systems

Concept Paper

The Meaning of "Structure" in Systems Thinking

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Abstract: "Systemic structure" is an oft-used term in Systems Thinking. However, different authors use different, sometimes conflicting definitions of "systemic structure," many of which are nebulous, and therefore its meaning is not clear. In this paper, we review the various definitions and interpretations and develop a logical, practical definition that may be applied to develop a deep understanding of system behavior: in Systems Thinking, "structure" is the cause-and-effect manner in which system components interrelate to yield system behavior; and the rules, laws, protocols, procedures, policies, and incentives/rewards that govern those interactions.

Keywords: Systems Thinking; structure

Citation: Monat, J.P.; Gannon, T.F. The Meaning of "Structure" in Systems Thinking. *Systems* **2023**, *11*, 92. https://doi.org/10.3390/systems11020092

Academic Editor: Vladimír Bureš

Received: 28 December 2022
Revised: 1 February 2023
Accepted: 3 February 2023
Published: 9 February 2023

1. Introduction and Background

There are several different versions of Systems Thinking, many of which use the term "structure." This work focuses on those versions that embrace either the Iceberg Model, causal loop diagrams, system dynamics, or the existence of a link between underlying forces (such as mental models) and patterns to help explain the behavior of simple, complicated, and complex systems. In Systems Thinking, the Iceberg Model (details available in [1]) posits that the systemic structure lies between underlying forces (such as mental models) and patterns, as depicted in Figure 1.

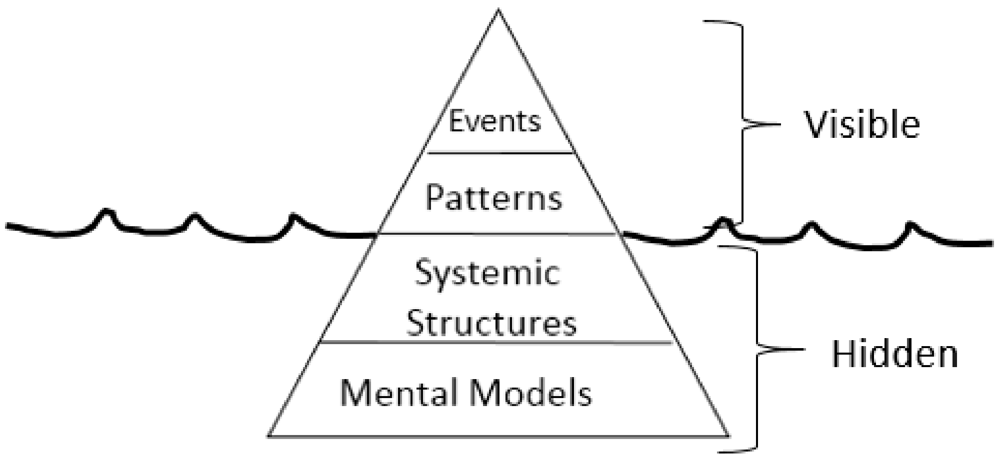

Figure 1. The Iceberg Model.

The model argues that in human-designed systems, structures form as a result of mental models and that patterns, in turn, form as a result of the structure. In natural systems, underlying forces such as gravity, electromagnetism, centrifugal force, and hydrophilicity replace "Mental Models" as the lowest level of the iceberg.

Conventional definitions of "structure" include:

1. The arrangement of and relations between the parts or elements of something complex [2].
2. The arrangement of particles or parts in a substance or body; arrangement or interrelation of the parts as dominated by the general character of the whole [3].
3. The way in which the parts of a system or object are arranged or organized, or a system arranged in this way [4].
4. The mode of building, construction, or organization; arrangement of the parts, elements, or constituents [5].
5. The structure of something is the way in which it is made, built, or organized [6].

If one researches synonyms for "structure," Google responds with "configuration," "arrangement," or "organization."

However, these definitions are not clear, nor do they provide actionable descriptions. For example, the meanings of "organization," "arrangement," "mode," and "way" are not clear: is it the physical arrangement of the system components? Or is it the sequential organization? Or perhaps the reporting relationships in an organization? A better, Systems Thinking-specific definition is required.

2. Literature Review

Several researchers have proposed definitions of system structure. We are not aware of any empirical studies that have been done; most of the following definitions represent the opinions and conceptual analyses of the authors.

Daniel Kim [7] states that "Systemic structures are the ways in which the parts of a system are organized. These structures actually generate the patterns and events we observe. Structures can be physical (such as the way a workspace is organized, or the way a machine is built) as well as intangible (such as the ways employees are rewarded, or the way shift changes are timed.)" In this definition, the meaning of the word "way" is not clear. Does "way" refer to the physical relationships among components, the sequential relationships, the reporting relationships, the authority or power relationships, or something else?

Senge et al. [8] say that "structure is the pattern of interrelationships among key components of the system:

1. organizational hierarchy
2. process flows
3. attitudes
4. perceptions
5. product quality
6. the ways decisions are made"

Their definition refers to structure as a *pattern*. In addition, most Systems Thinking experts would categorize "attitudes" and "perceptions" as mental models instead of structures. In addition, can "product quality" be a system component?

Meadows [9] states that "structure is the system's interlocking stocks, flows, and feedback loops. System structure (feedback loops and underlying forces) is the source of system behavior. System behavior reveals itself as a series of events over time (a pattern!)." This definition includes not only the feedback loops that interrelate system components, but also some system components themselves as well as underlying forces, which we believe are not part of structure but instead are causative factors that *yield* structure.

Monat and Gannon [1] state that structure is "the manner in which a system's elements are organized or interrelated. The structure of an organization, for example, could include not only the organizational chart but also information flows, interpersonal interactions and relationships, rules and procedures, authorities and approval levels, process flows, routes, attitudes, reactions and the incentives and fears that cause them, corporate culture, and feedback loops." Here again, the meaning of the word "manner" is not clear. In addition, Monat and Gannon include some mental models and behaviors in their definition of structure.

Stillwell [10] argues, "when a pattern of transactions occurs over a period of time, it creates a structure that becomes the "cultural norm"—a climate of trust or mistrust. In a reinforcing process, our behaviors strengthen the cultural norm, which strengthens the behaviors, and so on." This definition argues that patterns cause a structure when, in fact, the Iceberg Model suggests that it is the other way around: structure causes patterns.

Spirkin [11] states, " ... ... When studying the content of an object, we enumerate its elements such as, for example, the parts of a certain organism. But we do not stop at that, we try to understand how these parts are coordinated and what is made up as a result, thus arriving at the structure of the object. Structure is the type of connection between the elements of a whole. It has its own internal dialectic. Wholeness must be composed in a certain way, its parts are always related to the whole. It is not simply a whole but a whole with internal divisions. Structure is a composite whole, or an internally organized content. ... ... Structure is an extremely abstract and formal concept. Structure implies not only the position of its elements in space but also their movement in time, their sequence and rhythm, the law of mutation of a process. So structure is actually the law or set of laws that determine a system's composition and functioning, its properties and stability." This definition alludes to the organizational relationships among system components and also the rules that govern the system's behavior. However, the meanings of "how" and "type" are not clear.

