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The process must fit the problem: Integrating root cause analysis with the system dynamics modeling process for difficult problems

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Abstract

System dynamics has the theoretical potential to productively model any dynamic social problem where entity flow can be aggregated without significant loss of information and to offer practical solution strategies based on the model. However, in practice, as Jay Forrester observed, the field is presently stagnated "on a rather aimless plateau… there is very little penetration into the big issues." We argue the central reason is that for the more difficult problems, the present modeling process does not fit the problem because it lacks root cause analysis. This too often results in models that omit a problem's root causes and therefore the correct high leverage points. The paper begins the conversation for filling this gap by presenting an educational example of a comprehensive process for integrating root cause analysis into the system dynamics modeling process.

Abbreviations: root cause analysis (RCA), System Improvement Process (SIP), social force diagram (SFD), integrated system model (ISM).

NOTE: The paper is running too long. It will be shortened once we fix its various problems and finalize the main argument.

A series of increasingly more focused questions

The paper explores a deeply fundamental issue. As a tool for modeling and solving social problems of a dynamic nature, system dynamics offers enormous potential. Models with "aggregated human actions" as well as other aggregated behaviors "are at least potentially better representations that any others" for solving social system problems (Meadows, 1980, p. 26).

However, this potential has not been realized in society's largest problems, those of such scale and public interest they must be addressed by governments. Fifty years after the birth of system dynamics, Forrester (2007) observed that while there are many applications of system dynamics in government, "there is very little penetration into the big issues" and stated the research question this paper attempts to answer: “Why is there so little impact of system dynamics in the most important social questions?”

In particular, society has been unable to solve the global environmental sustainability problem, epitomized by the looming climate change crisis. A long series of increasingly sophisticated models beginning with the iconic World2 and World3 models (Forrester, 1971; Meadows et al., 1972) , and continued with efforts like the Triple Value Model (Fiksel, 2012), Threshold21 (Barney, 2002), DICE (Nordhaus, 2018), and iSDG and IFs (Pedercini et al., 2020), as well as global models focused on climate change like C-Roads (Sterman et al., 2012), have not yet led to successful solution. The latest IPCC report states bluntly that time is running out. “Global warming of 1.5C and 2C will be exceeded during the 21st century unless deep reductions in CO2 and other greenhouse gas emissions occur in the coming decades” (Masson-Delmotte et al., 2021).

What is missing in these models, as well as any model that attempts to solve a difficult problem and fails? Probing the depths of that question begins with examination of the problem type.

Scholars have long noted the notorious difficulty of many large-scale public interest problems. Labeled “wicked problems,” this class of problems was found by Rittel and Webber (1973) to be “inherently different from the problems that scientists and some classes of engineers normally deal with. … Social problems are never solved. At best they are only re-solved—over and over again.” Ten characteristics of wicked problems were expounded. The general hypothesis was that wicked problems are intractable due to their extreme complexity and social nature, which places them in a class of problems far more difficult than “tame” problems that are successfully solved.

Yet the long steady march of science should eventually turn wicked problems into tame ones. How can that be done? How can public interest wicked problems be turned into tame ones?

Taming difficult problems with a deeper point of view

Our research offers surprisingly good news. It’s already been done by industry for its own top wicked problem: How to consistently mass produce products of very high quality and low cost. Solving this problem had proved impossible since the beginning of the Industrial Revolution around 1760 in England. As described below it was solved around 1950 starting in Japan.

Industry’s solution to its top wicked problem was continuous improvement of root cause analysis (RCA) based processes of all kinds, such as product design, manufacturing, and customer service. RCA provides the foundation of industry’s most advanced large-scale problem-solving processes, which has led to entirely new industries, such as personal computers, smart phones, the internet, the virtual workplace, and mass airline travel, all of which are low cost and reliable. Highly challenging business problems are now solved routinely, like how to put a man on the moon in ten years or how to create a covid19 vaccine in less than 12 months.[1]

A root cause is the deepest cause in a causal chain (or the most basic cause in a feedback loop structure) that can be resolved. RCA is the systematic practice of finding, resolving, and preventing recurrence of the root causes of causal problems (Andersen and Fagerhaug, 2006, p. 12; Doggett, 2004; Okes, 2019, p. 5).

Wicked problems, as well as many less difficult problems, are causal problems. A causal problem occurs when problem symptoms have causes, such as illness or a car that won't start. Examples of non-causal problems are math problems, scientific discovery problems, information search problems like criminal investigation or system optimization, card games like poker and bridge, multiple choice problems, and puzzle solving.

All causal problems arise from their root causes. Thus, RCA is the basic process all of us follow when we solve causal problems, whether we use RCA terminology or not. RCA employs hundreds of supporting tools and techniques (George et al., 2004, 100 tools; Pyzdek, 2003, over 100 tools; Tague, 2005, 136 tools). RCA is generic and for difficult problems must be wrapped in a process tailored to the problem class.

Formal RCA originated with the "King of Japanese Inventors," Sakichi Toyoda (1876-1930), in the early twentieth century when he formalized how he applied RCA with the now ubiquitous Five Whys method (Imai, 1986, p. 50). Use of RCA in Japan spread and began to mature, and received an enormous boost with arrival of W. Edwards Deming in 1947, who introduced a comprehensive process (the Plan/Do/Check/Act cycle, aka the Deming Cycle) for combining RCA with statistical quality control (Gabor, 1990, p. 20 and 74). This was the process that solved industry's wicked problem of how to consistently mass produce products of very high quality and low cost.

The process was received so well by Japanese industry that soon the Deming Prize (an annual award for quality beginning in 1951) was a national competitive event and came to be as prestigious in Japan as the Nobel Prize was in the West (Ibid, p73). The prize was so difficult to win that most contestants first spent 3 to 5 years honing their operations to peak process maturity (Ibid, p95). Almost instantly the emphasis on RCA-based continuous process improvement served as a potent component of the Japanese post-war economic miracle in the 1950s and 1960s, when Japan rose from devastation in the war to become the second-largest economy in the world, largely due to the unmatched high quality and low cost of exported products.

Finally in 1981 Deming's "philosophy" migrated to the west, when Ford Motor Company invited Deming for training (Ibid, p3). The reason? American auto manufacturers had lost so much market share to Japan they faced financial disaster.

[1] To achieve a high mission success rate, NASA created its own Root Cause Analysis Tool (NASA Safety Center, 2013). Six Sigma, the leading RCA-based quality control process, is used by used by 100% of aerospace, motor vehicle, electronics, and pharmaceutical companies (including vaccine development and manufacture) in the Fortune 500 (Marx, 2007).

Ford learned and implemented Deming's teachings so well that Ford went from the brink of bankruptcy in 1980 to the most profitable auto manufacturer in America. "Less than a decade after their first encounter [with Deming in 1981], Ford would be hailed as the model of American management" (Ibid, p4). The paradigm of RCA-based processes for all important processes and continuous process improvement has since spread to all large-scale industries, in the form of Total Quality Management, Lean Production, ISO 9000, Six Sigma, and more. For a cohesive review of these mega-tools see (Tague, 2005, pp. 13–34). Industry wide organizations to manage quality standardization and continuous improvement have appeared, such as the American Society for Quality and the Institute of Electrical and Electronics Engineers.

The foundation of RCA is the root cause point of view. While perceptions vary, we see the principles below as the core of that viewpoint and modern RCA-based processes. All the principles arise from the first, which states the essence of the viewpoint:

1. All causal problems arise from their root causes.
2. A causal problem can only be solved by finding and resolving its root causes.
3. The more difficult the problem, the more mature the process used to solve it must be.
4. Continuous process improvement is required to achieve and maintain high process maturity.

The third and fourth principles encapsulate the philosophy of Kaizen, "the single most important concept in Japanese management—the key to Japanese competitive success. Kaizen means improvement, …ongoing improvement involving everyone: top management, mangers, and workers" (Imai, 1986, p. xxix). The key is to cultivate an organizational culture that is "process-oriented" rather than "innovation and results-oriented." Continuous process improvement is a form of institutionalized organizational learning, seen by some as *the* key requirement for long-term organization success (Senge, 1990).

By now the answer to the question of "How can public interest wicked problems be turned into tame ones?" should be apparent. Those working on *public* wicked problems must adopt the same foundation as those working on *private* wicked problems. That foundation is the root cause point of view.

