What's behind the blue arrow?

The notion of causality in System Dynamics

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Abstract

System Dynamics (SD) is considered a causal modeling approach. Causality is a key and peculiar characteristic of SD: SD models are supposed to contain and represent only causal relationships. However, SD researchers are often not explicit about the notion of causality employed in their work, and there not seem to be a commonly adopted and clear definition of causality in the field. This paper investigates and compares the notions of causality emerging from the work of three major SD authors. The objective is to assess the extent to which a convergence towards a common definition of causality in the field exists, and whether the notion of causality used by the various authors is influenced by the particular field of application. The analysis conduced indicates that the notions of causalities used are similar, and that existing differences could be explained by different fields of application and different backgrounds of the authors.

Introduction

System Dynamics (SD) is a methodology developed to analyze complex systems initially conceived at the Massachusetts Institute of Technology (MIT) in the early 1960s. In System Dynamics simulation models are built to analyze the relationship between structure and behavior of dynamic systems. The modeling approach used in System Dynamics emphasizes the importance of properly representing non-linearity, feedback loops and accumulations, which are considered the key factors determining the dynamic behavior of a system. System Dynamics models contain representations of both physical and decisional structures and are ideally suited to represent complex socio-economic and environmental systems.

The notion of causal relationship is at the very core of the System Dynamics theory: SD models should represent exclusively causal relationships between variables. Also, SD modeling is often seen in contraposition with correlational modeling, stressing the importance of representing causal relationships versus correlations. This dichotomy clearly appears in the analysis of Barlas (Barlas 1990) and Sterman: "Every link in your diagram must represent (what you believe to be) causal relationships between the variables. You must not include correlations between the variables" (Sterman 2000, p. 141).

Despite the distinction between causal relationships and correlations is given such importance in SD, a definition of causality can be hardly found in the work of the major authors in the field. This problem does not seem to be specific to the SD field only: as Ottar Hellevik puts it "Most social scientists applying causal reasoning to empirical research problems do not worry much about the extensive philosophical debate concerning this concept. Cause, effect and similar terms seem clear enough as used in every day language" (Hellevik 1988, p. 25).

The notion of causality implicitly adopted by SD researchers determines what types of relationships are actually included in the model. Using different concepts of causality can lead to the construction of different model structures, and eventually have repercussions on the validity of the results produced. Relationships that a researcher considers causal, and thus become part of his/her explanation of system's behavior, might not be considered as such by scientists holding a different notion of causality, compromising the validity of the analysis. As all the other fundamental assumptions modelers make in their analysis, the notion of causality adopted should be made explicit, for the limitations of the results produced to be properly perceived.

In this paper I try to identify and analyze the notion of causality emerging from the work of three among the best known researchers in the field: Jay W. Forrester, the original initiator of the System Dynamics method and Germeshausen Professor Emeritus and Senior Lecturer at the Sloan School of Management, Massachusetts Institute of Technology (MIT); John D. Sterman, the Jay W. Forrester Professor of Management at the Sloan School of Management and Director of MIT's System Dynamics Group; and

Andrew Ford, Associate Professor of environmental science in the Program in Environmental Science and Regional Planning at the Washington State University in Pullman, Washington. The authors have been selected based on the prominence of their work and in the attempt of covering different filed of application of SD, including macroeconomics, microeconomics and environmental science.

Method

This paper does not intend to identify the actual notion of causality generally adopted by each author, which would require an extensive review of their many publications. Rather, I try to capture the character of the notion of causality emerging from three of their major books only. In order to do that, I analyze the modeling manuals that they have written, including the mathematical models there presented. More specifically, the texts considered in this analysis are: Principles of Systems, by Jay w. Forrester (1968); Business Dynamics, by John D. Sterman (2000); and Modeling the Environment, by Andrew Ford (1999).

These texts rarely contain explicit indications of the notion of causality adopted by the three authors: indirect indications can be identified by closely studying and interpreting some aspects of the analytical methods presented. The notions of causality associated to the three authors have thus been reconstructed based on reasonable interpretation of their writings. This implies that the basis of the findings presented here is somewhat uncertain; and that the emerging notions of causality do not necessarily reflect the original thinking of the authors.

