

Evolution and Behavior of System Structure: Eight Perspectives for Examining Complex Issues

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Abstract

Quantitative models based on systems thinking and system science are routinely used to explore and anticipate the likely behavior of broad and highly complex issues and problems. While such models can provide valuable insights, they are invariably simplistic and frequently face controversy in both structure and quantitative details. The end result is that, while they may prove valuable in understanding the dynamics of the system, their value in understanding the evolutionary and behavioral tendencies of the system may be quite limited. A qualitative approach based upon structural perspectives can suggest tendencies beyond the scope of quantitative models. This paper presents eight interrelated perspectives for examining a complex issue or problem and for inferring potential evolutionary tendencies or behavior based upon the structural characteristics of the system under study. Experience suggests these perspectives may be useful not only in dealing with qualitative system models, but also in validating and troubleshooting quantitative models.

Good system dynamic models contribute to deep understanding of an issue or topic and offer insight to those striving to understand systems or remediate problems. The literature of system dynamics work predominantly focuses on the current situation and near-term forecasts, where quantitative system dynamic models can be particularly accurate and useful. As the time-horizon for understanding the system is extended, the validity of models (system dynamics or otherwise) invariably decreases due to omitted information and mechanisms. In order to build models that are more useful, John Sterman suggests "...modelers must also take care to search for and include in their models the feedback loops, and structures that have not been important in generating dynamics to date but that may become active as the system evolves" (Sterman 2000).

As a long-range planning consultant, a practitioner of system dynamics, and a student in foresight and studies of the future the author routinely addresses longer-term issues and problems where quantitative modeling is difficult, controversial, sometimes arbitrary, and possibly futile. The author's research into model failure (Forrest 2001) and work in qualitative structural system modeling suggest that examining systems from a series of perspectives can provide valuable insights into the evolutionary and behavioral

tendencies of systems¹. These insights can suggest likely areas for shifting systems structural features, provide logic for testing and validating both qualitative and quantitative models, and serve as points for initiating and refining scenario planning alternatives.

This article presents a series of individual perspectives for examining systems and system behavior, highlights the relationship between the perspectives, and presents several brief examples of using these perspectives to address issues. These perspectives are derived from six fundamental concepts espoused in a number of academic disciplines:

1. Stocks drive systems (System Dynamics)
2. Feedback Loops serve as long-term (or primary) drivers of systems and provide leverage for influencing the behavior of a system (System Dynamics, Electrical Engineering).
3. System structure influences system behavior (System Dynamics, the work of Michel Godet)
4. System structure patterns and evolutionary tendencies are a function of the maturity of the system (Biology, Ecology and Biochemistry)
5. The dynamic equilibrium of an evolutionary system is a function of the stability of the both the system and its environment (Evolutionary Ecology)
6. Fitness in a fitness landscape and the resultant pattern of possible evolution is a function of the level of complexity of the landscape which is influenced by the complexity of the fitness function – the number of factors determining fitness, or in other words, the interconnectedness of fitness (Mathematical Biology and Self Organization)

The derived perspectives provide insight into potential behavior that informs the other perspectives, creating a cohesive framework for inferring behavioral and evolutionary tendencies. This paper focuses on introducing the framework of perspectives and their implications, not justifying the perspectives. Readers are referred to the references for details regarding the perspectives and their underlying logic.

Many of the interpretations and perspectives presented in this paper will be familiar to experienced systems thinkers but the interrelationships may not. A comprehensive approach to the perspectives is taken to provide closure and to insure less experienced readers do not overlook important insights that are available from applying systems thinking. The key interpretations are based on observations from system dynamics combined with quantitative research from a range of fields related to network and system structures. Applying these perspectives demands mental gymnastics as one zooms from macro- to micro- perspectives, from identified causalities to externalities, from

¹ Evolutionary and behavioral tendencies as used in this paper refer to the shifting of the active system structure over time and the behavioral implications of that shifting structure.

aggregated flows to flow networks, from implicit assumptions to external uncertainties, and from the rigorous stock-flow logic of system dynamics to intuition. Experience suggests that individuals having substantial systems experience are likely to be more adroit at the making these leaps. As in other qualitative approaches to systems thinking, experience with stock-flow thinking contributes rigor to the process.

Eight Qualitative System Perspectives²

This section identifies eight perspectives for identifying system characteristics and tendencies. The following section will show how these perspectives inform each other to create a cohesive logic for inferring likely patterns of system behavior and evolution.

System Maturity and Phases of System Evolution

While the concept of stability is frequently encountered in the literature of system dynamics, the concept of system maturity is not. Though stability and maturity may be related to some extent, the concept of maturity carries broader implications characterizing the behavior of the system. System maturity is a common topic in the fields of biology, ecology, and ecological evolution and is associated with both behavioral and evolutionary tendencies of systems. A recommended first step in addressing a system is a simple assessment of maturity (Troncale 2000). That initial perception is subsequently augmented and tested as one identifies more precisely the current evolutionary phase of the system.

A preliminary assessment of system maturity is a judgment based upon a combination of historical and current perceptions. The answers to several simple questions guide this assessment and provide a series of snapshots, creating a preliminary perception of functional maturity of the system under consideration:³

- How old is the system? (Or conversely, how maturely does the system behave?)
- Has the system operated through many feedback cycles?
- Does the system seem to be relatively stable?
- How does the structure seem to be changing?
- Is the system richly, or sparsely interconnected?
- Does the number of interconnections seem to be growing or declining?

The author does not suggest specific criteria for determining system maturity as the precise nature of maturity has some variation from discipline to discipline. The judgments suggested are intuitive and benefit from experience in system analysis and with similar systems. The goal for this preliminary perspective is to serve as a platform for elaboration and testing with subsequent concepts and perspectives.

² While some of these perspectives have quantitative application they are included for their usefulness in assessing qualitative models.

³ These questions are deliberately fuzzy to some extent. The sophistication of the answers and the perceptions of the viewer can be expected to vary depending upon the experience and predilections of the individual answering the questions. The cumulative response provides a basis for subsequent refinement. Overlaps and possible conflict of the questions is addressed in subsequent text.

Mature vs. Immature Systems.

An immature system will tend to be relatively young, having survived relatively few feedback cycles following its creation or a major disrupting event. Relationships in immature systems should be expected to be unstable and potentially erratic. Relationships within the system may seem somewhat chaotic and disorganized. One should expect new relationships to be created and tested and existing relationships to be modified or terminated. Whereas structure for immature systems should be expected to be transitory and evolutionary, the structure of mature systems should be relatively stable unless other factors are impacting on the system.

The results of an assessment of maturity can be dependent on the boundaries of the system being evaluated. A mature forest could conceivably have a constant number of trees in every age group. From a macro perspective the forest would be stable and mature. The constancy of numbers of older trees, however, requires the death of some trees as they age. At a local level, the death of a tree, the creation of a hole in the canopy, and the resulting competition to fill the void suggests a chaotic, immature system. Stability, or instability, alone is not an adequate basis for determining the maturity of a system.