Richardson (2011) argues persuasively that the foundation of system dynamics is "the endogenous point of view," and states this point of view is the *sine qua non* of both system dynamics and systems thinking. This foundation has proven to work on many problems. However, as Forrester has painfully pointed out, system dynamics has been unable to solve the most important social problems. There must be a reason for that phenomenon.

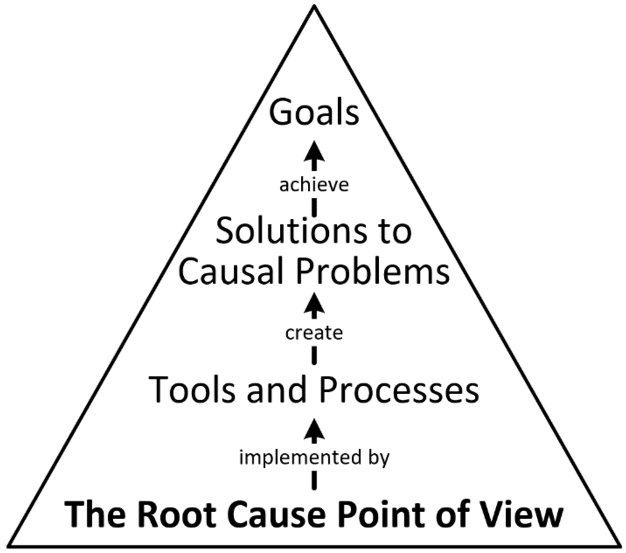

Figure 1. The Pyramid of Causal Problem Solving, showing how the root cause point of view serves as the foundation of modern causal problem solving. System dynamics is one of many tools used to implement the root cause point of view.

Figure 1 illustrates how the root cause point of view serves as the foundation of modern causal problem solving. Because system dynamics is a tool for solving causal problems, it is one of many tools used by RCA practitioners. Below the foundation of system dynamics rests the larger and more critical foundation of the root cause point of view. This presents an opportunity. *If system dynamics modelers wish to solve wicked problems, or any problem type more difficult than they can routinely solve today, then they can do what industry has done. Modelers can expand their paradigm to include the root cause point of view and drive model construction with explicit RCA.* That is the message of this paper.

Doctors use RCA to diagnose and treat patient illness without ever using the term root cause or root cause analysis. Countless professions do the same, since causal problems can only be solved by resolving their root causes.

System dynamics modelers are thus already performing RCA. However, because there is no explicit root cause point of view and no RCA-based process that seamlessly integrates with the system dynamics modeling process, for difficult problems their models tend to not include the root causes. Instead, the models contain intermediate (proximate) causes, which leads to superficial solutions that have less than the desired effect.

This process gap can be filled. The paper presents the System Improvement Process (SIP), a tool for solving difficult problems with RCA and system dynamics, and then combines SIP with two other processes. The resulting integrated process is presented not as *the* correct RCA-based process, but as an educational example of how to begin transition to the root cause viewpoint.

The potential of this transition is immense. Once the business world began formal use of RCA and changed entire corporate philosophies to the root cause point of view, it was able to solve previously insolvable highly difficult problems. We see no reason why system dynamics modelers cannot expect to do the same.

In fact, the transition is already underway. The fall 2021 *Fundamentals of Dynamic Social Systems* course (GEO-SD302) on system dynamics modeling at the University of Bergen introduces RCA as a structured problem-solving tool that can assist the modeling process. Course material by Repenning et al. (2017) states that "A good root cause analysis links the data obtained in your investigation to the problem statement to explain how the current system generates the observed challenges not as a special case but as a part of routine conduct." A modified version (to allow use on problems other than manufacturing) of Toyota's A3 Report is used to provide students with a simple proven tool for performing RCA, though it's not integrated with the modeling process or large social problems as is SIP. A case study is used to illustrate the RCA process, with "impressive" results.

Finding causal chains with the Five Whys method

RCA uses many tools to find root causes. All are supporting tools or variations of the core method: the Five Whys. Imai (1986, p. 50) describes the method:

> In the factory, problem solvers are told to ask "why" not once but five times [or as many times as necessary]. Often the first answer to the problem is not the root cause. Asking why several times will dig out several causes, one of which is usually the root cause. [For example:]
>
> 1. Why did the machine stop?
>   Because the fuse blew due to an overload.
> 2. Why was there an overload?
>   Because the bearing lubrication was inadequate.
> 3. Why was the lubrication inadequate?
>   Because the lubrication pump was not functioning right.
> 4. Why wasn't the lubrication pump working right?
>   Because the pump axle was worn out.
> 5. Why was it worn out?
>   Because sludge got in.
>
> By repeating "why" five times, it was possible to identify the real cause and hence the real solution: attaching a strainer to the lubricating pump. If the workers had not gone through such repetitive questions, they might have settled with an intermediate countermeasure, such as replacing the fuse.

Problem symptoms were the machine stopped. Answers to the first four questions are intermediate causes. The answer to the fifth question is the root cause. Application of the Five Whys has identified the problem's causal chain. Causal chains follow this basic form:

Root cause → Intermediate Cause(s) → Problem Symptoms

Causal chains can branch, as when a problem has multiple root causes. They can also encounter feedback loops. High level causal chain diagrams can treat loops or groups of loops as single nodes. This allows a complex causal structure to be clearly summarized. Unlike causal loop diagrams or system dynamics models, where emphasis is on feedback loop structure, emphasis in causal chain diagrams is on linear chains of cause and effect.

Why the root cause point of view is required for difficult problems

Earlier we concluded that "If system dynamics modelers wish to solve wicked problems, or any problem type more difficult than they can routinely solve today, then they must expand their paradigm to include the root cause point of view and drive model construction with RCA."

System dynamics experts may object and counter they are already finding what can be called root causes. If a model endogenously generates the "right output behavior for the right reasons" (Barlas, 1996), then it must contain the root causes of the problem. The right reasons occur "if the model has an internal structure that adequately represents those aspects of the system which are relevant to the problem behavior at hand." This objection arises from the endogenous point of view.

The "right reasons" occur if a model is valid. However, Barlas found that "judging the validity of the internal structure of a model is very problematic" because "there are no established formal tests (such as statistical hypothesis tests) that one can use in deciding if the structure of a given model is close enough to the 'real' structure." Sterman (2000, p. 846) explains that complete validation is impossible because all models are simplifications of reality. The best the modeler can do is establish a high probability of model validity.

The endogenous point of view embodies a critical prediction that dominates system dynamics modeling: *If a model can endogenously replicate reference mode behavior and is built "for the right reasons," then it must contain the root causes of the problem.* Let's call this the *Principle of Endogenous Causes*. Homer and Oliva (2001) summarize the principle: (italics added, references preserved)

> The *dynamic hypothesis* is a cornerstone of good system dynamics modeling practice. It "explains the dynamics as *endogenous consequences* of the feedback structure" (Sterman, 2000), and explicitly states how structure and decision policies generate behavior (Richardson and Pugh, 1981). Moreover, "The inclusion of basic mechanisms from the outset forces the modeler to address a meaningful whole at all stages of model development" (Randers, 1973). That is, a *dynamic hypothesis* is the key to ensuring that the analysis is focused on diagnosing problematic behavior and not on enumerating the unlimited details of a "system."

Sterman (2000, p. 95, italics added) states the principle this way: "A dynamic hypothesis is a working theory of how the problem arose. … In practice, discussion of the problem and theories about the *causes* of the problem are jumbled together in conversation with client teams. … Your goal is to help the client develop an *endogenous explanation* for the problematic dynamics."

The main technique for establishing model validity is the Principle of Endogenous Causes. Standard procedure in system dynamics papers and books is to demonstrate model validity with graphs showing reference mode behavior, supplemented with additional evidence of validity.

But in difficult problems a subtle trap lies waiting. It is surprisingly easy for a model to be able to endogenously replicate the reference mode and not contain the root causes. This happens when high system complexity (often combined with problem novelty) hides the root causes. How this failure occurs can be explained with two (imperfect) examples: (See Conclusion 2 section for a third example.)