To portray an initial picture of the notion of causality used in the texts mentioned above, I consider here only a limited set of dimensions of causality. This set of dimensions of causality has been derived from Mac Iver's Social Causation (1942); from Rosenberg's Philosophy of Social Sciences (1995); and from Abbot's analysis on the philosophy of causality in the social sciences (Abbot 1997). The following dimensions are considered:

1. Causality as **deterministic forces** vs. **probabilistic drifts:** Is causality determining with certainty a specific effect, or does it only define the probability for that effect to happen? Nineteenth century scientists tend to see causality as deterministic. Problems with this view of causality begin with the growth of quantum mechanics in 20th century, when philosophers prefers to retain a more probabilistic position on causality.
2. Causality **directly perceivable** vs. **not perceivable**: Can causal relationships in the real world be directly observed and measured? Early natural scientists see causality as directly perceivable, as a phenomenon that can be directly observed (e.g. one object hitting another and modifying its trajectory). Hume attacks this view of causality and argues that causality cannot be directly perceived: one might be able to observe that one event follows another, but not any ties between them. Most modern social scientists also share this view.
3. **Social** causes vs. **individual** causes: Are social forces the actual causes of human behavior, or do they only predispose individuals who will eventually base their

decisions on individual factors? This dimension of causality is well analyzed in Durkheim's work. Unlike most of 19th century scientists, Durkheim focuses on social causes as forceful, defining the view of causation often adopted by modern social scientists.

4. Causes as **explanatory** vs. causes as levers to **control** a phenomenon: Is the focus of the analysis on all possible causes of a problem, or on those that are within control of agents? Hume's view of causality as causal regularities leaves an open to all possible invariant sequences that can explain a phenomenon, including those that we do not normally consider as causes. Collingwood and others prefer to focus on those causes on which agents have control, a view that is now adopted, for example, in rational choice theory.
5. Causality necessarily **involving temporal succession** vs. causality as **instantaneous** relationship: Can one element affect another instantaneously or is that a process happening over time? Most of modern social scientists agree that causality involves temporal succession, i.e. it happens over time (this is the position of Hume, for example). However, there is a minority of philosophers who consider causality as a simultaneous, instantaneous relationship (like Collingwood and Russell do, for example).
6. Causality considering only **individual causes** vs. causality considering **multiple causes**: Can multiple elements be the cause of a certain effect or should the cause be identified in a unique element? Hume focuses on individual causes and makes frequent ceteris paribus assumptions that are often empirically not possible. Other philosophers (such as Ayer and Mackie) prefer to think that in reality many elements are continuously affecting the object of the analysis, which thus has multiple causes.
7. Causality as a **property of reality** vs. causality as a **property of mathematical propositions** only: Does causality actually exist in the real world, or is it a logical construction that belongs to our mathematical systems only? The view of causality only as a property of mathematical propositions or mental associations is developed in particular by the logical positivists of the 19th century, in contrast with the view of qualitative theorists such as McIver, who sees causality as a necessary logical law in the real world.

The following section contains a brief assessment of the notion causality emerging from the works of Forrester, Ford and Sterman, evaluated with respect to the seven dimensions above indicated. Eventually, in the summary section these notions of causality are compared and their differences analyzed.

Analysis

Jay W. Forrester

Jay W. Forrester studied electrical engineering and made exceptional contributions to digital computer technology. He pioneered the System Dynamics method and is currently Germeshausen Professor Emeritus and Senior Lecturer at the Sloan School of Management, Massachusetts Institute of Technology. Forrester is author of several texts of reference in the System Dynamics field, including: Industrial Dynamics (1961); Principles of Systems (1968); Urban Dynamics (1969); and World Dynamics (1973).

The notion of causality emerging from Forrester's book "Principles of Systems" is highly deterministic. Forrester considers causality as a property of the real system that can be represented in mathematical systems, and sees social causes as forceful causes. However, he does not seem to be persuaded that causality is directly perceivable.

1. Deterministic vs. probabilistic

Forrester seems to have a deterministic view of causation. He believes that the behavior of a system arise from its structure, and therefore that the same structure always generates the same behavior, as appearing several times in his text, for example: "It is in the positive feedback form of system structure that one finds the forces of growth. It is in the negative feedback, or goal seeking, structure of systems that one finds the causes of fluctuation and instability" (p. 1-7). Also, he seems not to take into consideration explanations based on accidental, random causes: "A search for orderly structure, for cause and effect relationships, and for a theory to explain system behavior gave way at times to a belief in random, irrational causes" (p. 1-2).