Consistency between the state of maturity engendered by the questions and the perceived behavior of the system serves to validate the perceived level of maturity. Inconsistency between the behavior of a system and its apparent maturity suggests other factors are involved and invites further study.

A typical pattern of maturation involves early experimentation as new connections and combinations are explored and tested while searching for more efficient combinations. More mature systems should exhibit some level of efficiency and dynamic equilibrium as the system's age should have allowed many cycles of its various feedback loops and for parsing of system dependencies to a relatively efficient configuration. A mature system may experience structural change and shifting behavior, but one would directionally expect slower, more deliberate change than in less mature systems. Systems including longer period feedback loops should naturally be expected to take longer to display mature stability.

An Evolutionary Pattern for Systems

Evolutionary ecologists routinely speak of a cyclical pattern of ecological evolution consisting of four sequential phases (Ulanowicz 1997)⁴:

⁴ The following descriptions of the four phases generally follow the language and patterns of system evolution described by Robert E. Ulanowicz in the book Ecology, The Ascendent Perspective. Consistent patterns of system evolution are described by other evolutionary ecologists using similar language (Hollings 1986)(Golley 1974). Ulanowicz supports his analysis and description of the four phases with a cohesive analysis built on a combination of thermodynamics, information theory, ecosystem energetics, and complexity theory. Reading of Ulanowicz's book is highly recommended to those who wish to explore the quantitative logic underlying this paper.

- Growth
- Development
- Maturation
- Senescence.

Economists, sociologists, and futurists frequently speak of similar patterns of evolution though the details and character of the phases vary somewhat. Recognition of the current phase of growth of a system provides additional insight into the likely behavior of a system. Recognition of the evolutionary phase of a system sets expectations for not only the current behavior of the system but also provides a basis for anticipating future shifts in system behavior. The four evolutionary phases and their implications follow. A variety of graphical representations are used to describe the maturation cycle focusing on different facets of the process and using different words for the phases. Several cycles are illustrated at the end of this topic.

The Growth Phase. The growth phase typically begins immediately after a system undergoes a major destructive perturbation or when the system enters a new domain. Events initiating growth phases commonly include catastrophes, technological breakthroughs, physical relocation or expansion, and successful promotions. In the growth phase there is little competition and necessary resources are generally adequate or readily available. During the growth phase stocks typically display rapid or exponential growth (within the bounds of enabling resources). The growth phase extends from initiation to the inflection point on a typical S-curve growth pattern. During the growth phase actors in the system generally focus more on growth and opportunity – exploiting available resources – more than upon efficiency. The environment during the growth phase is often turbulent, encouraging the creation and exploitation of redundant paths and connections to support growth and maximize utilization of available resources or opportunities. Successful systems eventually encounter resource limitations and/or competition for resources leading to the development phase.

The Development Phase. During the development phase growth slows – typically as a result of declining resource availability, demand saturation, or growing competition. Declining resources encourage efficiency and actors within the system typically begin seeking efficiency by pruning less efficient and redundant flow paths, thereby reducing overhead. Progression from the growth phase through the development phase is typically slow and the transition from the growth phase to the development phase is usually more evident after the fact than during the transition. For systems displaying the familiar S-shape “growth” curves, the transition from the growth phase to the development phase would be associated with the inflection point in the growth curve. System dynamic models show that the inflection point for simple S-curve models having rapid feedback should be at the mid point between base level and the peak (or carrying capacity) of the S-curve. Delays in the feedback process allow overshoot and either oscillation or collapse depending upon the nature of the critical resource.

The Maturation Phase. In the maturation phase the system growth slows and often peaks as resource limitations, competition, and other factors combine to restrict growth. The path connections will have been pruned to the most efficient paths. The flow path

alternatives of the system are streamlined and redundancy minimized. Overheads are minimal as efficiency is maximized. The major system elements become tightly linked along specific paths, leading to a fragility or brittleness of the system, making it more susceptible to disturbances and disruptions.

Senescence. Events in senescence are highly dependent upon the nature of the system and its environment. In absence of a major disturbance or disruption, system throughput and activity may stabilize – i.e. the system structure will stabilize and cease to evolve. Competition may lead to slow decline. Eventually a disruption will usually stress an ecosystem beyond the level of possible accommodation by the highly efficient flow structure and the system will begin to decline. The speed of decline will vary with the nature of the disruption and the characteristics and fragility of the system. While generalizations about senescent systems are difficult, the behavior of a senescent system will range from stagnancy to death.

Graphical Representations of Maturation Cycles. Several of the graphical representations for the maturation cycle follow. The examples come from a variety of sources and key on different facets of the process. While the phases may be named differently from those above there is strong correlation to the phases described in this paper.