Karash [12] states that "structure is the network of relationships that creates behavior. The essence of structure is not in the things themselves but in the relationships of things. By its very nature, structure is difficult to see. As opposed to events and patterns, which are usually more observable, much of what we think of as structure is often hidden. We can witness traffic accidents, for example, but it's harder to observe the underlying structure that causes them." This definition argues that structure causes events and patterns and that structure is the nature of system component relationships. The meaning of "nature" is not clear.

Gharajedaghi [13] states that "Structure defines components and their relationships." This tells what structure does but does not elucidate what stricture is.

Mcnaughton [14] states that "The system structure or pattern of organization represents a logical model of the systems for the system-of-interest. This logical model is independent of any specific physical realization of any of the systems. This logical model may also be called a conceptual model of the system-of-interest." This definition equates the systemic structure to both a pattern of organization and a logical model.

Austin [15] says, "The structure of a system contains:

1. Components. Components are the operating parts of a system consisting of input, process, and output. Each system component may assume a variety of values to describe a system state.
2. Attributes. Attributes are the properties of the components in the system.
3. Relationships. Relationships are the links between the components and attributes."

This definition includes system components and their attributes as well as the component relationships.

Barile and Saviano [16] provide the following definitions:

1. "Structure: A set in which the elements are qualified as components recognized as having the capacity to contribute to perform specific functions (necessary to carrying out specific roles in the context of an emerging system). The components can be put in relation respecting specific constraints (rules).
2. Actual structure: Set of physical, concrete components, with a known function provided with a connecting mechanism or linker device predisposed for linking up other components."

This definition purports that systemic structure is the physical system components and the mechanisms that interconnect them; however the nature of the connecting mechanism is not specified.

Anderson and Johnson [17] ask, " ... what is structure, exactly? The concept is difficult to describe. In simplest terms, structure is the overall way in which the system components are interrelated—the organization of the system. Because structure is defined by the *interrelationships* of a system's parts, and not the parts themselves, structure is invisible." They further state that "Thinking at the structural level means thinking in terms of causal connections. *It is the structural level that holds the key to lasting, high-leverage change*." This definition notes that structure involves cause-and-effect relationships among system components.

Senge [18] says, " ... the structural explanation ... focuses on answering the question, "What causes the patterns of behavior?" In the beer game, a structural explanation must show how orders placed, shipments, and inventory interact to generate the observed patterns of instability and amplification ... ... structure produces behavior ... ... structure in human systems includes the "operating policies" of the decision makers in the system ... structures are made up of beliefs and assumptions, established practices, skills and capabilities, networks of relationships, and awareness and sensibilities—-in other words, the elements of the deep learning cycle." This definition notes that structure causes behavior patterns and that it comprises an array of concepts from beliefs to skills to practices to sensibilities. Later, Senge says, "In human systems, structure includes how people make decisions—the "operating policies" whereby we translate perceptions, goals, rules, and norms into actions."

Stroh [19] says that " ... systems structure includes tangible elements such as pressures, policies, and power dynamics that shape performance. It also includes intangible forces such as perceptions (what people believe or assume to be true about the system) and purpose (the actual versus espoused intentions that drive people's behavior)."

Cabrera and Cabrera [20] describe "structure" in a variety of ways, ranging from "patterns" to "simple rules that a thing follows" to "grammar and syntax" to "hidden contextual structure that contributes to meaning" to the physical or geometric relationships among system components.

Cabrera et al. [21] argue that "structure" is

- Action-reaction relationships,
- Feedback loops,
- Identity-other distinctions,
- Part-whole systems,
- Point-view perspectives,

Their empirical validation of the Distinctions-Systems-Relationship-Perspectives (DSRP) model of Systems Thinking is useful but does not fully clarify the meaning of "Structure."

A plot of the most common descriptors is presented in Figure 2.

Commonalities: Many of these "definitions" assume that the reader already has some concept of systemic structure and define it only obliquely. Most of them explain "structure" in terms of the relationship among system components. *Discrepancies*: However, some authors define "structure" as attitudes and perceptions while others define it as interlocking stocks, flows, and feedback loops, while still others define it as system component spatial position, motion, sequence, and mutation laws. Some resolution is required.

Different researchers have used a variety of diagrams and sketches to depict the systemic structure. Some of the common literature methods are listed in Table 1.

Table 1. The common methods of describing systemic structure.

Depiction Method	Type of Structure Described
Causal Loop Diagram	Cause-and-Effect
Stock-and-Flow Diagram	Cause-and-Effect

Table 1. *Cont.*

Depiction Method	Type of Structure Described
Matrix (Incidence Matrix, N^2 Diagram, SV-3 System–System Matrix, System Interrelationship Matrix)	Varies: Physical, sequential, cause-and-effect
Process Flow Diagram	Process Flows
Hierarchy Diagram	Reporting, authority, control
Sequence Diagram	Sequential
Sketches of Physical Arrangement	Geometric

