system) accounts for the position and velocity of all its particles at any instant (algorithmically), which determines unambiguously the future motion of the system. However, the occurrence of probabilities is justified and therefore statistical methods are adopted (Born 1969) in an algorithmic framework.

Forrester’s philosophy that informs his worldview has a pessimistic streak based on the inferred assumption that since we cannot control the variables, the present course is unsustainable. Sustainability efforts, in Forrester’s view, even if well intended, cannot tame the exponentialoids. “A major cut back of industrial activity, the treatment will at first seem as serious as the disease…” “Pollution generation declines as population falls…” “Exhausting natural resources creates population decrease…” “Technical solutions create pollution that creates population decrease…” “Crowding affects the quality of life and creates population decrease…” “Food shortages create population decrease…” “Each attempt to eliminate a pressure within the system leads to a new pressure” (possibly because of deficiencies in the structure of the model and the feedback loop arrangement!)

Although Forrester (1968) in his introduction to World Dynamics states that this model is offered as an interim “until a better model becomes available,” his model accentuated a sense of urgency. Forrester, as noted, correctly makes three general points: The world is a system (treated in this section), exponential growth cannot continue, and a comprehensive approach is necessary, which are the next points to consider.

2.1.1.2 Exponential growth cannot continue

Forrester’s (1971) assertion that “Exponential growth cannot continue forever” is a subjective observation statement. Exponential growth appears highly undesirable but Forrester offers no alternatives on how his elements that influence growth may apply sustainability forces to the exponential growth, that is: how the exponential growth may be tamed.

Forrester’s understanding and model of the exponential is algorithmic, based on an understanding of a world structure based on levels and rates as noted previously. Within the limited model, Forrester and followers solved the inverse problem, i.e. what has to change and how, in order to avoid depletion, pollution, and population explosion, but the work is vitiated by the model’s assumptions, that is the informing worldview.

The work of Chichilnisky (1997) on “What is Sustainable Development?”, although mostly in terms of her areas of expertise (Mathematics and Economics), alludes to an interpretation of consumption as a “vector” which is a quantum step in the understanding of the forces of sustainability, but also is vitiated by embracing Forrester’s worldview of the times.
Investigating a new model that fully takes into account the complexities of the human condition, and especially the mechanisms for change, is necessary if indeed humanity has the capacity to change and tame the exponentialoid. We expect that exponentialoids should be intrinsically vectorial in nature because they are caused by elements exhibiting the characteristics of complex systems. If this is the case, then the same elements that cause also modify exponentialoids.

### 2.1.1.3 A comprehensive approach is necessary

Some place the ultimate burden for achieving sustainability on an informed and motivated private sector; others, like Forrester (1968), place their hopes on the swelling of public political force affecting the governmental sector. Pearce (2006) and Chichilnisky (1997) place their hopes in adding the detrimental cost of emission to the accounting system employed by the General Economy.

Hart's hopes for the corporate world appear to be overtly optimistic: "corporations are the only organizations with the resources, the technology, the global reach, and, ultimately, the motivation to achieve sustainability." Of course, this was sustainability of course as understood in the worldview of his times.

Regarding the public-governmental-political arena: Edwards (1996) observes that "most policies that make it through the policy process have certain characteristics: they have a narrow focus, a high probability of success, short-term payoffs, they are tangible, easily perceived, have widely derived benefits, perceived affordability, and feedbacks. Although models have a role in policymaking, the Forrester (1971) models, according to Edwards, accomplished more in the arena of public opinion with the sale of more than seven million copies of Limits to Growth in more than 30
languages, than in policy making. According to Edwards (1996), “Models-for-policy should be used heuristically, not predictively.”

A heuristic comprehensive approach is necessary, one that moves both the private and public sectors. However there is also a large gap of wishful thinking that problem clarity will effect the intended changes. In other words, private and public opinion and policy are complex components.

2.1.2 Sterman’s approach

Sterman (2002) continues Forrester’s work and has moved from a ‘Systems Dynamic’, mechanistic and reductionist approach to a more ‘systems thinking’ approach that attempts to take into consideration the complexities of the human condition. Sterman’s model evolves in a worldview that establishes the link between the soft systems and the hard systems methodologies akin to that of Forrester.