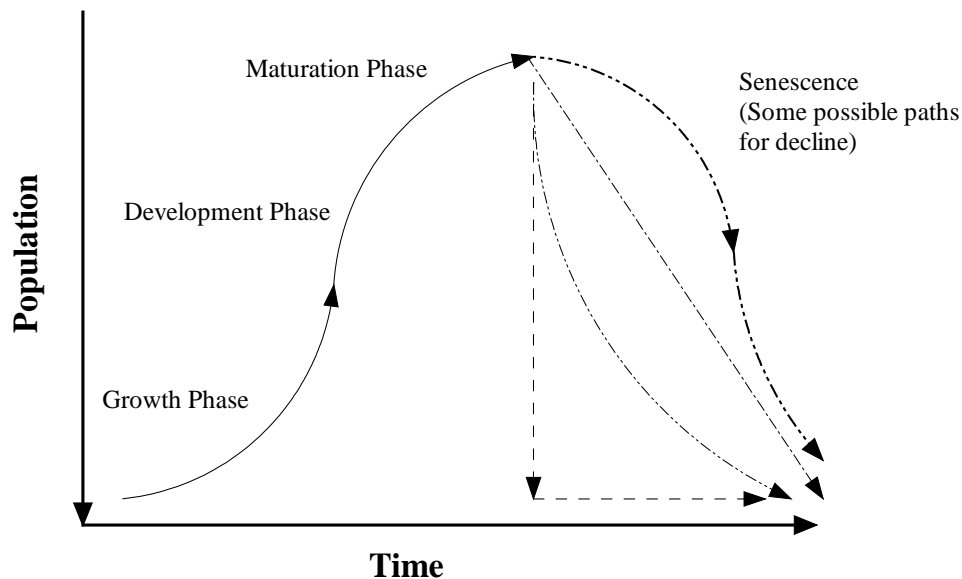


Figure 1. Development Phases for a typical S-Curve

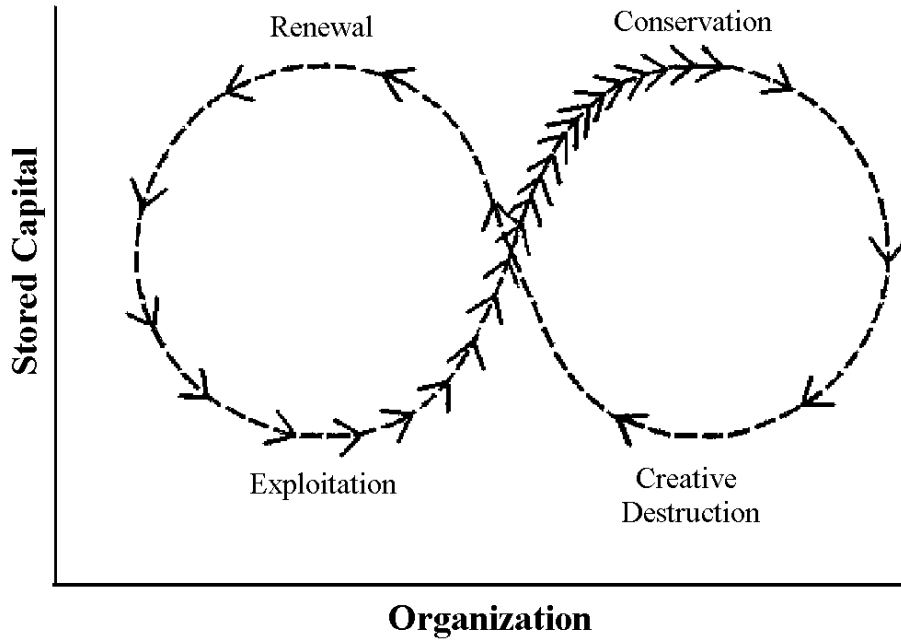


Figure 2. Hollings suggestion for how ecosystems progress through the cycle of renewal, exploitation, conservation, and creative destruction. The distance between successive arrows represents the relative speed of system evolution. Adopted from Ulanowicz (1997).

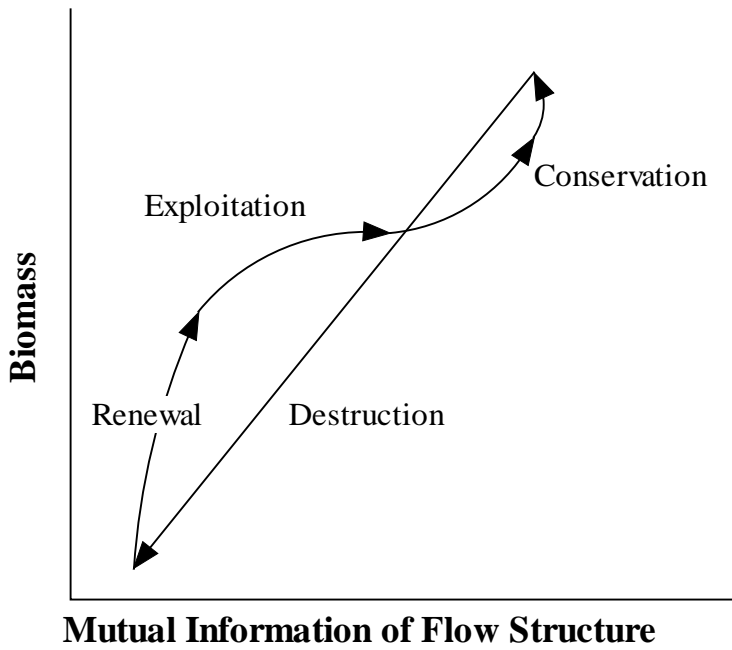


Figure 3 Ulanowicz's mutual information interpretation of Hollings model from Figure 2. (Used with permission.) The process moves increasingly slowly as through the process. Destruction is typically rapid.

Network Complexity and System Stability

Stuart Pimm (Pimm 1982) estimated that the number of effective connections⁵ per node in his collection of ecosystem food webs averaged about 3.1. The value of three arises again in the work of Wagensburg, Garcia, and Sole where they suggest a “magic value of about 3 bits per emitter [as] an actual upper limit to connectivity in real stationary ecosystems” (Wagensburg, Garcia et al. 1990)⁶. The potential significance of three is further reinforced by the work of Stuart Kauffman with Boolean networks of genetic transitions where he found that networks remain chaotic and unstable until the connections per node drop to about three or less, at which point the networks begin to exhibit spontaneous, unexpected collective order (Kauffman 1991). Ulanowicz uses a combination of Shannon diversity and information theory to calculate that the upper boundary limit for effective connections per node in stable systems is $e^{3/e}$, or about 3.15 (Ulanowicz 2002).

These works consistently suggest that flow systems having more than three effective connections per node will be unstable. Anecdotal evidence and preliminary research confirm that a nominal limit of 3 effective connections per node may have some level of validity in relatively mature and stable social and economic systems. In addition, preliminary market research suggests that markets having more than three effective suppliers will experience consolidation to approximately 3 or fewer effective suppliers. It reaches beyond current research conclusions, but we will assume for the purposes of this paper that immature systems having greater connectivity will be expected to organize to 3.2 or fewer effective connections⁷ per node as they mature.

Figure 4 shows effective connectivity from 41 ecosystem studies compiled by Robert Ulanowicz (Ulanowicz 2002). All of the studies show effective connectivity less than 3.15.

⁵ Effective connections are based upon a weighting of discrete connections based on the throughput of the highest flow. A supplier daily ordering 100 tires each from three different suppliers would have 3 effective connections. Another ordering 200 tires from one supplier, and 80 and 20 from others would have 1.5 effective connections.

⁶ The term stationary is used to systems displaying maturity and stability.

⁷ The terms effective connections, topological connectance, network connectivity, and average mutual information (in an information network) share common mathematical roots. Readers are referred to Ulanowicz’s book, [Ecology, The Ascendent Perspective](#) for mathematical details.