Example 1. *A patient has a fever. The intermediate cause is infection. The root cause is a damaged immune system, which has failed to prevent the infection.*

A system dynamics model of the fever and infection could easily be constructed. It would endogenously show how once the infection entered the body it replicated, causing the patient's temperature to rise to the point of a fever.

But if this was a case where there was a deeper root cause, such as a damaged immune system, then the model boundary would be inadequate and the model would omit the root cause, just as many doctors have done, when due to a faulty diagnosis (and a faulty mental model) they treated only the infection because they failed to spot its deeper cause. If the doctor had asked "Why did this patient get infected, when most people don't?" then she probably would have found the root cause.

Reference mode data would be a graph showing the rise in the patient's temperature. The model would be able to reproduce reference mode behavior. However, this is not enough to ensure the model contains the root cause.

Example 2. *The classic Five Whys problem of "Why did the machine stop?"* As explained earlier, the first four answers were intermediate causes, while the fifth answer was the root cause.

It would not be hard to build a system dynamics model for each depth of analysis. The first would endogenously model the first intermediate cause. The second would model the first and second intermediate causes, and so on, as each model enlarged its boundary. Only the fifth model would have a correct boundary and include the root cause. All the models could replicate reference mode behavior, which is a graph showing the machine running and then stopping.

These two examples illustrate how revolutionary Sakichi Toyoda's invention of the Five Whys was. It offered an easy formal method for applying RCA to causal problems of any type or level of difficulty, and became the foundational method of formal RCA.

The examples should also illustrate why the root cause point of view is required for applying system dynamics to difficult problems. All the example models could replicate reference mode behavior endogenously and were valid "for the right reasons," in that they correctly modeled what the client and modeler knew about the problem. The example models all satisfied the Principle of Endogenous Causes. Yet all the models except the fifth one in the second example omitted the root cause.

This is why in the Five Whys method "problem solvers are told to ask 'why' not once but five times."

A practical strategy for moving off the aimless plateau

In the language of Thomas Kuhn (1996), this paper has identified two significant anomalies (violations of expectations) for an established paradigm:

> *Anomaly 1*. The foundation of system dynamics is the endogenous point of view. Cases exist (such as the two examples above) where a prediction this point of view makes fails. To make our argument crystal clear, the prediction arises from the Principle of Endogenous Causes.
>
> *Anomaly 2*. A long series of system-dynamics-based ISMs (World2, World3, and successors, as described by (Pedercini et al., 2020)) has not led to successful solution of the environmental sustainability problem, the world's most important social problem. Yet in theory, system dynamic modeling should be able to solve this problem (or any difficult large-scale social problem). Not perfectly, but enough to bring quality of solution up to an acceptable level that optimizes the common good.

The root cause point of view explains both anomalies. We hypothesize that both occurred for the same reason: Model construction was not driven by an appropriate RCA-based process and these were problems so difficult that normal modeling processes were inadequate, causing the root cause(s) to be omitted. For the second anomaly, see Figure 7 for a detailed example of omitted root causes.

This hypothesis opens the door to a practical strategy for moving off the aimless plateau, because we have identified anomalies that are worthy of correction and a means of correction.

> What makes an anomaly worthy of serious scrutiny? Kuhn tells us there's no general answer. The kinds of factors which enter the process are that the anomaly might be seen as *calling into question the paradigm's fundamental generalizations*, or that it *inhibits applications with a particular practical importance*. When factors like these conspire together [as they do in the two anomalies above], the anomaly becomes more than just another puzzle within normal science. It become generally recognized as a real problem. (Preston, 2008, p. 50, italics and comment added)

When significant anomalies accumulate and become "generally recognized as a real problem," something in the paradigm must change. Kuhn distinguishes two types of change: "In normal change, one simply revises or adds a single generalization, all others remaining the same. In revolutionary change, one must either live with the incoherence or else revise a number of interrelated generalizations together" (Kuhn, 2002, p. 29).

Fortunately, the two anomalies can be accommodated by normal change. The single fundamental generalization is the Principle of Endogenous Causes. Presently the implicit principle is: *If a model can endogenously replicate reference mode* *behavior and is built "for the right reasons," then it must contain the root causes of the problem.*

We suggest amending the principle by adding: *For difficult causal problems, the probability of being built for the right reasons must be maximized by driving model construction with a mature RCA-based process that fits the problem type.*

While only a single generalization has been changed the impact is large, because now the root cause point of view drives model construction. Technically this is not a Kuhnian revolutionary change. However, we expect it will be dismissed as impossibly radical change by some, because system dynamics modelers are not accustomed to thinking in terms of root causes, causal chains, and driving analysis with RCA. Instead, they think in terms of endogenous behavior and feedback loop structure that grows organically from work with the client and study of the problem. We thus foresee the potential for considerable paradigm change resistance, which Kuhn found to be the norm:

> The proponents of competing paradigms are always at least slightly at cross purposes. Neither side will grant the non-empirical assumptions that the other needs to make its case. [They are therefore] bound partly to talk through each other. Though each may hope to convert the other to his way of seeing his science and its problems, neither may hope to prove his case. The competition between paradigms is not the sort of battle that can be solved by proofs. (Kuhn, 1996, p. 148)

How then do scientists accept a new paradigm?

> …scientists will be reluctant to embrace it unless convinced that *two all-important conditions* are met. *First*, the new candidate must seem to resolve some outstanding and generally recognized problem that can be met in no other way. *Second*, the new paradigm must promise to preserve a relatively large part of the concrete problem-solving ability [of the existing paradigm]. (p169, italics added)

This paper hopes to overcome this reluctance by meeting the above two conditions and by demonstrating how an RCA-based modeling process (SIP) can be applied just as easily *and more efficiently* than the present standard modeling process, because of less rework due to defects in the form of faulty solutions.

To meet the first condition, the demonstration includes evidence the proposed paradigm change can correct the second anomaly in the section on *Applying SIP to the Environmental Sustainability Problem*. The section offers what we feel is strong evidence an appropriate form of RCA can work, based on the major insights below. No other analysis we are aware of offers any of these insights:

1. Explanation of why all major types of past solutions have largely failed. The solutions were defective because they did not focus on resolving specific root causes. Instead, they unknowingly attempted (in vain) to resolve intermediate causes.

2. The theoretical existence and plausibility of the four main root causes found. All are so counterintuitive they are rarely discussed in the literature. Even then they are never framed as root causes, but are seen as one of many potential factors.

3. The fact that no large-scale solutions have pushed on any of the high leverage points associated with the root causes. The problem thus appears to be solvable. It is not an intractable wicked problem after all.

4. A small amount of empirical evidence confirming the existence and behavior of the root cause of subproblem A, provided by the Truth Literacy Training study (see Supplementary Materials).

There is also a seventy-year history of evidence showing how industry has used RCA to successfully solve its own difficult causal problems, beginning with adoption of Deming's RCA-based process in Japan around 1950. RCA is generic and works for any difficult causal problem in the *business* world. It can therefore work for any difficult causal problem in the *social* world, if a suitable process designed to fit the problem type is used.

While this evidence is far from conclusive, it does suggest a clear research path forward for moving off the aimless plateau.

SIP fits difficult large-scale social problems. This class of problems is the most demanding one possible, as these are the hardest wicked problems. If the paper can demonstrate that a customized version of RCA can probably work on this class, then we can assume the same holds for any class of social system problems, if the class can benefit from feedback loop modeling.

Kuhn's second condition was that the new paradigm must preserve most of the existing paradigm. Figure 1 explains how this condition is met. The new paradigm (the root cause point of view as the foundation of modern causal problem solving) sits under and enhances the existing paradigm of system dynamics modeling, while preserving everything in that paradigm.

The two paradigms work together. The system dynamics modeler is driven by *a search for feedback loop structure* causing reference mode behavior. If it's a difficult problem, explicit RCA is required to generate the high-quality hypotheses that need modeling. In an RCA-based modeling process, the problem solver is driven by *a search for casual chains* using the Five Whys, a higher level, simpler, and much easier task. As the causal chain diagram develops, its components are modeled in a causal loop diagram and a system dynamics model as needed. The three-step iterative sequence is:

Causal Chain Diagram → Causal Loop Diagram → System Dynamics Model

This sequence shows how RCA and system dynamics modeling can work together to solve difficult problems. Examples of causal chain diagrams may be found in Figures 5, 6, 8, and 9.