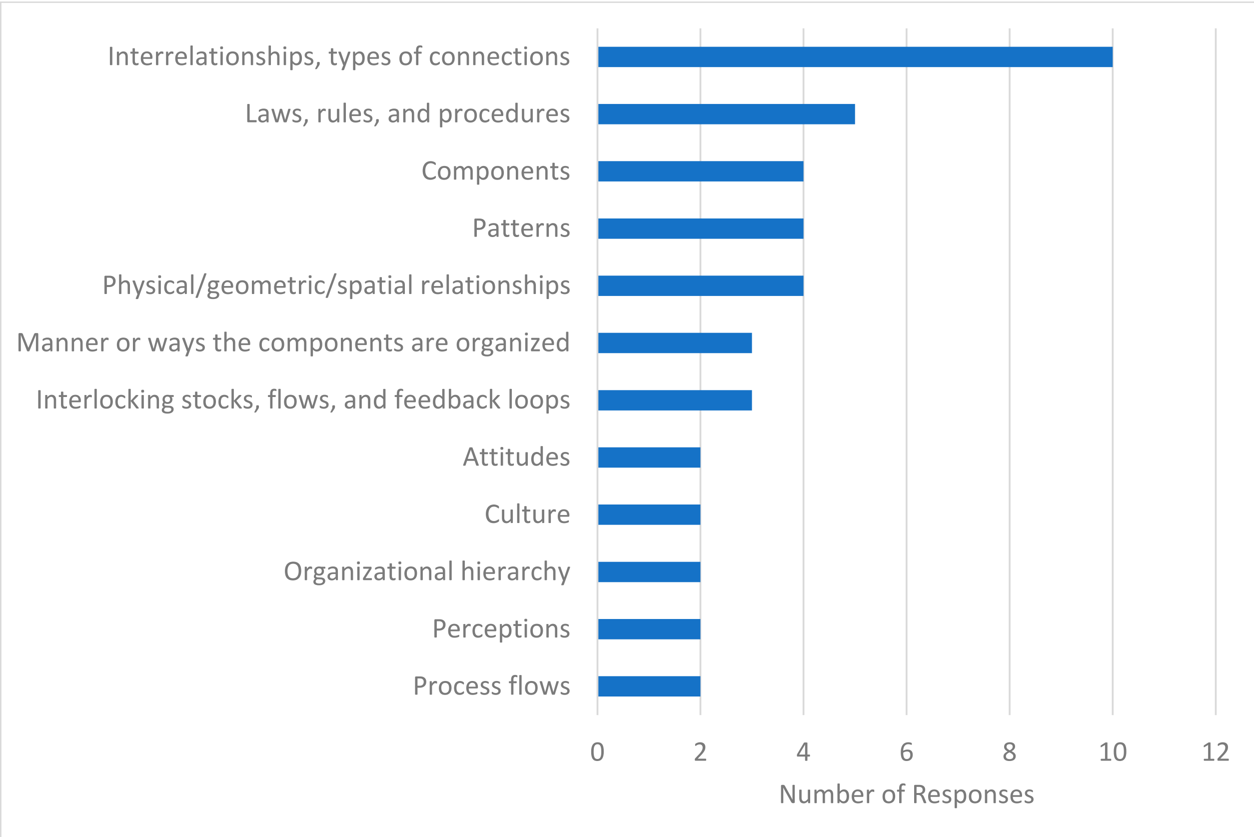

Figure 2. The most common literature descriptors of "Structure." (Only those that appeared two or more times are shown).

3. Discussion

3.1. Theoretical Underpinnings

Structure tends to be harder to understand as system complexity increases. Some researchers [22–26] who embrace the distinctions among simple, complicated, complex, complex adaptive, and chaotic systems argue that one can only perceive cause-and-effect retrospectively or even that there is no relationship between cause and effect (see Table 2).

We find these arguments misleading, and not all authors agree with these system complexity distinctions. Although it may be very hard to model or predict the full system behavior (especially emergence) in complex adaptive systems, one can often glean important insights by studying the cause-and-effect relationships in various portions of the system; structure still exists. In a complex adaptive system such as a termite colony, for example, although one may not be able to predict all systemic emergent properties, research has elucidated the cause-and-effect between pheromone-impregnated soil pellets and attractiveness, yielding a reinforcing feedback loop that eventually results in a six-foot tall termite mound. Senge, Meadows, and Monat and Gannon [27] present many additional examples of cause-and-effect relationships and structure in complex systems. Senge, for example, says that " ... a fundamental characteristic of complex human systems: cause and effect are often separated in time and space." Senge also refers to "dynamic complexity" in which cause and effect exist, but are subtle. Meadows says that "Systems theorists used to think that self-organization was such a complex property of systems that it could never be understood ... ... New discoveries, however, suggest that just a few simple organizing principles can lead to wildly diverse self-organizing structures." Monat and Gannon [27] identify nine cause-and-effect structures within the complex adaptive system of a large corporation. Holland [26] talks extensively about rules-based structure in complex adaptive systems. Thus, as system complexity increases, the cause-and-effect may become more inscrutable, but structure still exists. (In truly chaotic systems, we suspect that the cause-and-effect relationships exist but are simply too numerous and intertwined to make sense. In this case, it may be more useful to think of the problem from a statistical mechanics perspective than a cause-and-effect structural perspective.) As complexity increases, so does the uncertainty and lack of predictability. However, whether the precise systemic cause-and-effect relationships are known or unknown, subtle or obvious, or separated in time and space, in our opinion the definition of "structure" should remain the same across the various levels of system complexity.

Table 2. The levels of system complexity as described by Stacey's Complexity Matrix and Snowden's Cynefin model.

System Complexity	Explanation
Simple	Clear relationship between cause and effect
Complicated	Several well-defined relationships between cause and effect
Complex, Complex Adaptive	Exact cause-and-effect relationships are unknown and possibly unknowable; or may be perceived only retrospectively
Chaotic	No cause-and-effect relationships or relationships are unclear

With so many disparate and nebulous definitions of systemic structure, it would be useful to develop a crisp definition that can be easily applied to the analysis and understanding of systems. We may start this development by identifying several widely-accepted Systems Thinking tenets.

<u>Tenet 1</u>: "Structure" must link *underlying forces* (either mental models in human-designed systems or natural forces such as gravity and electromagnetism in natural systems) to *patterns* as shown in the Iceberg Model (Figure 1)—that is, the structure must explain how underlying forces eventually result in systemic patterns [1,7,8,17,28,29].

<u>Tenet 2</u>: "Structure" involves a description of "the way" that or "the manner" in which system components interrelate [1,7,11,16,17]. The meanings of "the way" and "the manner," however, are not clear, as some references mention physical or geometric relationships while other references cite sequential, temporal, or organizational relationships. A crisp definition of "structure" must clarify what is meant by "the way" that system components interrelate.

<u>Tenet 3</u>: Systemic "structure" must be consistent with and explain the shape of the system's Behavior-Over-Time (BOT) plots [1,8,29–34]. Indeed, it is frequently explicitly stated or inferred [7,8,12,17,34] that a system's BOT plots *reveal* its structure.

Therefore, bearing these fundamental tenets in mind, "structure" must describe how the system components interrelate, that is, the impact of each component on the other system components, in a way that explains how and why the systemic patterns arise. Clearly, the description of component interrelationships must be more than just spatial, hierarchical, temporal, sequential, or reporting, because those relationships do not fully explain the impact of one system component on another. To explain the impact of one component on another, one must understand the *cause-and-effect relationships* among the components.

A proposed definition that satisfies the three fundamental tenets described above is: In Systems Thinking, "structure" is the cause-and-effect manner in which the system components interrelate to yield the system behavior; and the rules, laws, protocols, procedures, policies, and incentives/rewards that govern those interactions. Exactly which components impact other components in cause-and-effect relationships may be depicted in either causal loop or stock-and-flow diagrams. However, to completely describe structure, we must show not only the component cause-and effect interrelationships in a causal loop diagram (CLD) or stock-and-flow diagram (S & F,) but also explain how and why those relationships exist, viz. the rules of interaction.

For example, for the case of a thermostat controlling room temperature, the causal loop diagram shown in Figure 3 is appropriate.