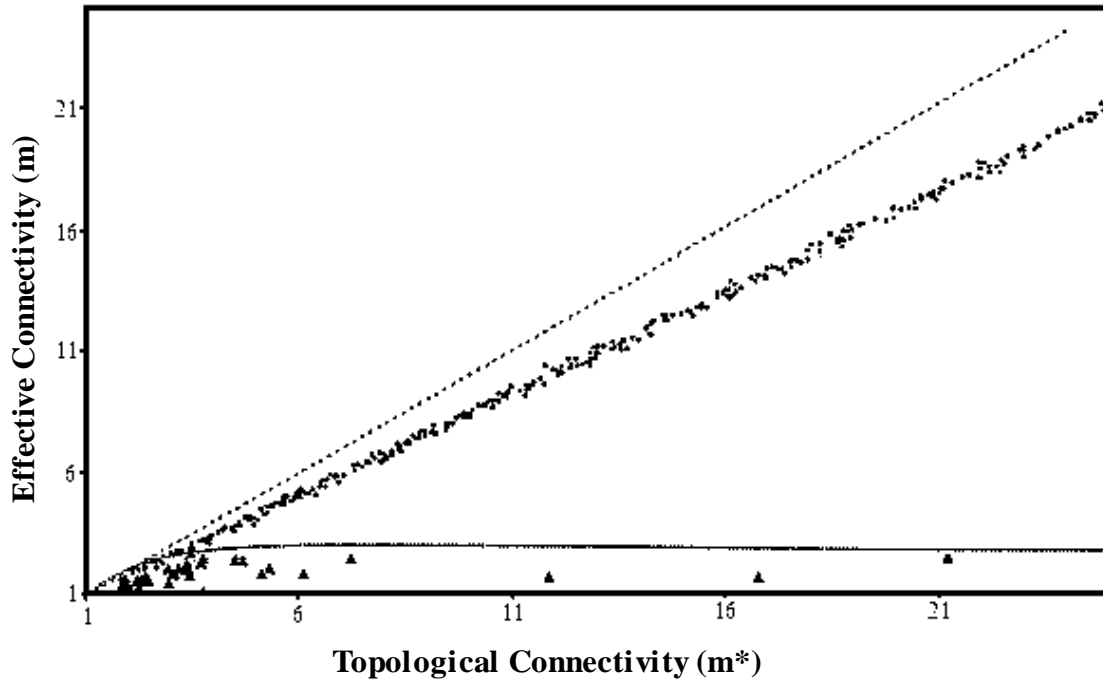


Figure 4. This graph copied from Robert Ulanowicz (2001) shows the effective connectivity and topological connectivity from 41 ecosystem studies as triangles. The dashed line separates infeasibility (effective connections cannot exceed topological connections) from feasible. The small dots reflect the effective connectivity of 359 randomly generated networks. The gray line at a value of approximately 3 marks the division between stable systems (below) and unstable systems (above). All ecosystem studies have an effective connectance of less than 3.15. (Reproduced with permission of Robert Ulanowicz.)

Figure 5 shows the number of effective U.S. automobile manufacturers from 1896 to 1970. In the early years many companies developed vehicles but sales were dominated by only a few. Between 1905 and 1910 the introduction of models led the number of effective manufacturers to exceed 3. During this period while the number of manufacturers were unstable, consolidation began with Buick, Cadillac, Oakland and Oldsmobile merging to form General Motors. By 1915 Henry Ford's inexpensive Model T acquired enough market share to bring the number of effective manufacturers back down to the stable range. But other manufacturers began to copy Ford's manufacturing, and production and increased competition reduced Ford's market share. The number of effective manufacturers rose to 3 but consolidation pulled the value back to the range of 2 to 2.5 where it stayed through the remainder of the period.

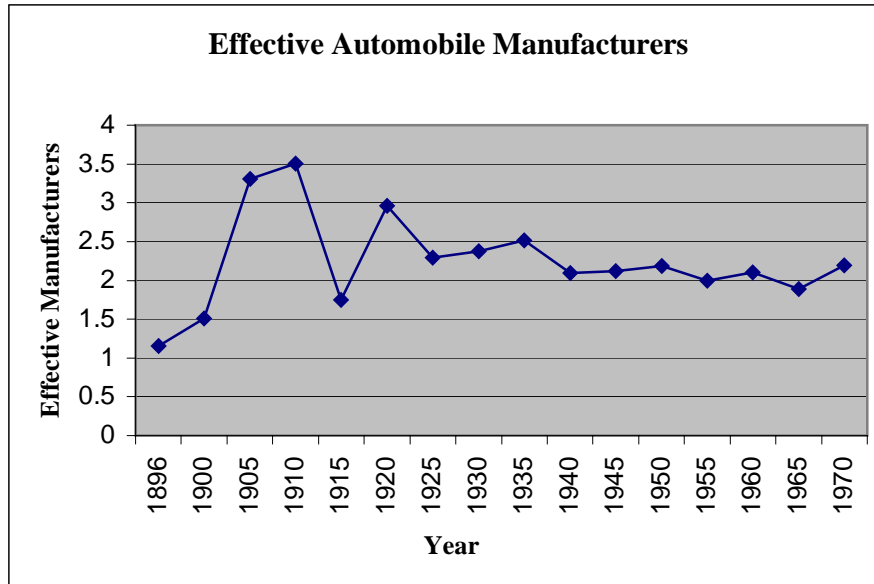


Figure 5. Profile of Effective Automobile Manufacturers in the United States.

In flow networks the strength of each flow connection is calculated relative to the largest flow and normalized such that the greatest flow has a value of 1. The number of effective connections is simply the sum of the normalized strengths of each flow.⁸ As a result if we know the total flow and the flow from the dominant source (or the percent from the major source) we can calculate the number of effective sources.⁹ The limit of 3.15 effective sources for a stable network suggests that within a stable network the dominant flow can have no less than 31.75 percent (1 divided by 3.15). Given that the methods in this paper are focused on perceived system structures rather than quantified flows, this value will be rounded off to 30 percent for the purposes of this paper.

Contemplating a system from the perspective of flow input diversity or connectivity provides a basis for anticipating future shifts in network density and a logic for anticipating which connections are likely to be pruned.

- Systems having more effective input flows than 3 (or conversely where the major flow constitutes less than 30 percent of the total) should be expected to be unstable.
- Systems having numerous effective input flows will evolve toward 3 or fewer.
- Systems will tend to prune input flows that are less efficient¹⁰ than the alternatives.

When visualizing the effective connectivity of a node, one should think in terms of units of approximate equivalency. In ecological studies the flow might be carbon, or calories,

⁸ A node receiving flows of 40, 30, and 30 units from three sources would have 2.5 effective connections ($40/40 + 30/40 + 30/40$) whereas a node receiving 80, 15, and 5 units from three sources would have 1.25 effective connections ($80/80 + 15/80 + 5/80$).

⁹ A node where 40 percent of the flow is from one source would have 2.5 effective connections.

¹⁰ The perceived efficiency of a source is a function of many possible factors: quality of the flowing material, usability of the flow material, overheads necessary to obtain or utilize that stream, and can, in human systems at least, be purely perceptual with no physical basis.

or a mineral. In economic systems the flow might be automobiles, dollars, or MM Btu of energy equivalent. Choosing an appropriate basis can be tricky. A fox, for example, may eat rabbits, mice, frogs, snakes, and birds. Clearly one rabbit is not equal to one frog. There is a quality or intensity of the flow that should be taken into account. Preliminary experience with this metric suggests that estimating the percentage of flow for the dominant flow is a good way to estimate the flow connectivity. The level of flow connectivity serves as a reference point for considering the environmental stability of the system and environment as described in the following topic.

Environmental Stability and Optimal Flow Connectivity

Evolutionary ecological studies have found that environmental stability has strong influence on the level of redundancy or overhead shown in ecosystem flow networks¹¹. Findings by theoretical ecologists working with flow networks reveal interesting relationships between the level of effective connectivity in mature systems and the stability of their external environments. These observations seem to have potential application to systems in general.