An example of how much simpler and easier the causal chain construction task is than the modeling task may be seen in Figure 8. The causal chain diagram has only ten nodes and is standardized, which speeds construction and communication. The subsequent causal loop diagram (supplementary material) has 26 nodes and addressed analysis needs so well that no system dynamics model was needed. For subproblem A, the causal chain diagram also has ten nodes, while its system dynamics model has 29 nodes with 3 stocks and 3 named loops.

Lessons learned from the Toyota Production System (TPS)

In 1984 a group of MIT researchers "concluded that the auto industries of North America and Europe were relying on techniques little changed from Henry Ford's mass-production system. These techniques were not competitive with a new set of ideas pioneered by Japanese companies" (Womack et al., 1990, p. 3). To address the problem MIT launched a five year, five-million-dollar study that culminated in *The Machine that Changed the World: The Story of Lean Production* (Ibid).

The book coined the term "lean" to describe the way the Japanese approach centered on elimination of waste (anything that adds cost without adding value) from a process, and positioned lean production as "the next paradigm of manufacturing beyond mass production" (Lander and Liker, 2007). Lean was modeled on TPS, since it was Toyota who evolved Deming's comprehensive RCA-based process into a large-scale system that could solve industry's top wicked problem (how to consistently mass produce products of very high quality and low cost) better than any other solution.

To clearly describe TPS, Liker (2004), after 20 years of visits to Japan and exhaustive study of TPS there and in the US, distilled how those individual elements work together into 14 principles. Figure 2 organizes the principles into a layered diagram, with the foundation of the process at the bottom and where improvement activity actually occurs at the top. Each layer drives the layers above it.

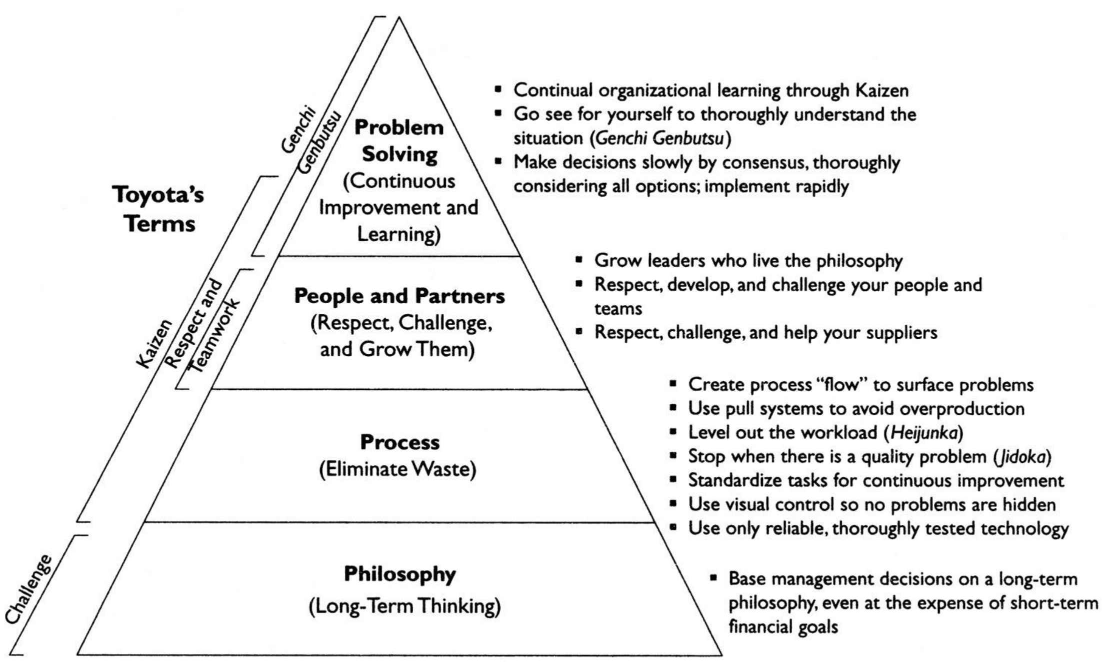

Figure 2. The 4 P model of how TPS works. The four high-level principles are from a Toyota document, while the 14 low-level principles listed on the right were synthesized by Liker. (Liker, 2004, p. 6)

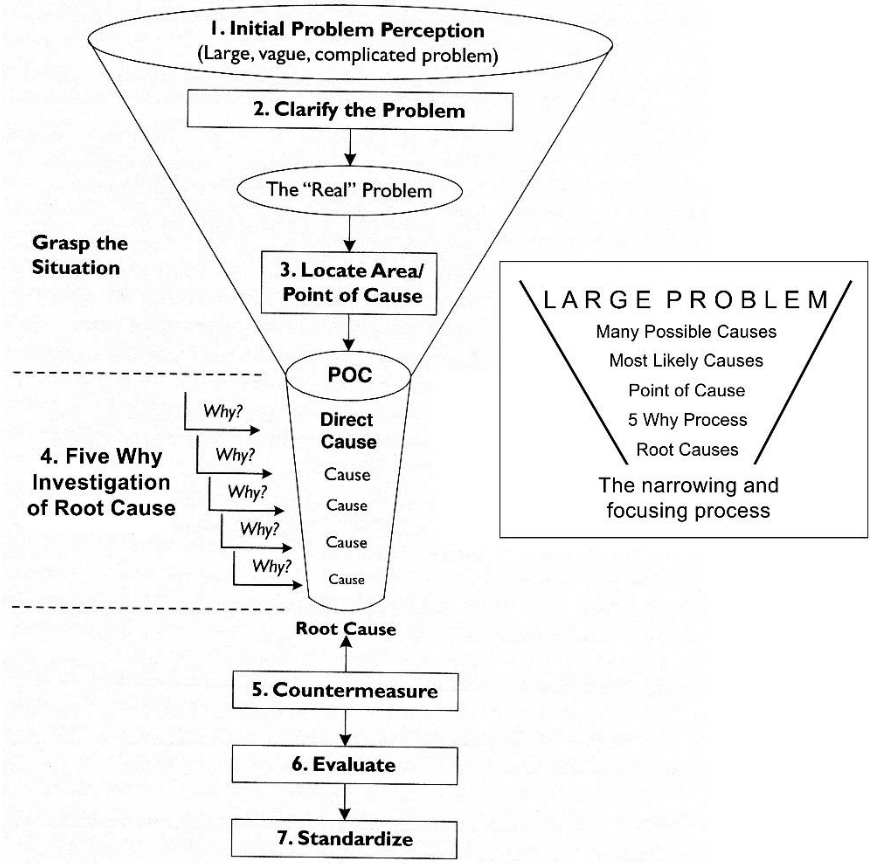

Figure 3. Toyota's practical problem-solving process (Liker, 2004, p. 256; Liker and Meier, 2006, p. 346) The first four steps narrow the large problem to its root causes.

The key lesson to learn from TPS is that despite the vast complexity of the overall process, a single RCA-based process (Figure 3) drives the problem-solving portion of TPS (the top layer in Figure 2) and implements Kaizen. The process in Figure 3 is supremely mature, as it is the result of over fifty years of continuous improvement. The process works like this:

Before RCA can begin, the problem must become crystal clear. "Trainers who teach this methodology within Toyota have found the most difficult part to learn is grasping the situation thoroughly *before* proceeding with five-why analysis" (p255, italics in the original). Therefore, the process provides three steps to do that, to "Grasp the Situation." The output of these steps is the point of cause, the specific area where the root cause is likely to be found. Step 4 then applies the Five Whys to find the root cause(s). This goes quickly due to a deep grasp of the problem and a focused point of cause. Then a countermeasure is designed to resolve the root cause and applied, which explains the upward arrow between countermeasure and root cause. Next the results are evaluated. If not satisfactory, appropriate process steps are repeated until the quality of solution desired is achieved.

Toyota refers to root cause solutions as "countermeasures rather than solutions, because that would imply a permanent resolution to a problem. Over the years, the company has developed a robust set of tools and practices that it uses as counter-measures, but many have changed or even been eliminated as improvements are made" (Spear and Bowen, 1999).