The emphasis of this approach is on finding a process for understanding the dynamic behavior of our social systems, thus the work remains significant, but at the level of ‘systems thinking,’ ‘systems dynamics,’ ‘classical control theories,’ and ‘artifacts’ (Strand et al 1996). Figure 472.2 is an updated Forrester loop for Resource Consumption as interpreted by Sterman.

3 SUMMARY

Forrester’s (1969) and Sterman’s (2002) formal models are closed systems by their own admission, well defined (have clear boundaries), and are self-contained (in the sense that any transformation or state of changes of the system or parts of it are internal or due to a well defined input function). As such, they are models not embedded in an ambience but have internalized a highly abstract representation of the ambience (sinks and sources). In a sense, a risk was taken when idealizing a worldview to study something overly artificial and producing an ‘artifact’.

Regarding contextuality as defined, the main question for Forrester’s and Sterman’s models is whether the specific aspects (generators of complexity) chosen are the necessary and sufficient set needed to understand all the consequences they cause. Failure to do so, in Chu’s et al.’s (2003) words, results in ‘impoverished’ models even though as duly noted, it was the state of the art at that point in time, and thus a major milestone in creating strategic thinking and marshalling public opinion to address the problems. In other words, we need a model that as an abstraction is a better idealization in our evolved understanding of complex reality.

The position of this paper is that concurrent to better understanding of the dynamic behavior of our complex systems is a worldview of the
dynamics of social and artificial systems. Such a worldview is informed by philosophy as well as historical thinking before a commitment is made to a hard system, since according to chaos theories (Lorentz, 1972, 1993; Gleick, 1987; Thiétart and Forgues, 1995), the wrong assumptions at the beginning will have severe impact on the outcome.

Because time is of the essence, we must devote an inordinate amount of time and effort to the identification and clarification of a worldview where the already identified exponential growth, the concepts embraced by the term “sustainability,” the elements that influence the forces of sustainability or lack thereof and the forces that have historically moved those elements are understood. This worldview will construct a model of the relationship between exponentialoid growth and sustainability using the elements that influence the exponentialoid growth in order to study adequate responses.

4. REFERENCES

Chu, D., Strand, R. and Fjelland, R., 2003, Theories of Complexity – Common denominators of complex systems, Wiley Periodicals, Inc. 8(3)19-30
Lorenz, E., 1972, Predictability: Does the Flap of a Butterfly’s Wings in Brazil Set off a Tornado in Texas, Presented at the 13th meeting of the American Association for the advancement of Science, Washington DC.
Lucas, C., 2005, The Philosophy of Complexity, revised
www.caresco.org/lucas/philos.htm, date accessed 7 July 2005
Pearce, D. W., 1989, Economics and the Environment, Edward Elgar,
Cheltenham.
Construction Industry’s Contribution to Sustainable Development [Pearce
Report], New Construction Research and Innovation Strategy Panel
(nCRISP), London (available at: http://www.ncrisp.org.uk) accessed 24
May 2006.
Pearce, D. W., 2006, Is the construction industry sustainable? Definitions
and reflections, Building Research and Information, Taylor & Francis,
34(3), 201-207.
Pearce, D. W., Turner, R. K., 1990, Economic and natural resources and
the Environment, Harvester, Hemel Hempsted.
Pearce, D. W., Markandya, A. and Barbier, E., 1989, Blueprint for a Green
Economy, Earthscan, London.
Pearce, D. W., and Warford, J. J., 1993, World without end: Economics,
Environment, and Sustainable Development, Oxford University Press,
Oxford.
Sterman, J. D., 2002, All Models are Wrong: Reflections on Becoming a
Systems Scientist, System Dynamics Review 18(4): 501-531
Tavistock Institute, 1966, Independence and Uncertainty – A study of the
Thiétart, R., A., and Forgues, B., 1995, Chaos Theory and Organization,
Organization Science, 6(1)
changes in the ecological footprint for world regions, Ecological
Economics (52)43-62
Wackernagel, M., Shulz, N. B., Deumling, D., et al., 2002, Tracking the
ecological overshoot of the human economy, Proceedings of the National
Academy of Sciences, USA 99(14), 9266-9271
Waldrop, M., M., 1992, Complexity, The Emerging Science at the Edge of