Sole sourcing in nature is rare, except in stable, highly consistent environments, such as rain forests where plants and animals sometimes develop single host relationships – where a flow network would show a single connection. Flow networks in ecosystems displaying less stability and more variation typically display more connections per node. A number of separate studies of different mid-western U.S. ecosystems all arrived at average connections per node ranging from approximately 3.0 to 3.19. The optimal connectivity in systems is clearly related to the level of turbulence.¹²

These insights provide a basis for modifying and informing perceptions from previous perspectives.

- Systems that display singular, sequential inputs exhibit behavior consistent with evolution in a relatively stable environment, display characteristics of being relatively mature, and are likely to be relatively fragile and more susceptible to environmental instabilities.
- Systems displaying a linear flow of singular inputs (an isolated chain) will be viable only in relatively stable, predictable environments.
- Changes in environmental stability will shift the optimal system structure. An increasingly stable environment will support streamlining of system structure and increasing system efficiencies, an increasingly unstable environment will favor increasing complexity of system structure (locate and secure new input flows and

¹¹ Flow networks trace the flow of energy, compounds, or elements through an ecosystem. Flow networks may be more detailed, less aggregated, and more complete than typical system dynamics models.

¹² The quantitative study of levels of turbulence – including metrics for environmental turbulence – and optimal connectivity is one of the author's research goals for the coming year.

stocks) in order to provide spare capacity and increased reliability of supply to offset increased uncertainty of supply related to environmental instability.¹³ Consideration of environmental turbulence – historic, current, and anticipated – provides a basis for modifying the behavior expected from previous characterizations and for projecting possible structural evolutionary tendencies.

Boundary Conditions and Instability

Examination of system boundaries is broadly recognized as an important step in validating system models. Emphasis within the field of system dynamics is typically on insuring important feedbacks are not omitted and that exogenous variables are identified and constraints recognized (Sterman 2000). Expanding the boundary evaluation to include environmental stability seems prudent in view of the previous section:

- How stable is the external environment?
- How is the stability of the external environment changing over time?

Instability directly or indirectly related to exogenous variables serves to flag variables as possible sources of environmental instability for the system under study. Examination of stocks related to those variables provides additional insight into potential instabilities. Perceptions of likely instability provide a basis for anticipating shifting connectivity patterns within the system.

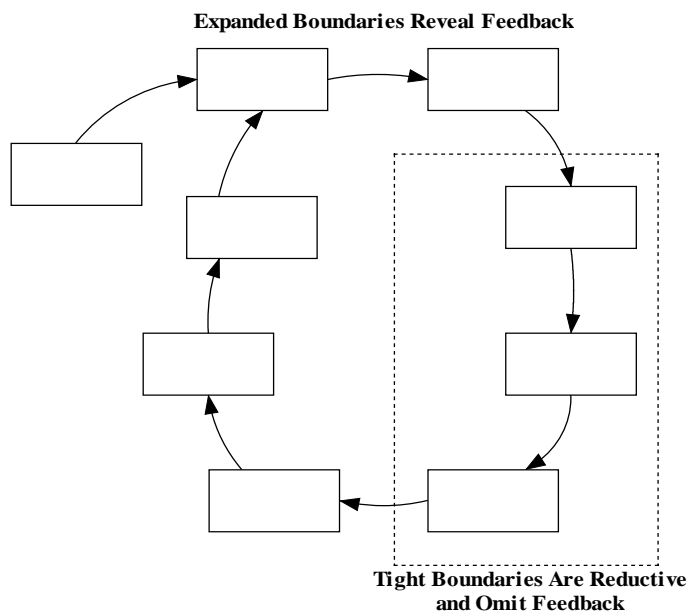


Figure 6. Model boundaries influence the recognition of feedback and potential sources of environmental instability.

¹³ Increased flow connections clearly provide increased capacity and reliability only to the extent that the new connections are independent.

Stocks and Flows

Stocks and flows are familiar to experienced system dynamicists but may need some explanation for some readers. Stocks are the accumulators in systems. Flows are actions. Stocks reflect what has happened historically – their levels are the product of history. Flows reflect present conditions. If we freeze time, stocks have a level and flows cease to exist. Recognizing stocks and flow elements in models provides insight into system characteristics. Stocks are particularly important for they drive models (Forrester 1971) and provide continuity through their persistence.

Rigor in stock/flow thinking is beneficial in avoiding traps inherent in interpreting causal models. Causal loop and influence diagrams used in qualitative system dynamics are frequently written such that the distinction of stocks and flows is not readily evident in the elements of the diagram.

Focusing on stocks, their vulnerabilities, and stability provides insight to the stability of the system. Flows provide the means by which stocks directly affect one another. Recognition of stocks is important for building a stock is typically a relatively slow process and contributes to the temporal character of a system's dynamics. Stocks frequently decline gradually as well, but are subject to sudden decline due to catastrophic events. Flows are typically much more variable than stocks. The permanence of stocks serves as a stabilizing factor in considering system dynamics and tends to create delays in linked system behaviors.

Fluency in recognizing stocks and flows in systems and in understanding the implications thereof is a skill that aids in analyzing system behavior. Recognition of persistence or vulnerability of stocks provides insight into likely stabilizers and destabilizers of future behavior.

The Concept of Enabling Stocks

Most system representations deal with only the most visible elements of the system. Hidden assets support or enable the existence of stocks and flows in system dynamic models and are referred to in this paper as enabling stocks. For example, in a stock-flow depiction of a water system, a flow of water could be enabled by a riverbed, a canal, a pipeline, and possibly pumps, depending upon the nature of the flow. A lake would be enabled by a dam and an impermeable bed. These enabling stocks are not typically shown in conventional systems models for they are not routinely involved in the dynamic behavior under study. Recognition of enabling stocks provides insight into potential vulnerabilities of the system and the reliability of these enabling stocks is important to the continuance of historical system behavior. Failure or instability of these stocks can shift the system into totally new behavior patterns.

A thorough review of enabling stocks requires looking at each flow and stock and asking, “What enabling stocks support this flow (or stock)?” and in turn for each enabling stock, “How stable and reliable is this stock and what are its vulnerabilities and limits?” This perspective provides an enhanced sense of the environmental stability of a system and a list of recognized candidates for wildcard events and possible turbulence.

In practice, the examination of every variable in a causal diagram for implied stocks and flows and those, in return, for implied enabling stocks, is likely to require more effort than is practical. A spot check of enabling stocks for those variables perceived as most important, vulnerable, or where instability is of concern seems prudent when examining the potential boundaries of the model. Sensitivity to the importance of enabling stocks also serves as a potential flag for problem areas during the development of both qualitative and quantitative system models.