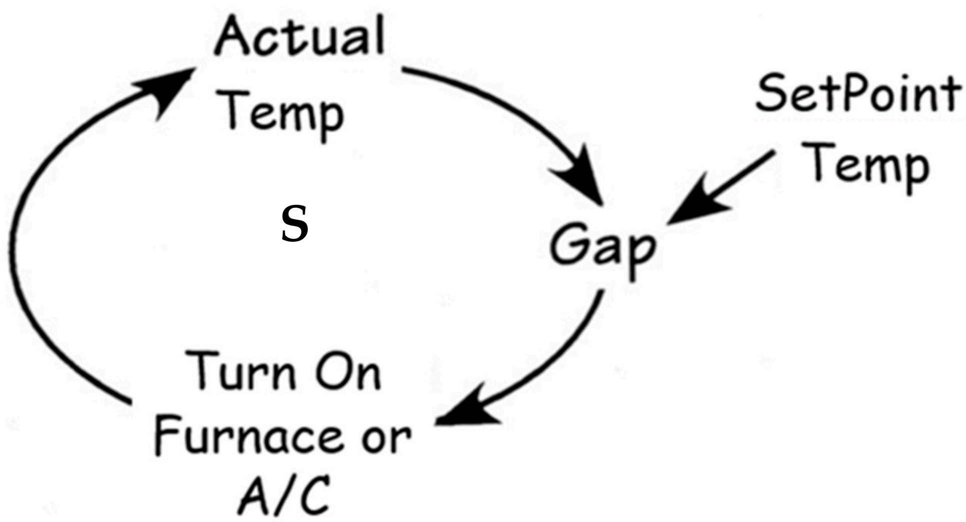

Figure 3. The furnace-thermostat causal loop diagram.

The CLD represents the first half of the description of the system's structure. To complete the description, we add the following *rules of interaction*: "The temperature Gap in the above CLD will cause a thermostat (which detects the gap) to turn the furnace on if the Actual Temperature is below the Setpoint Temperature; or it will cause the A/C to come on if the Actual Temperature is above the Setpoint Temperature. This causes the Actual Temperature to come closer to the Setpoint Temperature, reducing the gap and stabilizing the system." This description elucidates the *cause-and-effect relationships* among the system components and clearly relates the underlying forces (heat transfer and control via a boiler or an air conditioner, and a thermostat to control room temperature) to the observed pattern (a behavior-over-time plot would show the actual temperature smoothly asymptoting to the set-point temperature).

A full description of the systemic structure must include not only a CLD or stock-and-flow diagram, but also the rules, laws, protocols, procedures, policies, and incentives/rewards that govern the component interactions, because two different systems may have identical CLDs but be governed by different rules. For example, Figures 4 and 5 below show a CLD and stock-and-flow diagram, respectively, for population growth. These same diagrams are also accurate for the growth of a savings account, spread of a disease, spread of plant seeds, and the growth of ice thickness on a pond. Although the *rules of interaction* for the first three examples are all similar (stock growth rate = stock quantity $\times$ some efficiency factor) the rules of interaction for ice growth are different: stock growth rate = efficiency factor/(stock value.) The Behavior-Over-Time plots of the first three examples show an exponential growth (Figure 6) while that for ice thickness (Figure 7) displays a square-root dependence. Thus, a full description of the systemic structure must include the rules, laws, protocols, procedures, policies, and incentives/rewards that govern the component interactions, as well as either a CLD or stock-and-flow diagram.

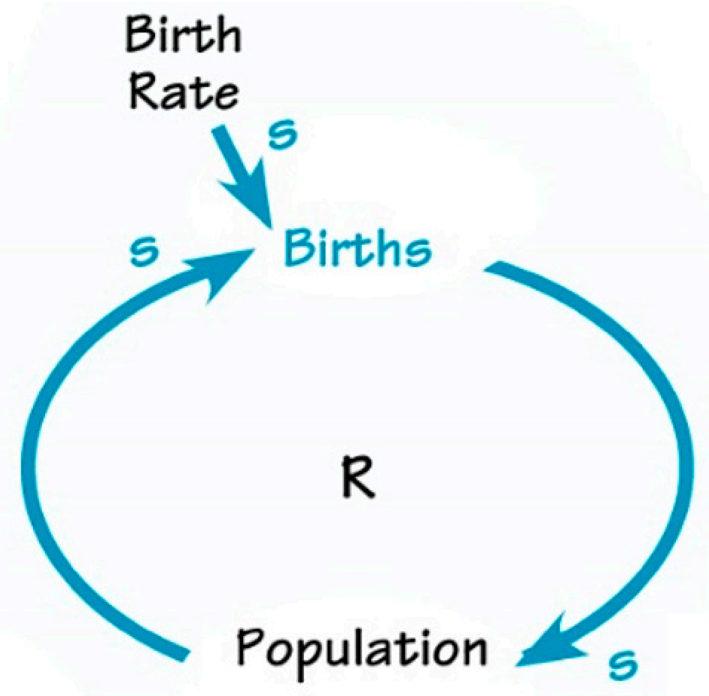

Figure 4. A CLD for population growth, savings growth, disease spread, seed dispersal, and ice thickness growth.

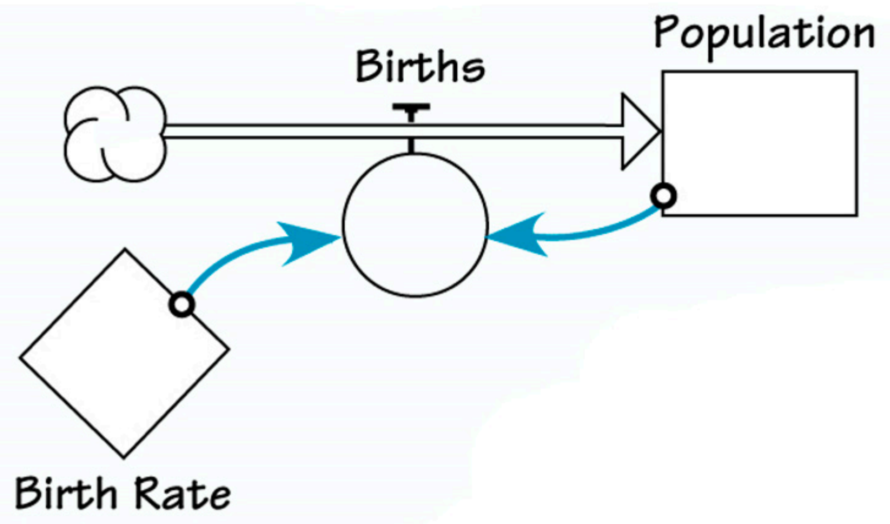

Figure 5. A stock-and-flow diagram for population growth, savings growth, disease spread, seed dispersal, and ice thickness growth.

Systems Thinking structure is **not** the architecture showing how a building, bridge, or spaceship is built as in Figure 8 (which shows the *geometric* relationships of the system components); the way that a poem or piece of music is configured as shown in Figure 9 (which shows the *sequential* relationships of the components); the *geometric* relationships of the planets in the solar system as shown in Figure 10; or the organizational structure of a corporation as shown in Figure 11 (which indicates *reporting* relationships). Although these conventional structures provide useful information, they do not show the *cause-and-effect relationships* among the system components.