2. Directly perceivable vs. not directly perceivable

As well as the other authors analyzed, Forrester does not provide explicit indications on this subject. It is however possible to derive indirect hints based on his opinion regarding the possibility of *correctly measure* causality. *Perceiving* reality and *measuring* it are clearly distinct concepts, but somehow related: one cannot measure reality if he/she does not perceive it; and the more directly one perceives reality, the more accurately he/she can measure it. According to Forrester, causality or any other phenomena cannot be correctly measured, as it clearly appears from this paragraph discussing model validity: "There is nothing in either the physical or in the social sciences about which we have perfect information. We can never prove that any model is an exact representation of reality" (p. 3-4). Moreover, when discussing general forms of feedback loops, he points out that: "Information is not determined by the present true condition, which is not instantaneously nor exactly available, but instead by the past conditions that have been observed, transmitted, analyzed and digested" (p. 1-10). These sentences seem to suggest that Forrester has a view of causality as a phenomenon that can never be exactly perceived.

3. Social causes vs. individual causes

Forrester does not give direct hints about his view of social and individual causes. However, his analysis focuses on social causes rather than individual causes, suggesting that he considers social causes as forceful. His focus is on the larger social systems and on general principles, and compares the structure of systems principles to the structure of physical laws: "A systems structure should give to education in human affairs the same impetus that the structure of physical laws has given to technology" (p. 1-4). Forrester search for unifying principles highlights that he is searching for causes that are at work in all social systems and not specific to an individual.

4. Causality as way to explain a phenomenon vs. control it

Forrester investigates causal relationships among variables in a system with both the purpose of explaining the behavior of the system and provide information to properly control the system. This approach stems out particularly well in his discussion on models' validity: "It is towards this goal of better understanding, easier communication and improved management of social systems that we proceed" (p. 3-5).

5. Causality involving temporal succession vs. instantaneous relationship

Regarding the time dimension of causation, Forrester seems to make a clear distinction between the type of causation involved in the determination of stock variables and of flow variables. An indication in this sense emerges from his discussion on feedback loops, the basic causal structure in System Dynamics: "A feedback loop consists of two distinctly different types of variables—levels (states) and rates (actions). […] The level variables can not change instantaneously […]. The rate equations (policy statements) of a system are of simple algebraic form; they do not involve time or the solution interval; they are not dependent on their past values" (p. 4-8, 4-9, 4-10). Despite this technical distinction, however, Forrester indicates that not only he accept causation as a process over time, but that he consider the process of integration over time as fundamental characteristic of systems. He clearly states his perspective when digressing on the nature of differential equations: "Integration (or accumulation) shifts the time-character of action, produces delays between action streams, and creates the dynamic behavior in systems" (6-11).

6. Individual causes vs. multiple causes

Forrester clearly sees elements as possibly affected by multiple variables. This is evident in the various models presented in his book, and particularly clear when he describes how a system should be represented in a flow diagram: "The simple level equation, as in Figure 7-1 is identified by the rectangle, the rates in and out that are being integrated […]" (p. 7-1). Stocks are therefore affected by multiple flows. Similarly, flows are affected by multiple variables: "this symbol [the flow symbol] should show […] the information inputs on which the rate depends" (p. 7-2).

7. Property of reality vs. property of mathematical systems only

Forrester seems to believe that causality is a property of reality and of the mathematical models that attempt to represent it. This is particularly evident when he talks about the integrations process (a causal process): "Integration occurs naturally in the both physical and biological worlds. The integration processes of the real world are represented in our models by the level equations" (p. 6-11).

John D. Sterman

John D. Sterman is Jay W. Forrester Professor of Management at the Sloan School of Management and Director of MIT's System Dynamics Group. He is author, among other important publications, of Business Dynamics, probably the most comprehensive modeling manual in the System Dynamics field.

From the analysis of Sterman's book "Business Dynamics" causality appears as a crucial matter, but one that it is extremely difficult to objectively assess. Sterman almost entirely rules out the possibility of directly observing causality in social systems, and seems to exclude also the possibility to assess whether causality is a property of the real world. He points out that theories (and models) represent what *we think* is causality in the real world.

1. Deterministic vs. Probabilistic

John Sterman seems to have a deterministic view of causality. At the beginning of his book, he states that "A fundamental principle of system dynamics states that the structure of the system gives rise to its behavior" (p.28). This view of structure that determines behavior is highly deterministic, implying that the same structure, e.g. the same causal relationships, always leads to the same result.