Delays

Delays are powerful features in real-world systems and networks that are frequently minimally considered in qualitative systems models. Often all causalities are treated equally and shown as an arrow. Some practitioners indicate longer delays by putting a break in an arrow. Very long delays relative to the time frame of the model are frequently omitted either through lack of recognition or because they are deemed not pertinent to the time horizon of the model. Contemplation of delays and their impacts offers additional insights into possible behavior of the system under study. Recognition of delays – whether inherent, omitted, explicit, or hidden – and their potential magnitude and period provide a basis for considering the potential dynamics (and maturity) of the system. Discussing delays in detail is far beyond the scope of this paper and should be familiar to practitioners of system dynamics. Readers unfamiliar with the following concepts are referred to the book [Business Dynamics](#) (Sterman 2000) for an excellent overview of material and information delays and a discussion of variable vs. constant delay time periods.

A delay occurs when the output of a process lags the input. Delays permeate all systems via accumulations, processing, and information delays. Delay length often plays a role in deciding what causalities and relationships to include while setting system boundaries for a model.

All delays involve at least one stock with the nature of the delay depending upon the characteristics of the stock. Conveyors, ovens, and accumulating stocks all contribute different dynamics to downstream processes. Information delays result from the fact that it takes time to receive and process data and to subsequently act on that data. If information delays are relatively long, they may complicate recognition of system characteristics and causalities. Information delays can also interfere with system control and response, contributing to system instability. Variable delays will also influence the dynamics of a system and potentially aggravate instabilities.

Once again experience with system dynamic models proves very valuable to the qualitative modeler. Recognition of the delays in a model, the relative magnitudes of the

delays, the characteristics of the delays, and the implicit boundaries of the model with respect to delays provide insight into the levels of variability within the model and provides a basis for contemplating the boundaries of the model and for evaluating information about the systems behavior and for anticipating potential response and control issues.

Feedback Structures¹⁴

The concept of feedback structures is fundamental to system dynamics. Disturbances ripple through nonrecursive linear systems with no enduring influence on behavior. Feedback loops provide mechanisms for current conditions to influence future conditions and frequently to dominate long-term system behavior. Two important characteristics of feedback loops are their type – positive or negative – and delay period.

Short period feedback loops tend to be visible and dominate short-term behavior. Slower, longer-term feedback loops are frequently less visible as human perception of causality encounters difficulty in connecting cause and effect relationships that are separated in time and space (Senge 1990). Careful attention must be given to identifying longer-term feedback structures when addressing moderate- and longer-term topics and issues such as unintended consequences. Recognition of feedback structures suggests avenues for potential future behavioral departure from current trends. Recognition of the delay period of the feedback structure provides a basis for anticipating the temporal impacts of the feedback loop.

Characterization and recognition of a feedback loop as positive or negative is beneficial when possible, but is often difficult in highly complex systems where a long sequence of fuzzy and possibly interrelated webs of feedback are involved. Sterman states that ambiguity when identifying the polarity of causal links suggests that multiple conflicting causal paths are hidden within the arrow of causality and that they should be broken out until unambiguous polarity can be assigned to the causal arrow (Sterman 2000). This approach is helpful in clarifying causal loop structures and mechanisms. For causal diagrams where the polarities can be established one should expect to find several to many negative feedback loops for every positive feedback loop. Failure to offset positive feedback loops with negative feedback loops is a clear sign that the model is reductive and that potential mechanisms for future behavioral shifts have been excluded. Brainstorming of potential negative feedback loops provides a basis for identifying overlooked and potential mechanisms and thereby suggesting potential unintended consequences.

Focusing on feedback structures, their period, and their polarity provides insight to the overall dynamics of the system, a sense of the temporal dynamics of the system, a basis

¹⁴ Readers unfamiliar with feedback structures and feedback polarity are specifically referred to John Sterman's discussion of feedback and feedback polarity in [Business Dynamics](#).

for recognizing missing and potential elements and structures, and for considering unintended consequences.

Structural Dependency

When evaluating a system for robustness and for potential weaknesses, robustness will be maximized when flow sources (both stocks and enabling stocks) are fully independent. In practice, full independence is rare. Most sources share some attributes and dependencies that serve as potential vulnerabilities to the system. Items such as shared infrastructure (roads and electric power grids for example), common upstream sources, and technological standards create commonalities across sources that create multi-source vulnerability to singular events or shifts.

This perspective augments the perspective created by stocks, flows, and enabling stocks by encouraging recognition of the structural dependencies – the shared vulnerabilities – of the system. The perspective of structural dependency is based on a reductionist view of the stocks and flows, by burrowing down into their dependencies and recognizing shared dependencies across sources.

Fitness Complexity

The concept of macro-interdependency as used in this paper is related to the overall complexity of the dependencies of a node.¹⁵ Within this perspective the fitness of a node in a system will be a function of the number of dependencies of that actor. The fitness of a truly independent node would be fixed. The work of Stuart Kauffman with fitness landscapes shows that the nature of the fitness landscape – a map of fitness as a function of the condition of the dependent variables – and of the evolutionary alternatives available shift as the number of variables is increased. Nodes with relatively simple fitness formulas have large areas of high fitness (or viable possibilities) and the map is smooth. Evolution from low fitness to higher fitness is possible, as the smoothness of the fitness map allows incremental improvement toward the peak fitness. As the complexity of the fitness formula increases (i.e. the number of variables increase) the fitness map tends to be squeezed to a plane – the areas of high fitness shrink as more factors must be “good” for overall fitness to be high. And, perhaps more importantly, the fitness landscape becomes increasingly rough – with low peaks separated by cliffs and valleys. The roughness of complex fitness landscapes generally denies the ability to evolve incrementally toward high fitness as small increments of change generally only moves the actor toward a low, nearby peak or – if on the peak – off of a peak to a lower fitness. In such a landscape major mutations (major changes, new ideas) are the only viable method for escaping a local peak.

¹⁵ In contrast to flow connectivity, which focuses on singular items flowing to a node, the fitness complexity reflects the number of items flowing to (or needed by) the node. A node having greater numbers of needs will have a more complex fitness function and thereby a higher fitness complexity.

This perspective suggests three key insights for testing and informing other perspectives:

- Actors in systems displaying increasing interdependence can be expected to find it increasingly difficult to maintain fitness widely different from the average (as the fitness map squeezes toward a plane).
- Actors in systems displaying increasing interdependence are likely to become increasingly fragmented (due to the increasingly rough fitness landscape),
- Incremental progress or movement in an increasingly interdependent system should be expected to grow increasingly difficult and the need for drastic changes will grow (also related to the roughness of the fitness landscape)

Linking Qualitative System Perspectives

The perspectives described mutually inform each other to create a cohesive approach for anticipating behavioral and evolutionary tendencies of a system under study. This section presents an overview of the primary relationships among these perspectives. Space restrictions allow consideration of only the most obvious relationships. Experience and familiarity with the perspectives and their insights is likely to suggest more subtle relationships between the perspectives.