Once evaluation shows the countermeasure is satisfactory and stable (it works well reliably, with acceptable variation), it is standardized. The solution is spread throughout the company by standardization: applying it at all places with the same problem, updating training courses, written standards, and so on. Every act of standardization is one more act of continuous improvement and organizational learning.

Because of Toyota's long-term financial success and domination of the largest manufacturing industry in the world, auto manufacture, TPS has become one of the most studied and copied large-scale industrial processes in the world (Bhamu and Sangwan, 2014; Liker, 2020; New, 2007). At its core is Toyota's practical problem-solving process. This process is the best process we could find for use in integrating RCA into the system dynamics modeling process.

The System Improvement Process (SIP)

This section describes SIP, an RCA-based process designed to solve difficult large-scale social problems, defined as those where serious solutions have failed for 25 years or more and involve political systems with millions or billions of people. For further detail please see supplementary materials.

Surveying the business and academic literature, we found no such method was available so we were compelled to develop one, a common occurrence on novel classes of problems. NASA (2013) encountered the same situation:

> After extensive review, NASA found that none of the commercially available tools and methods would support a comprehensive root cause analysis of all the unique problems and environments NASA faces on the Earth, in the ocean, in the air, in space, and on moons and planetary bodies. Existing tools were designed for a specific domain (e.g., aviation), a specific type of activity, a specific type of human error (e.g., errors of omission) or had a limited set of cause codes. The NASA RCAT [Root Cause Analysis Tool], a paper-based tool with companion software …was designed to address the shortcomings identified in existing tools.

Figure 4 summarizes how SIP works. The SIP matrix is *the* mental model of SIP. All work goes on inside a cell, so you always know where you are in the process and what to do next. SIP uses a step-by-step fill-in-the-blanks matrix, with one instruction per cell. A completed matrix contains one hypothesis and/or measurable result per cell. SIP is very iterative.

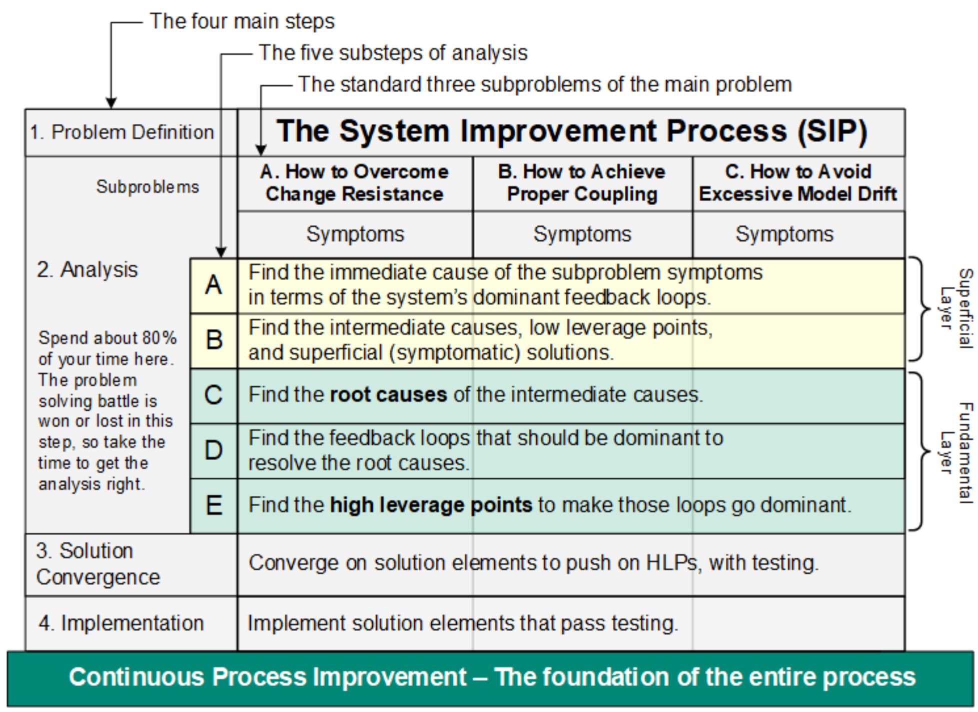

Figure 4. The SIP matrix, showing the standard three subproblems. Each subproblem employs a social force diagram and necessary models.

SIP defines the problem in step 1. Step 2 decomposes the one big problem into smaller and hence much easier to analyze subproblems. The three subproblems present in all difficult social problems are shown. Each subproblem is then analyzed using substeps A to E. Step 3 uses that information to converge on solution elements. Finally, step 4 implements those solution elements that have passed testing. The process is flexible and highly iterative. The four main steps work as follows:

Step 1. Problem Definition

This defines the problem using a standard format that implies no preferred analysis or solution: Move system A under constraints B from present state C to goal state D by deadline E with confidence level F. Moving from the present state to the goal state requires a mode change. SIP treats difficult social problems as social systems stuck in the wrong mode. The format is flexible and can be changed as needed. This step equates to the first portion of Figure 3's Clarify the Problem step.

In probing how to solve wicked problems of public interest, Head and Alford (2015) reviewed a topology for classifying management problems:

> Type 1 situations are those where both the definition of the problem and the likely solution are clear to the decision maker. … Type 2 situations are those where the definition of the problem is clear, but the solution is not. … In Type 3 situations, both the problem definition and the solution are unclear…. We suggest that Type 1 situations constitute "tame" problems, whereas Type 3 situations, and perhaps many Type 2 ones, will contain some features of "wicked" problems.

The engineering-like standard format turns a problem into a Type 2 problem. It is already partially tamed, because we have eliminated the first of Rittel and Webber's ten primary characteristics of wicked problems: "There is no definitive formulation of a wicked problem."

Step 2. Analysis – Problem decomposition

Decomposition is required because "In nearly all situations there are multiple causes of problems, and thus the analysis must be comprehensive" (Liker and Meier, 2006, p. 342) Multiple root causes tend to be dispersed among different subproblems.

Working from the problem definition, analysis begins by decomposing the one big problem into the three subproblems present in all difficult large-scale social problems, plus additional subproblems as needed. This decomposition can transform the original problem from insolvable to solvable, because you are no longer trying to simultaneously solve multiple subproblems and resolve multiple root causes without realizing it. This step equates to the second portion of Figure 3's Clarify the Problem step and the Locate Point of Cause step.

The most efficient approach to problem decomposition is standard subproblems. For example, industry uses cause-and-effect diagrams with standard and custom subproblems (Figure 5), as well as these groups of standard subproblems:

The four Ps of marketing: Product, Place, Promotion, Price (McCarthy, 1960).

The original four Ms of manufacturing: Materials, Methods, Machines, Measurement (Ishikawa, 1986, p. 19).

The 4Ms of TPS: Man, Method, Material, Machine (Liker and Meier, 2006, p. 342)

The nine Ms of quality control: Markets, Money, Management, Men, Motivation, Materials, Machines and mechanization, Modern information methods, Mounting product requirements (Feigenbaum, 1991, p. 59).

SIP was iteratively developed while applying it to the environmental sustainability problem. The trickiest part of that work was proper problem decomposition, as the problem was impossible to analyze coherently without the right subproblems. We eventually realized that the environmental sustainability problem is a member of the class of difficult large-scale social problems, such as sustainability, corruption, war, systemic discrimination, large recessions, high income inequality, and poverty in a world of plenty. It appears that all problems in this class have the same three subproblems, as described below:

A. How to overcome systemic change resistance. Also called solution change resistance, lack of political will, inertia, defending the status quo, and barriers to change, systemic change resistance is the tendency for a system to resist proposed solutions. The system dynamics literature (Sterman, 2000, p. 5) uses the term "policy resistance", defined as "the tendency for interventions to be delayed, diluted, or defeated by the response of the system to the intervention itself." Policy resistance refers to resistance to *implemented* solutions, while change resistance refers to *proposed* solutions. Change resistance is the most important subproblem to solve (in the short term) and must be solved first if possible (Harich, 2010).

To deal with "the important social questions," the need to model change resistance was stressed by Forrester (2007) himself: "How often do you see a paper [with a system dynamics model] that shows all of the following characteristics?" The last two were: "8. It examines why the proposed policies will be resisted. 9. It recognizes how to overcome antagonism and resistance to the proposed policies."