2. Directly perceivable vs. not directly perceivable

Sterman appears quite skeptical but not entirely contrary to the possibility of directly observing causal relationships. As in the case of Forrester, Sterman does not explicitly state his view on this subject: I tried to derive some hints based on his opinion regarding the possibility to correctly measure causality. When discussing the needs to run proper scientific experiments to investigate causality, he highlights the difficulty of estimating causal relationships in social sciences: "Scientists have learned from bitter experience that reliable answers to such questions are hard to come by and require dedication to the scientific method – controlled experiments, randomized, double-blind trials, large samples, long-term follow-up studies, replication, statistical inference, and so on. In the social and human systems we often model, such experiments are difficult, rare, and often impossible" (p. 142). Saying that controlled experiments are "often impossible", Sterman leaves an opening for situations in which causality can be correctly estimated. Later on in his book, when discussing about delays, Sterman says that "When numerical data are not available, estimation by direct inspection of the relevant process can yield good estimate" (p. 467). This also seems to indicate that he is not completely against the possibility of directly measuring causality.

3. Social causes vs. individual causes

Sterman sees social causes as forceful, and in particular considers the system where people operate as the major driver of people behavior, rather than the individual reasons of different subjects. This emerges quite clearly from his introductory discussion about complex systems: "However, people have a strong tendency to attribute the behaviour of others to dispositional rather than situational factors, that is to character and especially character flaws rather than the system in which these people are acting" (p. 28).

4. Causality as way to explain a phenomenon vs. control it

Sterman investigates causality in the attempt of both explaining and correcting a problem. When describing the principles for successful use of SD, he stresses the importance of including in the mathematical models both causal mechanisms that explain a phenomenon (structures) and those that can correct it (policy levers): "Models must strike a balance between a useful, operational representation of the structures and policy levers available to the clients while capturing the feedbacks generally unaccounted for in their mental models" (p. 81).

5. Causality involving temporal succession vs. instantaneous relationship

Sterman seems to consider causality as a process over time. Indirect information about his view on this subject can be derived by his discussion about time delays. Time delays are used to introduce the *time* dimension in a relationship between two or more variables. Describing how time delays work in real complex systems, Sterman points out that "delays are pervasive" (p. 411) and that if time lags are not explicitly represented in a model, it does not mean that they do not exist: "Your causal diagram should include delays that are important to the dynamic hypothesis or significant relative to your time horizon" (p.150).

6. Individual causes vs. multiple causes

Sterman accepts the idea of multiple causes. His text is rich of examples of variables being determined by multiple causes. A simple and clear example is given in the chapter dedicated to causal loop diagrams: "Variables are related by causal links, shown by arrows. In the example, the birth rate is determined by both the population and the fractional birth rate" (p. 138).

7. Property of reality vs. property of mathematical systems only

Sterman seems to be inclined, but entirely persuaded, to accept causality as a property of real systems, and mathematical model as an attempt to imitate the reality. An important hint in this sense emerges from his discussion about the causal structure of models: "A system dynamics model must mimic the structure of the real system well enough that the model behaves the same way the real system would" (p. 141). However, his skepticism about our ability to observe causality is also reflected in this part of the book, and he specifies that "Every link in your diagram must represent (what you believe to be) causal relationships between the variables" (p. 141).

Andrew Ford

Andrew Ford is Associate Professor of environmental science in the Program in Environmental Science and Regional Planning at the Washington State University in Pullman (Washington). He is author, among many other publications, of "Modeling the Environment, an Introduction to System Dynamics Modeling of the Environmental Systems", one of the most widely used modeling manuals for SD.

From the analysis of Ford's book "Modeling the Environment", causality emerges as a property of reality, directly perceivable and deterministic, and is used both as a way to control and explain phenomena. The following paragraphs present a more detailed assessment of his notion of causality based on the seven selected criteria.

1. Deterministic vs. Probabilistic

Ford seems to have a deterministic view of causality. As a usual practice in SD, he turns probabilistic measures into deterministic relationships. For example, in the Salmons Smolt's Spring Migration model (p. 137) mortality rates (a measure of the probability of dying per time period) are multiplied by the stock of salmons in order to calculate the actual flow of deaths.

2. Directly perceivable vs. not directly perceivable

It is quite difficult to derive Ford's view on this point from his writing. Some indications can be derived from the section of his book dedicated to parameters' estimation. Parameters are often used to represent the intensity of a causal relationship, and the author's view on the possibility to correctly perceive parameters values hints to his view on the possibility to directly perceive causality. Under these assumptions, Ford seems to be inclined to accept that in some situations causality can be directly perceived. For example Ford (citing Kitching) talks about "a variety of situations where the measurement of real values may be difficult or even impossible" (p. 176). This sentence seems to leave open the possibility of situations in which it is actually possible to measure real values. A few paragraph before, he also says that "some parameters may be known with perfect accuracy" (p.174). This idea that in some cases relationships can be perfectly measured strengthens the impression that in his view causality can be directly observed.