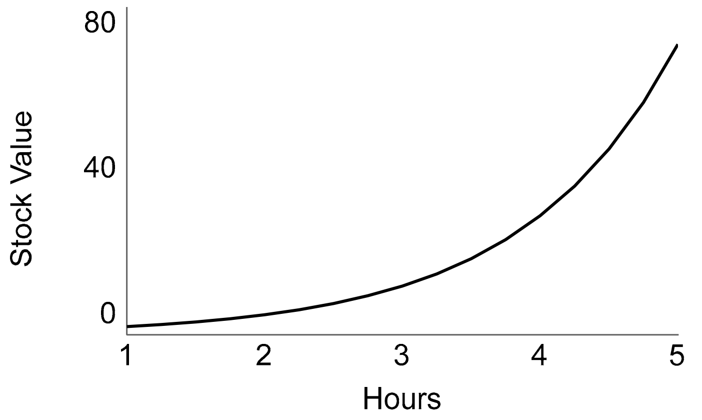

Figure 6. Exponential growth.

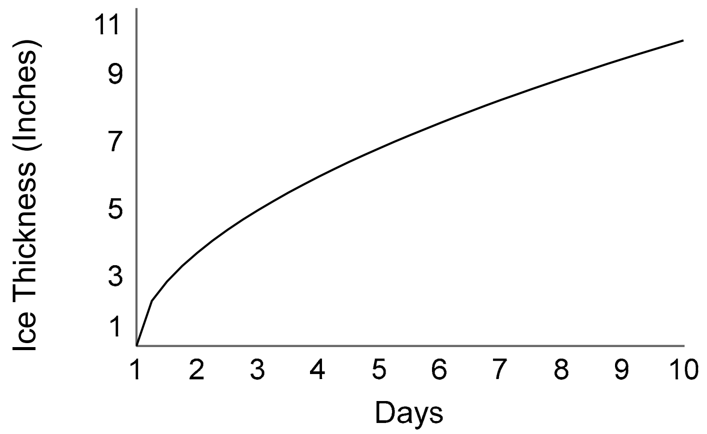

Figure 7. Square-Root Growth.

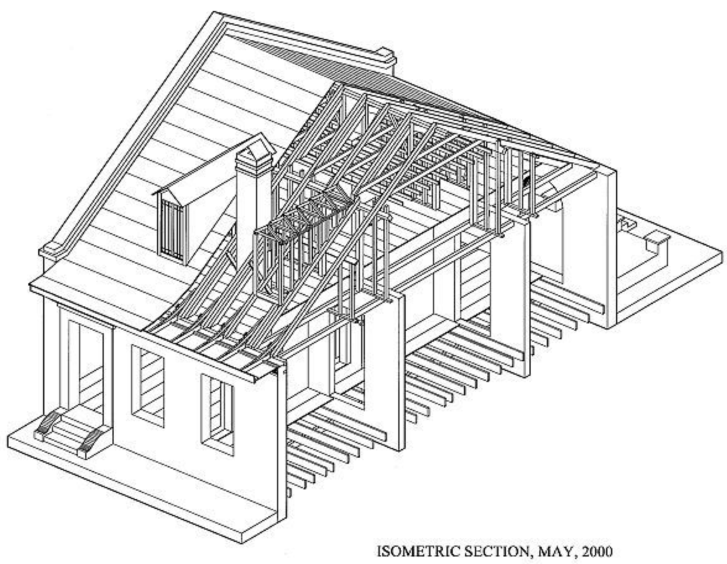

Figure 8. A house structure showing geometric relationships of components [35].

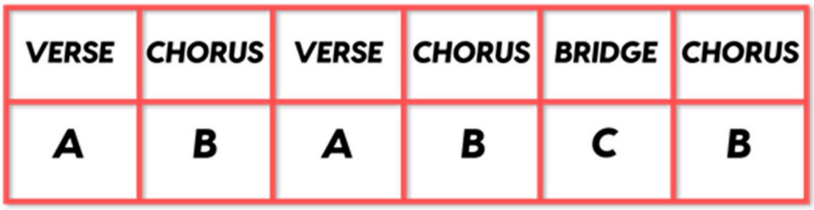

Figure 9. A song structure showing sequential relationships of components.

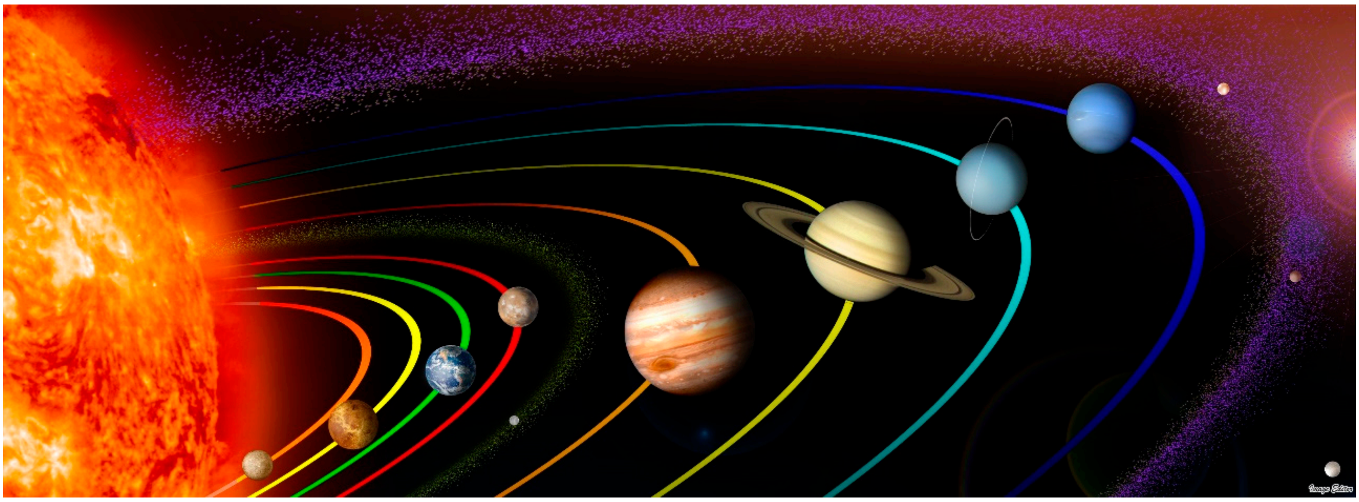

Figure 10. A solar system structure showing geometric relationships of components "The Solar System PIA 10231, mod 02, is licensed by Flickr under Creative Commons attribution 4.0 International CC by 4.0" [36].