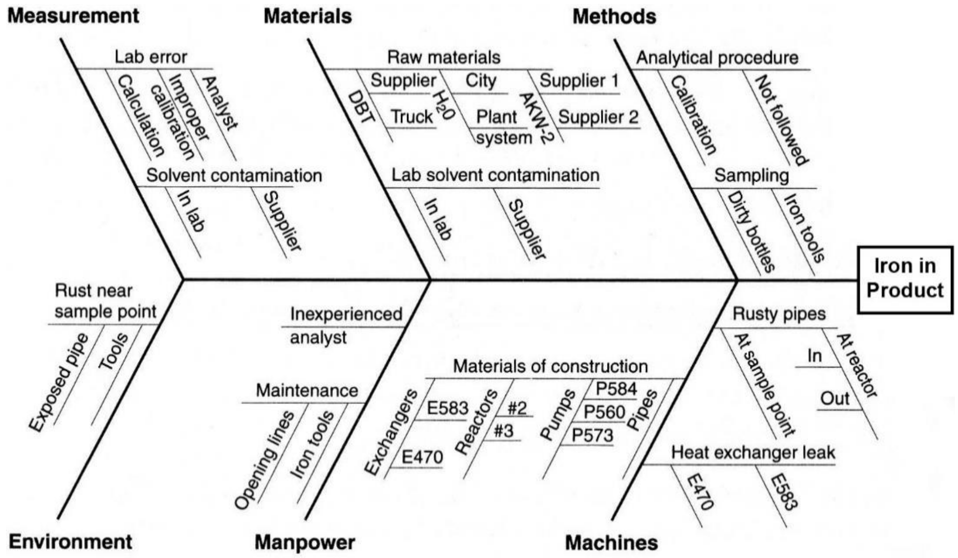

Figure 5. Cause-and-effect diagram example (Tague, 2005, p. 248). The causal structure of the "iron in product" contamination problem has been diagrammed using standard subproblems like Measurement and custom subproblems as necessary. Possible causal chains are drawn. Further investigation will determine which lead to root causes. Cause-and-effect diagrams are also known as fishbone diagrams or Ishikawa diagrams (Ishikawa, 1986, p. 18 and 148).

B. How to achieve proper coupling. This is the original problem to solve. Proper coupling occurs when the behavior of one system affects the behavior of one or more other systems in a desirable manner, using the appropriate feedback loops, so the systems work together in harmony in accordance with design objectives. For example, if you never felt hungry you would starve to death. You would be improperly coupled to the world around you. In the environmental sustainability problem, the human system is improperly coupled to the greater system it lives within, the biosphere. The definition of proper coupling enforces a particular feedback loop pattern perspective, making the analysis substeps much easier.

Forrester's (2007) second characteristic, "2. It displays a compact model that shows how the difficulty is being caused," is subproblem B.

C. How to avoid excessive solution model drift. A solution is a model of understanding about how a system should respond when the solution is implemented. If the model is correct the solution works. Excessive solution model drift occurs when a solution model works at first and then doesn't. The solution has drifted, due to change in the problem, change in how the solution is managed, etc. All social systems continually evolve, so solution model drift is the norm. To avoid excessive drift, solution managers must continually evolve solutions as the system evolves or solutions must be self-evolving.

The solution model drift subproblem equates to the process control phase of industrial RCA-based process management. After initial solution success, "…don't be too hasty to declare victory. The last battle has yet to be fought. The battle against creeping disorder, the battle against entropy. The battle to ensure the gains you made are permanent." (Pyzdek, 2003, p. 649) In the long term this is the most important subproblem of them all, because if it's not solved a political system will eventually be overwhelmed by multiple problem recurrence.

These three subproblems are present in all difficult large-scale social problems. This is because:

A. High successful change resistance is present because prior proposed solutions have repeatedly been rejected or weakened. On the environmental sustainability problem, change resistance has been so high for so long that the third edition of *Limits to Growth* (Meadows et al., 2004, p. 24) stated emphatically that:

> [The second edition of *Limits to Growth*] was published in 1992, the year of the global summit on environment and development in Rio de Janeiro. The advent of the summit seemed to prove that global society had decided to deal seriously with the important environmental problems. But we now know that humanity failed to achieve the goals of Rio. The Rio plus 10 conference in Johannesburg in 2002 produced even less; it was almost paralyzed by a variety of ideological and economic disputes, [due to] the efforts of those pursuing their narrow national, corporate, or individual self-interests. …humanity has largely squandered the past 30 years…

B. The proper coupling subproblem is present because the original problem to solve is, we found, always best defined as one of improper coupling.

C. Excessive solution model drift is present because if it wasn't, the governance system would be able to solve the problem. Difficult social problems start small and gradually grow large. Solutions that worked when problems were small, such as small manageable amounts of pollution, discrimination, and recession, no longer work when the problems grow large or evolve to no longer fit their solutions. The model drift subproblem reflects how difficult "Social problems are never solved. At best they are only re-solved—over and over again" (Rittel and Webber, 1973). The need to avoid excessive model drift is what Young (2017, p. 218) refers to with "We need governance systems that can adapt easily to changing circumstances…." and is what the resilience school calls the ability of a system to adapt to change by remaining within desired ranges of system behavior (Folke et al., 2010).

Step 2. Analysis – Social Force Diagrams

Each subproblem is then analyzed using the Five Whys and a social force diagram (SFD) as in Figure 6. The diagram structures the analysis into an efficient format. This step equates to Figure 3's step 4, Investigation of the Root Cause and the beginning of step 5, Countermeasure.

"The question not asked cannot be answered" (Judson, 1980, p. 33). SFDs provide a structured approach to asking the right questions at each of the many points in RCA of a difficult problem.

Essential causal structure is the nodes, relationships, and interacting feedback loops that provide a cohesive description of a causal problem's root causes and leverage points. SFDs are a type of cause-and-effect diagram that captures only