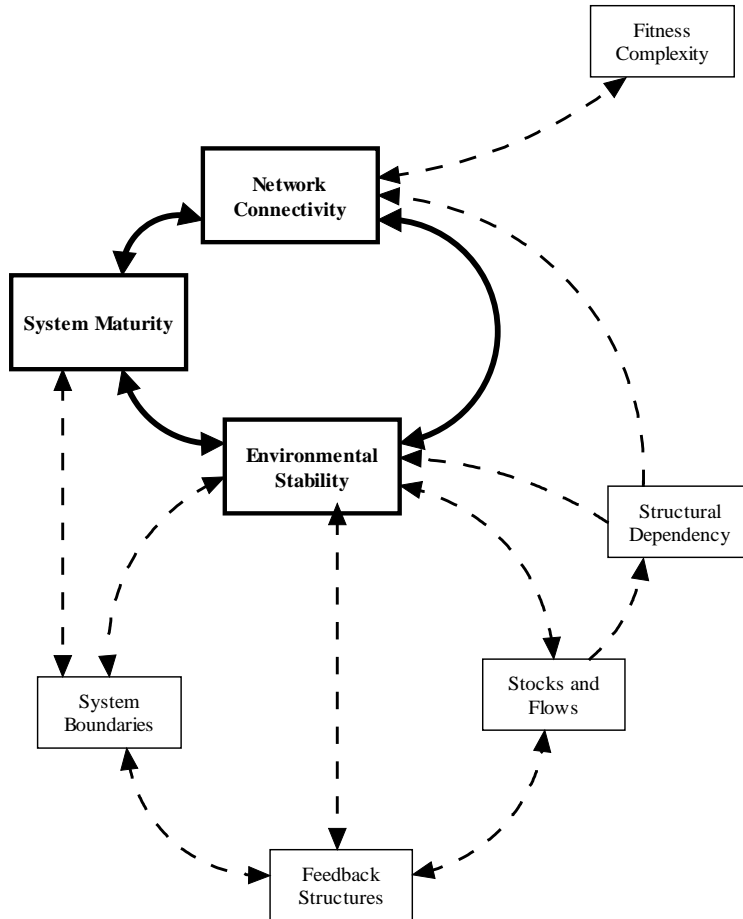


Figure 7. Proposed logic for linking system perspectives

The core logic of the proposed perspective approach to systems behavioral and evolutionary tendencies lies in the core relationships between perceived system maturity, environmental stability, and network connectivity. Observation provides insights and expectations with respect to the state of maturity of the system under study. Examination of the relationships within the system provides insight to the existing state of effective connectivity in the system. Perception of inconsistencies between the perceived maturity, existing connectivity, and current and historic environmental instability suggest further exploration and examination of the model are appropriate.

Consideration of the other perspectives informs the model definition and evaluation. For example, the model boundaries and feedback structures provide insight to the level of maturity and the possible nature of cyclic feedback phenomena on environmental stability. Examination of stocks and flows further contributes to the perception of environmental stability and provides insight to the structural dependency and the robustness of the system components. These in turn provide additional insight to the environmental stability and network connectivity of the system. Persistent inconsistencies in the perspectives may indicate that the system is in transition as changes in environmental factors are creating turbulence and structural stress and/or change.

Comparing environmental turbulence and network connectivity over the historical time has proven useful in resolving persistent inconsistencies.

Once the historic and current perspectives are understood, focus can shift forward to the future. Recognition of trends and vulnerabilities related to stocks provides a basis for elaborating on the feedback structures and boundaries of the model, of increasing or decreasing environmental turbulence, and of trends in connectivity.

A Brief Example

Globalization is frequently referred to in terms of increasing communication and trade around the world. The long-term impact of globalization remains uncertain with interpretations ranging from homogenization to mega-corporations. Applying the perspectives suggests alternative impacts and directions for global evolution.

For the purposes of this example, the process begins by contemplating the state of the planet from the perspective of the United States with respect to system maturity. Network flow connectivity and environmental turbulence are then considered. The boundaries throughout this example are the planet earth. Historic trends are considered. The current state will be assessed. And, the impact of increasing global trade and interdependence and increasing communications will be considered. Differing experiences and perceptions could easily lead readers to a different descriptions and conclusions. Some of the interpretations that follow may stimulate some controversy. Surfacing these differences in-group processes provides avenues for closing perceptual gaps among group members. In this example, the interpretations are used to illustrate not only how the perspectives can work and mutually inform each other, but also to use selected perceptions to support the validity of the perspectives as a useful tool. The discussion is deliberately general – at an overview level. Readers are encouraged to fill in the gaps and develop their own understanding of the logic presented. Within the presented framework, assessments of specific industries and regions where factors such as the number of effective suppliers can be estimated can be much more specific than the general overview that follows.

The Current Situation

Global population is soaring. While it is debatable whether or not we have exceeded sustainable populations and economic activity, signs of human induced environmental stress and possible resource shortages are clearly visible. Though the booming population might indicate the planet is still in the growth phase from a human perspective, the clear stresses and looming shortages suggest the development phase, possibly approaching the point of restricted growth that characterizes maturation. The growth of human population over history is arguably dominantly attributable to improvements in technology related to food production and health care. Improvements in technology have led to incremental increases in longevity and infant survival that have driven the growth in population. These improvements which act as environmental turbulence have come at a rate that has precluded equilibrium – i.e. new increases in longevity and infant survival have arrived at a rate that is leading population to grow at an exponential rate. At the same time,

technology has mitigated the negative potential impacts of resource limitations such as food and resources. Thus the overall planetary state might be described as developmental, with technology encouraging growth, and resource issues threatening to plunge the planet into maturity, i.e. the disruptions and opportunities of technologic improvement have offset or delayed the limitations of resources, allowing continued growth. The population is in a state of dynamic quasi-equilibrium between these two factors. Continued growth depends upon continued technological progress with the familiar “overshoot and collapse” alternative should technology fail to overcome the looming shortages.

Historically the global economy has been a patchwork of local economies, beginning with families and tribes and evolving through fiefdoms and nations to an increasingly interconnected web of international trade and dependency. Technologies of communication and transportation have combined with political policies to enable and encourage international trade, particularly following the proliferation of computers and the Internet in the 1990s. Over the past ten years global communication and transportation has become practical at virtually all levels, enabling every possible international connection. The creation and exploration of the interests and synergies of these connections has been a major contributor to turbulence in the economic and business sectors as manufacturing, jobs, and trade issues shape and reshape business relationships. Experimentation reigns as new connections – countries, suppliers, and customers – are tested and potentially cast aside as new connections are tested. From a “final form” perspective the global economy is clearly still in its early infancy and growth phase.