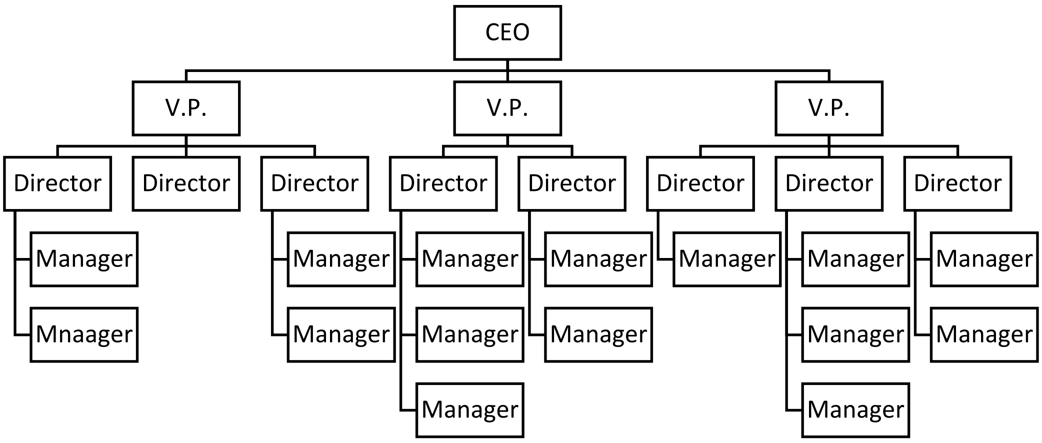

Figure 11. A corporate structure showing authority/reporting relationships of components.

3.2. How to Identify Systemic Structures

Several tools and techniques are available to help determine a system's structure. One approach is to draw a CLD and ask, "What is the cause and effect of one system component on another? What rules govern their relationships?" Another approach requires examination of the Iceberg Model for the system and asking what structure would link the underlying forces/mental models to patterns of the system behavior. One of the best ways to determine structure is to look at a BOT plot (which shows patterns) and ask, "What would cause that behavior?" It is well-known [7,8] for example, that exponentially increasing BOT plots indicate reinforcing feedback loops; Behavior-Over-Time plots that are steady or converge indicate stabilizing, balancing, or negative feedback loops; BOT plots that neither converge nor diverge indicate ineffective or absent feedback loops; and that BOT plots that oscillate indicate feedback loops with delays (Figures 12–15).

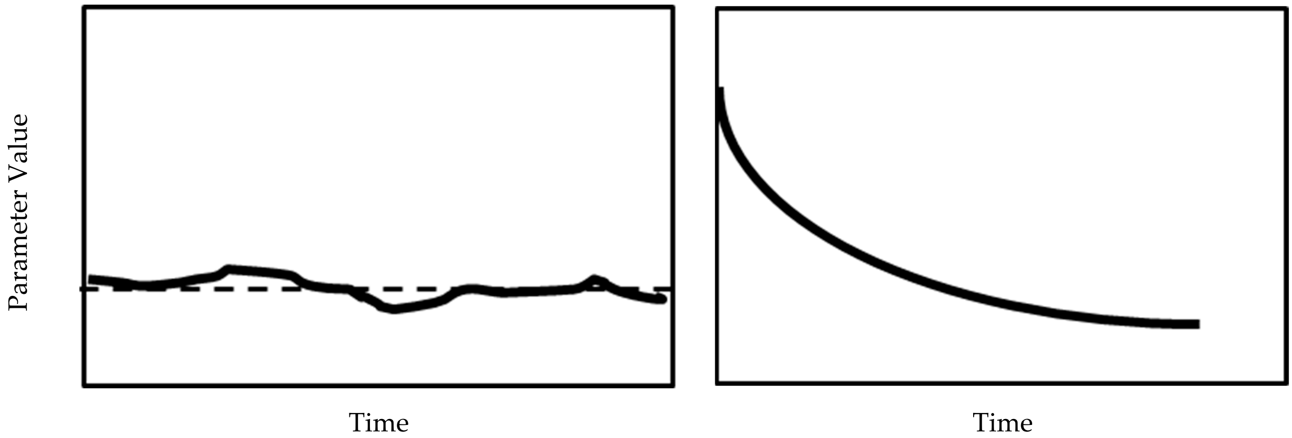

Figure 12. Behavior-Over-Time plots that are steady or converge indicate stabilizing, balancing, or negative feedback loops.

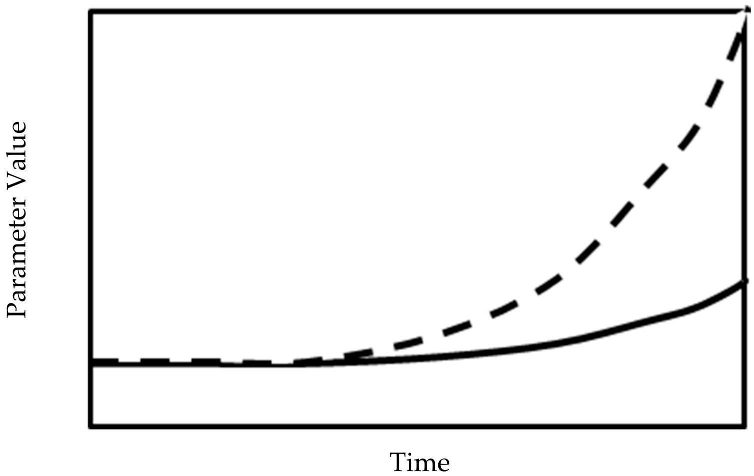

Figure 13. Behavior-Over-Time plots that diverge over time indicate reinforcing or positive feedback loops.

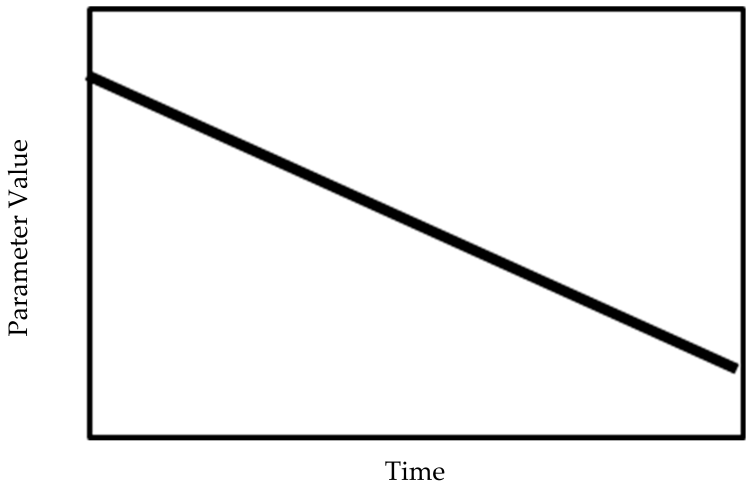

Figure 14. Behavior-Over-Time plots that neither converge nor diverge indicate ineffective or absent feedback loops.