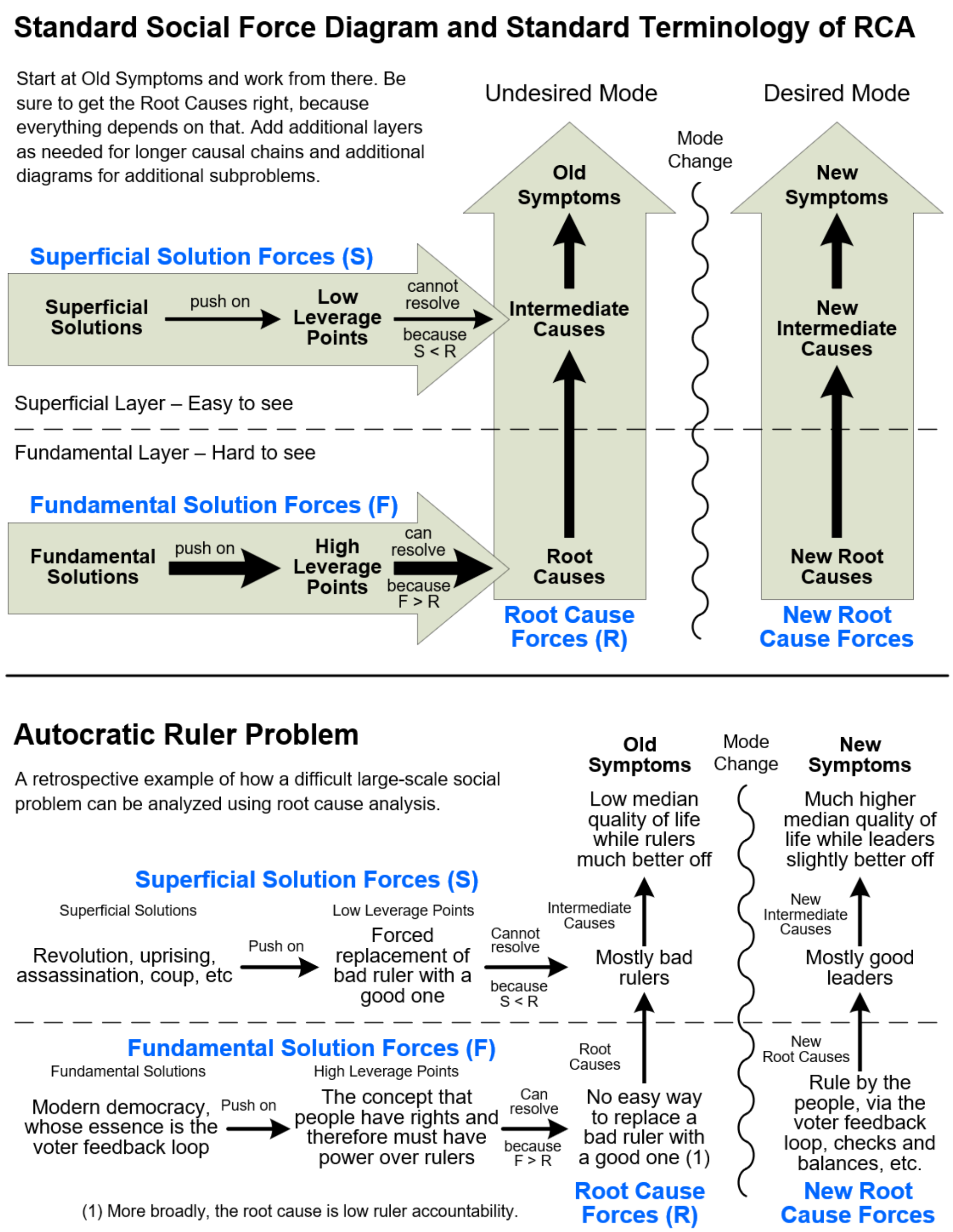

Figure 6. Social force diagram format and an illustrative example. Use of standard terminology and the standard format greatly facilitates static hypothesis construction. Complex SFDs can have multiple intermediate causes and high-level feedback loops.

high level essential causal structure, while a system dynamics model captures all essential causal structure.

The strategy is to first learn from the past to construct the superficial layer. WHY did past solutions fail? That leads to the intermediate cause, followed by identification of the low leverage point and the superficial solutions that seemed promising but failed to solve the problem. Next one asks WHY does the intermediate cause occur? What is its deeper cause? That line of questioning will lead to further intermediate causes (if any) and eventually penetrate the hard-to-see fundamental layer, where the root causes may be found. Resolving the root causes by pushing on high leverage points with fundamental solutions will initiate the desired mode change, causing the system to escape lock-in to the present undesired mode and rapidly self-evolve to the desired mode of behavior.

Forrester's (2007) last two requirements when modeling important social problems are: "8. It examines why the proposed policies will be resisted. 9. It recognizes how to overcome antagonism and resistance to the proposed policies." The superficial layer of a SFD for the change resistance subproblem implements requirement 8. The fundamental layer and mode change implement requirement 9.

Mode lock-in and mode change

Mode lock-in (also called homeostasis or dynamic equilibrium) occurs when a system's feedback loops work together to hold the system into a particular mode via compensating feedback. The stronger the lock-in, the stronger the automatic resistance to mode change. Examples of lock-in are thermostats, the self-regulating behaviors of living systems like cells, species, and ecosystems, and the checks and balances of constitutional governments.

The central role of lock-in in the environmental sustainability problem has long been noted, most famously by Hardin (1968): "Each man is locked into a system that compels him to increase his herd without limit—in a world that is limited." In difficult large-scale social problems, some portion of the human system is locked into an undesirable mode and is unable to easily change to the desired mode. Lock-in occurs due to the unrelenting strength of a problem's dominant feedback loops.

In SIP, an unsolved problem is locked into the wrong mode. The analyst's job is to find the root causes causing that, and design high leverage point solutions that when implemented will elicit a mode change leading to the desired mode. This requires reengineering the system's feedback loop structure such that when fundamental solution force F is applied, a new root cause force R is created, and the system's current dominant feedback loops are replaced by new ones, causing the mode change to rapidly occur.

The Autocratic Ruler Problem

One of history's most stubborn problems was autocratic rule by countless warlords, dictators, and kings. The problem was eventually solved by invention of modern representative democracy. This took thousands of years and much painful trial and error because the root cause was unknown. However, now it is known, allowing the lower diagram in Figure 6 to be constructed.

The diagram shows why superficial solutions failed to solve the problem for so long (bad rulers kept reappearing once one was removed), why the fundamental solution worked (good leaders now tended to appear), and why, once the mode change occurred, the institution of democracy automatically spread (it was now much more attractive due to the new symptoms) beyond its invention nations (the United States and France). Democratic systems have tended to stay in the new mode due the new root cause force of rule by the people, supported by the right new feedback loops: voter feedback, checks and balances, government transparency, etc. If these loops become weak the new mode will regress to the previous mode, as it threatens to do today in many democracies with authoritarian leaders (Norris and Inglehart, 2019).

Strong definition of root cause

For the class of difficult large-scale social problems like sustainability, a strong definition of root cause is required: A root cause is that portion of a system's feedback loop structure that, using the checklist below, explains why the system's structure produces a problem's symptoms. The checklist allows numerous unproductive root causes (particularly intermediate causes posing as root causes) to be eliminated. The five requirements of a root cause are:

1. It is clearly a (or the) major cause of the symptoms.
2. It has no worthwhile deeper cause. This halts the asking of "Why did this occur? What is its cause?" at an appropriate point.
3. It can be resolved, by pushing on its high leverage point(s) to initiate the desired mode change in complex problems, or to merely change the node with the root cause in simple problems. (Mode change versus node change) Resolved means the problem will probably not recur due to that root cause.
4. Its resolution will not create other equal or bigger problems. Side effects must be considered.
5. There is no better root cause. All alternatives have been considered to the point of diminishing returns.

The first three requirements are from (Harich, 2010). In the spirit of continuous process improvement, two more have since been added.

The second of ten "distinguishing properties" of wicked problems identified by Rittel and Webber (1973, italics in original) was "Wicked problems have no stopping rule. … There [is no] criteria that tell when *the* or *a* solution has been found." Requirement 3 of the strong definition of root cause provides that stopping rule. If high leverage point testing shows that the root causes of a problem can be resolved with a high degree of confidence, the solution may be considered found and the Solution Convergence step of SIP can stop, even though the exact solution that directly alleviates problem symptoms cannot be definitively described beforehand. It appears organically, as a result of the social system's evolutionary response to the mode changes induced by resolving the root cause forces. For example, the Autocratic Ruler Problem (Figure 6) was solved by the fundamental solution of modern democracy. But the exact solution, a nation's constitution and related laws, varies and is always evolving.

The five substeps of analysis

Analysis precedes iteratively using the sequence of problem decomposition, construction of the static hypothesis for each subproblem using SFDs, formulation of the dynamic hypothesis of each subproblem using causal loop diagram, and finally formulation of the simulation model using system dynamics. Static refers to causal chains, while dynamic refers to feedback loops. The role of the dynamic hypothesis and simulation model is to confirm the static hypothesis and provide supporting detail.

Each subproblem is analyzed separately, with causal connections as necessary. Using the SFD as input, the five substeps of analysis are used in building the dynamic hypothesis. The substeps serve as a "cookbook" procedure for achieving a solid first iteration of a subproblem's essential causal structure, using a highly structured form of the Five Whys. By modeling *only* the loops related to the intermediate and root causes, and the low and high leverage points, the essential causal structure of a problem can be identified exactly, closely examined, and then reengineered to achieve the desired mode change. Everything else is ignored. The result tends to be a relatively sparse model.

The five substeps of analysis are:

A. Find the immediate cause of the subproblem symptoms in terms of the system's dominant feedback loops. – Create a feedback loop model that produces the symptoms. Next study the model to see which loops are dominant and causing the symptoms. Those loops are or contain the immediate cause. In more complex problems there will be a chain of intermediate causes.

B. Find the intermediate causes, low leverage points, and superficial (symptomatic) solutions. – If we want to find out what to do right, we must first learn from the past by finding out what's being doing wrong and why. Superficial solutions push on low leverage points. Low leverage points are strategies for attempting (in vain) to resolve intermediate causes. SFDs clearly explain why superficial solutions fail, a tremendously helpful insight.

SFDs model three main forces: superficial solution forces (S), fundamental solution forces (F), and root cause forces (R).

Superficial solutions work only partially, temporarily, or not at all because the superficial solution forces can never exceed the root cause forces. Figure 6 shows this law of behavior with $S < R$. The equation means "S is always less than R." By contrast, fundamental solution forces work because $F > R$, meaning "Fundamental solutions will succeed because they can be designed such that $F > R$."