The youthful, exploitative, behavior of the global environment provides an interesting contrast to the state of US businesses. Markets and opportunities in the United States are more mature, arguably, on the whole, in the developmental or maturation phases. Competition is relatively intense and pressures for profits are high. The government and business have combined to create a stable, predictable environment for business in the US. Reliable power and distribution systems combined with technological advances to enable a strong push for optimizing flow paths surrounding a company, focusing on the most efficient and profitable alternatives. Concepts such as ISO 9000, single sourcing, and just-in-time supply strategies recently emerged to minimize overhead and maximize profits. The perspective of environmental stability and optimal flow connectivity suggests that such strategies are only viable in extremely stable environments.

From a social perspective we have seen communication ability grow progressively through the past two hundred years with the pony express, the telegraph, telephone, radio and television. Over recent years communication has flourished with the cell phones, email, and the Internet. We communicate not only with those near us – family, friends and neighbors – but also with strangers whom we have never met, via list serves, websites, and email. While some have projected global communication will create homogenization, the perspective from evolution in a fitness landscape suggests increasing interconnectivity would lead to increasing fragmentation and a leveling of the fitness landscape. Such seems to be the case. Ideas, concepts, rumors, lies, and facts inundate us. The rising flow of information encourages a portion of society to listen selectively and to reject foreign and unfamiliar concepts. Communication within groups is reinforcing and

supporting group thinking, leading to single issue political and action groups, and encouraging isolated extremist thinking and even terrorism. The trend toward single focus groups seems to support Kauffman's suggestion that increasingly complex fitness factors promote fragmentation. Kauffman's suggestion that fitness levels are squeezed toward a plane as fitness complexity rises is less clearly visible in historic trends. While wealth and educational gaps seem to be rising, virtually all US citizens have telephones, radios, televisions, and other amenities and have similar levels of access to information.

An increasing level of interdependence has been developing across the scale of globalization. The health of national economies is increasingly dependent upon the health of other economies (such as the United States dependence upon Mexico and vice versa). Within countries, the sharing and cross connecting of utilities make not just the local level vulnerable to a blackout in the event of a local problem but expand that vulnerability across regions and perhaps the entire nation.

The combined perspectives highlight a number of tensions and their structural roots. Among those are:

- The tension of technological advancement and resource depletion
- The tension of a relatively mature planet from a resource perspective accommodating the turbulence of immature globalization and connectivity
- The tension of mature industries pursuing highly efficient sourcing strategies in an increasingly interdependent global environment
- The tension of fragmentation and confrontation of ideas and movements

Social, political and business entities and people are struggling to deal with the shifting possibilities, opportunities, challenges, and threats as new connections are enabled, recognized, activated, and pruned, and complain of the "challenge of keeping up", the "volume of information and communication", and of "the pace of change" suggesting that the systems and methods they are using are not accommodating the current level of environmental turbulence.

Key Assumptions Regarding the Future

The perspectives fit well into scenario planning, contributing logic for interpreting alternative assumptions. To maintain brevity this example will consider only one case. For this example it is assumed that globalization continues with international connections, business activities, communication, and interdependency growing.

Impacts of Continuing Globalization

The perspective of fitness complexity suggests that the implications of increasing interconnectivity are fragmentation, increasing environmental turbulence, and a

compression in the range of possible fitness. These implications are examined briefly and the impacts traced through other perspectives.

Globalization is still in its relative infancy and growth phase as new connections are created and tested. Substantial turmoil remains as countries, companies, political movements, and even individuals struggle to deal with their new relationships, opportunities, threats, and abilities. Longer term, turmoil should subside as relationships stabilize.

Increasing fragmentation is to be expected over the near term – in the form of single topic political blocks, lifestyle alternatives, and other social/political phenomena – as the breadth of human personality, interests, and experience lead to differing perspectives and goals. The number of manufacturers of globally common products may defy the fragmentation phenomenon as global companies penetrate international markets, grow more ubiquitous, and local alternatives pare down to 3 effective suppliers that will be global rather than local in profile. The nature of products remains elusive. Pursuit of efficiency should lead to global homogenization and commoditization of mass products but technology is enabling mass customization of products such as custom fit blue jeans and bicycles. Human nature seems to favor customization and unicity suggesting that over the long-term mass customization might be the favored path.

Increasing turbulence can be expected to increase the overhead of society, business, and government as disruptions ripple through local and global economies. Events such as the recent New England blackout, acts of terrorism, and simple human errors threaten to impact our lives. Technology, security, and procedures will have increased focus on reducing the frequency of disruptive events and on minimizing the ripple effect. Turbulence will stimulate movement toward multiple independent suppliers – an increase in the average effective connectivity of our supply infrastructures implying a lowering of efficiency as a result of the overhead penalties of redundancy and independence. The logic of supply chains in the United States and the focus on dedicated, just-in-time supply are likely to encounter difficulties in a turbulent world. One would expect the typical number of effective suppliers in specific markets to rise toward the limit of 3.2 in many business areas and for critical necessities.

In a world of increasing globalization one would anticipate that global companies will increasingly seek access to local markets. Local suppliers should be expected to struggle in commodity businesses as larger, more efficient, and deeper pocketed competitors offer more for less. The possibility of mass customization could further shift the potential advantage to global suppliers. Two potentially countertrends offer potential insight into the ultimate balance between global and local supply:

1. Rising energy prices which would influence the competitiveness of shipping goods, thus making local supply more attractive – particularly for bulkier, heavier, and more fragile products
2. Virtualization, nanotechnology, and technology are combining in many areas to reduce the costs of local production. This trend has mixed benefits, however, as virtualization and nanotechnology are also making many products more easily deliverable.

In any event, it seems likely that in many markets international companies will continue to expand and acquire or bankrupt local suppliers.

Growing interconnectivity and interdependence imply that reductionist perspectives and problem solving approaches will grow less effective at solving the problems facing government, businesses, and individuals. Holistic approaches and systems thinking should gain favor. Techniques for aiding humans in recognizing and dealing with multiple issues and perspectives, feedback issues, and unintended consequences should be increasingly valued. Education will need to shift from simplistic answers to logic and to handling complexity. Design of organizations and infrastructures should balance efficiency with independence and robustness. This implies a massive shift in educational focus and philosophy for the bulk of the U.S. educational system.

Conclusion

This paper presents logic for merging insights from a variety of systems paradigms into a cohesive approach for inferring behavioral and evolutionary tendencies of systems based predominantly upon qualitative assessments of system structure. The logic presented is but one approach to qualitative system studies and resides in a matrix of facilitation, problem solving, and other system-related logics and perspectives. Extension and refinement of the logic is desirable and practical. Application of Michel Godet's MICMAC methodology (Godet 1999), for example, offers the benefit of suggesting leverage points for shifting system behavior, without requiring quantification of complex issue models. Incorporation of insights from other systems oriented disciplines offers the potential of broader applicability and stronger inferences. Integration of this logic into Geoff Coyle's more comprehensive ACTIFELD approach (Coyle 2004) seems to offer potential benefits. The ultimate goal for this paper is that it stimulates new thinking and ideas in other systems thinkers that will lead to stronger methodologies and solutions.

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