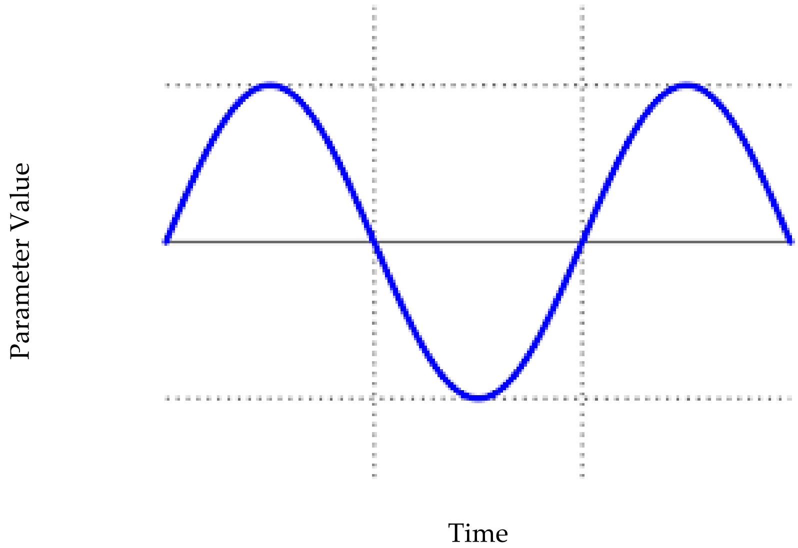

Figure 15. Behavior-Over-Time plots that oscillate indicate feedback loops with delays.

Senge et al. [8] provide several additional common BOT plots that may be used to infer the structure. Thus the system's BOT plot provides excellent clues regarding the systemic structure.

3.3. *Examples*

The Iceberg Model is a convenient construct within which to provide examples of the systemic structure; it shows how the structure is caused by underlying forces and how structure yields patterns. In this section we provide examples of structure in natural systems, human-designed systems, and business systems.

Example 1. *Structure in Natural Systems: The Spiral Pattern of Scales on a Pine Cone*

The Pattern: Spirals of scales in two directions on pine cones (Figure 16)

Figure 16. The spiral scale patterns on a pine cone. The oscillation suggests a feedback loop with delays.

Underlying Forces: The physical/chemical responses to growth hormone concentration.
The Structure:
(a) The causal loop diagram (CLD; Figure 17):

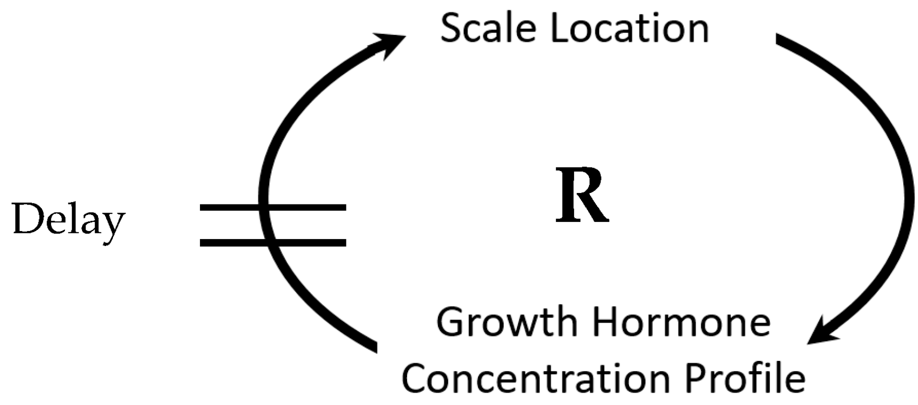

Figure 17. A pine cone CLD showing the structure. The scale location impacts the local concentration of the growth hormone; the local concentration of the growth hormone impacts the scale location in a reinforcing feedback loop.

(b) The Rules of Interaction: New buds form around the meristem where there is the highest concentration of growth hormone. However, when a new bud forms, the growth hormone is depleted at that site so that the next bud will form far from the previous bud. The radial growth outward from the meristem along with the growth hormone concentration profile results in a new flake forming at a fixed angle from each previous flake. The net result is a spiral.

Example 2. *Structure in Human-Designed Systems: Individual Weight Control*

The Pattern: An individual's weight oscillates around some fixed value (Figure 18).

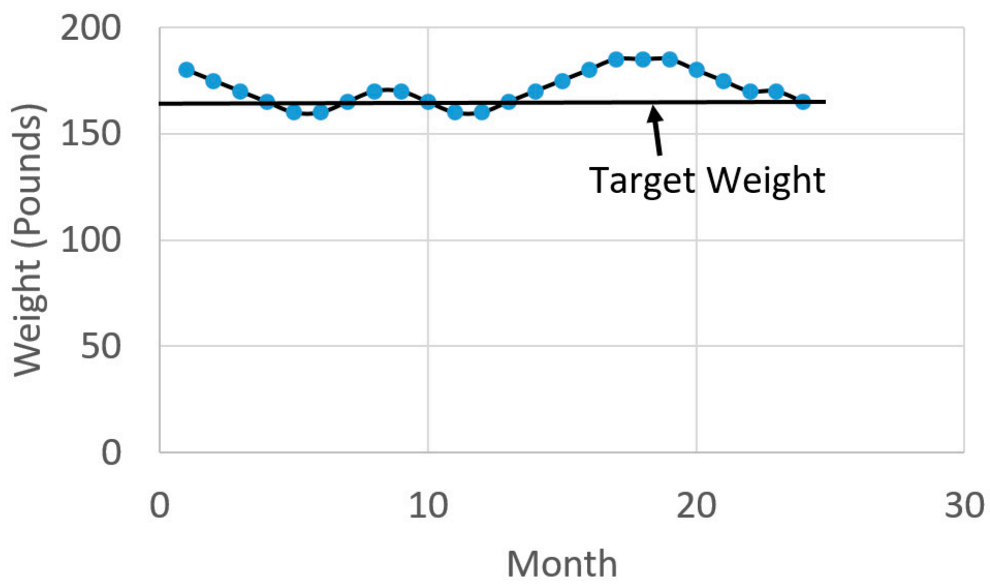

Figure 18. A behavior over time graph showing an individual's weight oscillation around a target weight. The curve suggests a stabilizing feedback loop with delays.

Underlying Forces: The belief that there is an ideal weight with respect to health, appearance, and well-being (a mental model) and conservation of energy/mass principles (physical/chemical laws) relating to caloric consumption, eating, and exercise.