3. Social causes vs. individual causes

As other SD authors, Ford represents social causes as forceful. Individuals are treated as aggregate and the individual differences in decisional aspects are not portrayed. Looking at, for example, the Tucannon Salmon model (p. 150), it is immediate to notice that the agents in the model are represented in an aggregate way, as a total population or sub aggregates, and not at the individual level. Individual causes are not represented, and the social causes are the forceful ones.

4. Causality as way to explain a phenomenon vs. control it

In his notion of causality, Ford seems to embrace both functions of causality: causality as a way to explain a certain behavior, and causality as a mean to control that behavior. In the introductory part of the book he says that "System Dynamics models are constructed to help us understand why these patterns occur" (p.10). This sentence underlines the importance in his view of studying the causal mechanisms that explain a phenomenon. Later in the book, when describing the various phases of modeling process (p. 172) he specify that the final phase is dedicated to "test the impact of policies", leaving no doubt about the importance of representing causality as a way to control a phenomenon. A few paragraphs later, he also specifies that the representation of the system used should explicitly contain causal relationships that can be used to control the behavior of the system: "The flow diagram [a representation of the system] […] should also contain variables to represent the two three policies listed previously" (p. 173).

5. Causality involving temporal succession vs. instantaneous relationship

In his models, Ford represents causality both in form of instantaneous and dynamic relationships. System Dynamics is a dynamic modeling methodology to study the behavior of a system over time. However, it is common in SD models that some relationships are represented as instantaneous interactions. For example the Kaibab Deer Herd model that Ford presents (p. 206) includes integral equations over time for stocks (e.g. deer population (t) = deer population (t – dt) + (net births – predation) * dt); as well as algebraic equations for auxiliaries and flows (e.g. net birth rate = F (equivalent fraction needs met)).

6. Individual causes vs. multiple causes

Ford often represents causality using multiple causes. Examples are abundant: at p.70, for example, Ford illustrates two examples of causal loop diagrams (a type of representation of causal relationships among variables) where population is affected simultaneously by births and deaths. In another causal loop diagram (p.71), he shows how energy content of house is affected by both heat loss and heat production.

7. Property of reality vs. property of mathematical systems only

Ford's position on this aspect of causality seems to be quite clear. In the introductory part of the book, he states that "The cause-and-effect connections in the real system will be represented by interconnections in the computer model" (p. 11). This indicates in a fairly clear way that he believes causality is a property of the real system, and that causality in mathematical systems (models) only mimics that of real systems.

Summary

Commonalities

The notions of causality emerging from the work of Forrester, Sterman and Ford have several common characteristics. First, the three authors seem to share a deterministic view of causality. The basic principle of System Dynamics that the structure of the system gives rise to its behavior, adopted by all three authors, highlights a highly deterministic perspective on causality. Being System Dynamics a structural modeling method, a different perspective on this subject is probably not common in the field.

Second, the three authors focus their analysis on social causes. Although this is not explicitly stated, they look at agents in an aggregate way; they do not portray individual causes (e.g. individual psychological or biological aspects of each subject in a group) but the social causes affecting all (or subgroups of) agents. The social causes are therefore the forceful ones, those that actually determine the behavior of agents and of the system more generally. This is not surprising: given the aggregated representation of agents used, System Dynamics is not a well suited method to represent individual causes. Other simulation approaches, such as Agent Based Modeling, might be better suited for that type of analysis.

Third, all authors analyzed investigate causality as a mean to both explain and control phenomena. Causal structures are analyzed to understand the behavior of a system in the past; modifications of such structures (policies) are simulated in the attempt of improving the behavior of the system in the future. It is a shared principle, in fact, that models are build to solve a specific problem, and that the ability of the model to explain the past behavior of the system is crucial to its usefulness as a policy testing tool.

Forth, it is a common perspective to the three authors that causality involves temporal succession. Practically, only part of the relationships in System Dynamics models contains explicitly the time dimension while some relationships are represented as instantaneous. However, it seems that this is not done in the belief that some relationships actually happen instantaneously, but in order to simplify the representation of the system. In some cases delays are so short compared to the time horizon of the analysis that they do not need to be explicitly represented, as this would make the model more complex without considerably adding to its dynamic behavior.