The Structure:

(a) The causal loop diagram (CLD; Figure 19):

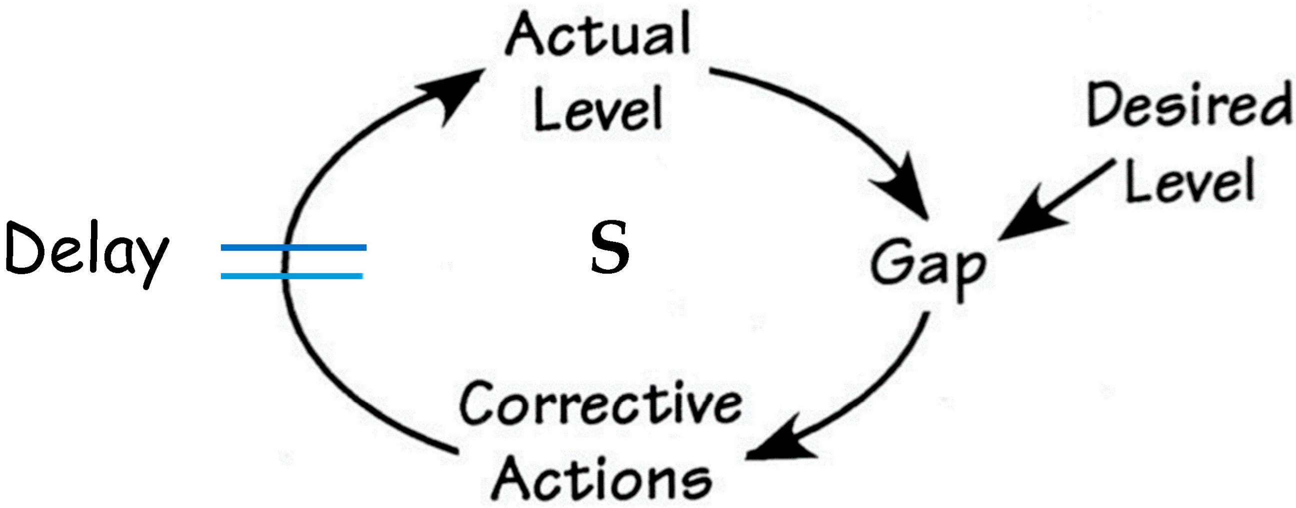

Figure 19. An individual's weight control CLD showing the structure.

(b) The Rules of Interaction: When an individual's actual weight differs from his desired ideal weight, he will adjust his food consumption and exercise level to bring his weight closer to the ideal. The delay between corrective actions and results yields an oscillation.

Example 3. *Structure in Business Systems:*

The Pattern: The exponential growth in sales of a capacity-limited product as shown in the BOT plot of Figure 20.

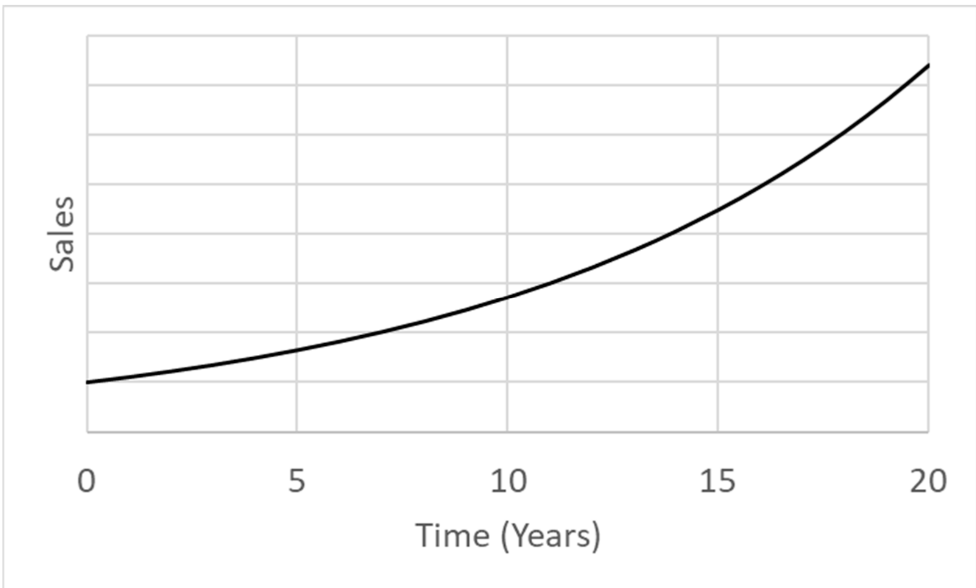

Figure 20. The exponential sales growth due to reinvestment of profits. The exponential growth suggests a reinforcing feedback loop.

Underlying Forces (Mental Models): If the product demand is so high that sales are limited by the production capacity, then increasing the capacity will increase sales. However, it costs money to increase production.

The Structure:

(a) The causal loop diagram (CLD; Figure 21):

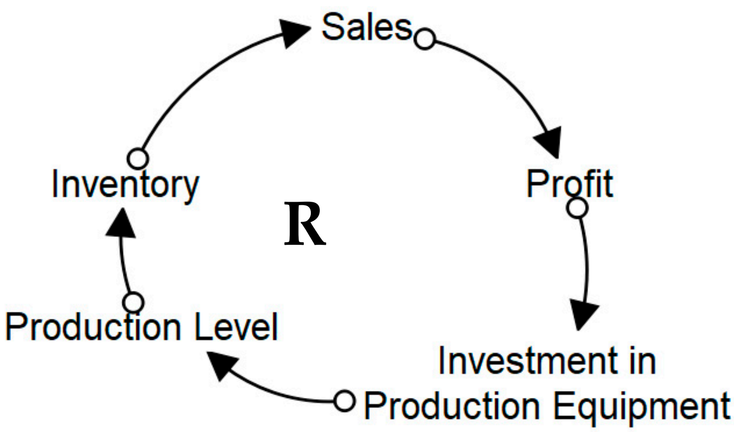

Figure 21. The sales growth in a capacity-limited production environment.

(b) The Rules of Interaction: The profit that is generated by sales is reinvested into additional production equipment, which increases the volume produced and thus the inventory of finished goods on hand. This allows an increase in sales. The assumption is that the demand is so high that whatever is produced will be sold.

We stress that rules, policies, procedures, protocols, and laws, whether natural or man-made, and whether overtly articulated or unspoken, often explain the cause-and-effect relationships among system components; they therefore are very often components of the systemic structure. In man-made systems, rules, policies, and procedures are often specified in company handbooks or similar policy manuals. However, some rules remain unspoken, such as the common knowledge that you do not bother the director on Monday mornings, or that you do not arrive late to the V. P.'s meetings, or that you do not take the last of the water in the cooler without replacing the jug. In natural systems, the natural "laws" exist whether they have been articulated by humans or not; they still govern cause-and-effect system component relationships.

4. Conclusions and Future Work

It seems that there is good agreement on the importance of "structure" in Systems Thinking, yet little agreement on the meaning of structure. Some experts argue that structure is the type or way that system components interact but do not specify what they mean by "type" or "way." Other researchers suggest that structure is the laws and rules governing system components interactions. Still, others argue that structure is the physical components themselves. Most experts agree that structure is somehow involved with causality, although some argue that cause-and-effect may not be knowable in complex or chaotic systems. We believe that in Systems Thinking, "structure" is the *cause-and-effect* manner in which system components interrelate to yield the system behavior; and the rules, laws, protocols, procedures, policies, and incentives/rewards that govern those interactions. This definition has a sound theoretical basis and should prove useful to researchers, practitioners, and academics who are trying to both develop and understand systems. An empirical study validating this definition would be of great value to the Systems Thinking community. In addition, future research on the distinctions among structure in simple, complicated, complex, and chaotic systems would be beneficial.

Author Contributions: Both authors contributed to all aspects of this paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not Applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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