Finally, Forrester, Sterman and Ford accept the idea of multiple causes. This clearly appears in their texts as well as in the models presented in their books, where variables are often determined by several others. Multiple causality is actually a typical characteristic of highly complex systems: systems composed by multiple, interacting causal loops necessarily include variables that are determined by more than one cause. The focus of System Dynamics is to represent complex systems and the assumption of multiple causality is common in the field.

Differences

The notions of causality emerging from the texts analyzed also have a few differences. A first difference refers to the possibility of *directly perceive* causality. The authors do not provide explicit indications on this subject, and I tried to derive indirect hints based on their opinions regarding the possibility of *correctly measure* causality. This is based on the supposition that one cannot measure reality if he/she does not perceive it; and that the more directly one perceives reality, the more accurately he/she can measure it. On this point, Forrester is convinced that causality cannot be correctly measured, and expresses his view in a rather clear way: “There are no phenomena, neither in the physical nor in the social sciences, about which we can have precise information […]”. Sterman seem to have a less strong position: he also appears quite skeptical but not entirely contrary to the possibility of correctly measuring causality. Ford is even more open and arguments that “some parameters may be known with perfect accuracy”.

The other difference among the authors’ views of causality concerns whether causality is considered a property of real system or of mathematical propositions only. Forrester sees causality as a property of real systems, which can be represented in mathematical systems, as emerging from his analysis of the integration process: “This process [the integration process, a causal process] is a phenomenon that exists naturally in the both physical and biological systems. The integration processes in the real world are represented in our models by stock equations”. Ford also have a similar position and describes model as an imitation of real systems: “The cause-and-effect connections in the real system will be represented by interconnections in the computer model”. Sterman seems to have a softer position on this matter, and reminds the reader that what it is considered causality has a subjective element: “Every link in your diagram must represent (what you believe to be) causal relationships between the variables”. Sterman seems to stress therefore causality as mental association, rather than as property of the real system.

Conclusions

From the analysis conduced, there seems to be a convergence in the notion of causality in the field of System Dynamics. The notions of causality emerging from the works of Forrester, Ford and Sterman are similar on most of the dimensions considered.

However, there are two dimensions for which the authors' opinions seem to differ: whether causality is directly perceivable; and whether causality is a characteristic of the real world. What can these differences be attributed to?

System Dynamics is a multidisciplinary field. SD method is applied to the analysis of systems of different nature: economic as well as social and environmental systems. A first tentative answer could be that the notion of causality used by the authors depends on the field to which the apply System Dynamics.

This hypothesis would fit well the case of Andrew Ford: he seems to consider causality as a property of the real world and to accept situations in which causal relationships in the real world can be perfectly estimated. Ford applies System Dynamics mainly to environmental issues, and his view of causality seems closer to that of the earliest natural scientists.

The filed of application seems to have some influence also on Sterman's view of causality. Sterman appears quite skeptical about the possibility of observing causality (although he does not completely rule it out) and seems to say that whether causality is a property of the real system is a subjective matter. Sterman applies System Dynamics mainly to the analysis of social and economic systems, and his notion of causality seems closer to that of most modern social scientists, yet still holding a deterministic character.

Forrester position is more complex: on one hand he does not seem to consider causality as directly perceivable; on the other hand, he considers it a property of the real systems. To a larger extent than Sterman and Ford, Forrester seems to conjugate the notion of causality of early natural scientists with aspects from that of modern social scientists. As Sterman does, Forrester also applies System Dynamics mainly to social systems, and therefore his partly different notion of causality cannot be explained by the different field application. In this case, a tentative explanation is that the duality appearing in Forrester's notion of causality might be due to his originally scientific (engineering) background, and to his later shift towards the social sciences.

The notion of causality emerging from the works of Ford, Sterman and Forrester seems therefore influenced somehow by both their field of application and their background. This result is however a bit speculative, at least for two reasons. First, as already mentioned, the authors analyzed are not explicit about their notion of causality, forcing me to develop my thinking on this subject based on indirect and implicit information. Second, this conclusion is paradoxically derived by implicitly using my notion of causality, which I cannot further develop in this paper, but hopefully elsewhere.

The analysis presented in this paper is limited to three of the major works in the System Dynamics field. Given the high relevance of the notion of causality for the System Dynamics method, it is to be hoped that further and more accurate analysis will be conduced in this direction. More clarity on the notion of causality used in the field could be greatly beneficial to all System Dynamics practitioners; and could increase the credibility of the work in the field, strengthening its impact on society.

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