C. Find the root causes of the intermediate causes. – This substep is the endpoint of applying the Five Whys. Because investigation is so well structured, finding the root cause(s) should be relatively easy compared to traditional methods. You know it's there because *something* must be causing the intermediate cause. A root cause explains why trying to resolve an intermediate cause doesn't work. This explanation may be static, using an SFD. It may also be dynamic, using a dynamic hypothesis and model, if these are needed to find the root cause.

The root causes of a difficult large-scale social problem must be systemic because "Only a system level cause can actually be considered the root cause of a problem" (Okes, 2019, p. 15). For social problems, systemic means "originating from the structure of the system in such a manner as to affect the behavior of most or all social agents of certain types, as opposed to originating from individual agents" (Harich, 2010). Whenever you see most of a system's social agents misbehaving in the same manner, what you have is a systemic problem with systemic root causes.

If analysis shows no F > R exists, the problem is insolvable. When this occurs, the problem should be redefined such that at least one F > R exists, and analysis should start over with the new equation(s) in mind. Or solution should not be attempted and the problem declared insolvable. But now you know exactly why it cannot be solved and will not waste any more effort on solving it.

RCA does not treat root causes as absolute truths awaiting discovery. "This is the root cause" is short for "This is the root cause we found." Different analysts can find different root causes in a complex problem. But if each lead to solution, this difference doesn't matter.

D. Find the feedback loops that should be dominant to resolve the root causes. – In this substep you find the feedback loops that, if you could change them to be dominant, would resolve the root cause and solve the problem. These loops usually already exist but are weak. Sometimes these loops may not exist at all, such as the way the voter feedback loop did not exist before invention of democracy.

E. Find the high leverage points to make those loops go dominant. – Here you find the high leverage points that when pushed will make the feedback loops found in substep D go dominant and solve the problem.

The key output of the Analysis step is the high leverage points. A high leverage point is a specific place in a system's feedback loop structure that solution elements push on in order to efficiently resolve the connected root cause. A high leverage point is thus a high-level solution strategy.

Step 3. Solution Convergence

Using Analysis step results as input, this step converges on the solution elements that can push on the high leverage points effectively. Because of the deep understanding accomplished in analysis, searching the solution landscape for solutions becomes an almost trivial task. This step equates to creation of the Countermeasure in Figure 3.

“When the root causes are discovered, the ‘answers’ to solve the problem become obvious” (Liker and Meier, 2006, p. 341). By comparison to step 2, step 3 goes quickly. In a large social problem, there are countless possible solutions. But there are only a few realistic ways to push on a single high leverage point. These become solution candidates.

The solution candidates are then tested. Testing reduces the number of candidates to the selected few that will be recommended for implementation. Testing takes many forms, principally simulation model scenarios, laboratory experiments, field experiments, and pilot programs. For difficult problems much iteration with the Analysis step will be required. The Solution Convergence step ends when there is a high probability the selected solutions will work to initiate the desired mode change scenario.

As convergence proceeds the analysis is updated to reflect how pushing on high leverage points causes the system to behave. This way you always know why a solution *should* work, and eventually why a solution *does* work. If a solution doesn’t work, the reason why is relatively easy to determine by inspection of the analysis and further iteration.

SIP, like TPS, is based on the Scientific Method. Each high leverage point is a testable hypothesis. Each solution test or implementation is an experiment testing that hypothesis. TPS implements “scientific thinking skills” by “assuming that answers will be found by test rather than deliberation. You make predictions and test them with experiments” (Liker, 2020, p. 9).

Step 4. Implementation

Here the most promising solutions become policy proposals and if accepted are implemented. Implementation tends to go smoothly, in an engineering-like manner with a minimum of surprise and solution adjustment, due to high predictability of how the system will respond, especially because the change resistance subproblem is part of the analysis. Once the change resistance subproblem is solved at the root cause level, the system “wants” to solve the problem as much as it resisted solving it before. This step equates to application of the Countermeasure in Figure 3.

Continuous process improvement

Underneath the four main steps lies continuous process improvement, the foundation of the entire process. This practice has taken SIP, the analysis, the sample solution elements, and countless other processes to where they are today. Continuous process improvement is required to perfect any highly productive process. Improvement actions include what happens after the Implementation step, which must include steps 6 and 7 in Figure 3, Evaluate and Standardize.

These two steps are not explicitly in SIP, which has been kept as simple as possible. The focus of SIP is on the hardest part, analysis. SIP was designed for one-at-a-time difficult social problem projects, rather than frequent repetitive use, as in manufacturing and service industries.

Applying SIP to the Environmental Sustainability Problem

The results reported here illustrate how SIP can be applied and how potentially powerful an RCA-based process that fits the problem can be.

SIP was iteratively developed while applying it to the environmental sustainability problem. The SIP matrix of Figure 4 was expanded into Figure 7 to summarize key analysis results. Additional rows were added for improperly coupled systems, analysis model, and immediate cause dominant loops. The one big problem of environmental sustainability was decomposed into four smaller subproblems. The columns are arranged to best accommodate shared cells. Each column was extracted from the SFD for that subproblem. For example, the SFD in Figure 8 became column D.

The analysis reached these key conclusions:

Summary of Analysis Results of Executing SIP on the Global Environmental Sustainability Problem

		A. How to Overcome Change Resistance	B. How to Achieve Life Form Proper Coupling	C. How to Avoid Excessive Model Drift	D. How to Achieve Environmental Proper Coupling	
1. Problem Definition		How to achieve global environmental sustainability in terms of the desired system goal state				
2. Analysis	Subproblems	**A. How to Overcome Change Resistance**	**B. How to Achieve Life Form Proper Coupling**	**C. How to Avoid Excessive Model Drift**	**D. How to Achieve Environmental Proper Coupling**	
A. Find immediate cause loops	Subproblem symptoms	Successful opposition to passing proposed laws for solving the environmental sustainability problem	Large for-profit corporations are dominating political decision making destructively	Inability to correct failing solutions (1) when they first start failing	The economic system is causing unsustainable environmental impact	Superficial Layer
A. Find immediate cause loops	Improperly coupled systems	Not applicable	Corporate and human life forms	Not applicable	Economic and environment systems	Superficial Layer
A. Find immediate cause loops	Analysis model	Basic Dueling Loops of the Political Powerplace	Complete Dueling Loops model. This adds the Alignment Growth loop.		The World's Property Management System	Superficial Layer
A. Find immediate cause loops	Immediate cause dominant loops	The Race to the Bottom among Politicians		Intelligent Adaptation loop in evolutionary algorithm model	Industrial Growth and Limits to Growth (the IPAT factors)	Superficial Layer
B. Find inter. causes, LLPs, SSs	Intermediate causes	System acceptance of the fallacious paradigm that Economic Growth Is Good above all else	Strong resistance from corporate proxies to solving problems that corporations don't want to solve	Laws giving corporations advantages over people	Externalized costs of environmental impact	Superficial Layer
B. Find inter. causes, LLPs, SSs	Low leverage points	More of the truth: identify it, promote it, magnify it	Logical and emotional appeals and bargaining	Citizens must directly reverse laws that favor corporations	Internalize costs	Superficial Layer
B. Find inter. causes, LLPs, SSs	Superficial solutions	Technical research, environmental magazines and articles, awareness campaigns, marches, sit-ins, lawsuits, lobbying, etc.	Corporate social responsibility, green investment funds, NGO/corporate alliances, etc.	Media use, campaigns, lobbying to get bad laws repealed	Main solutions at system level are regulations and market-based. At agent level main solutions are 3 Rs and collective mgt.	Superficial Layer
C. Find the **root causes** of the intermediate causes		The inherent advantage of the Race to the Bottom, which causes that loop to be dominant most of the time (2)	Mutually exclusive goals between top two social life forms, *Corporatis profitis* & *Homo sapiens* (3)	A high rate of defects in the political decision-making process	High transaction costs for managing common property sustainably	Fundamental Layer
D. Find the loops that should be dominant to resolve root cause		You Can't Fool All of the People All of the Time	Alignment Growth	A Politician Decision-making Feedback loop of some kind	Sustainability Growth and Impact Reduction	Fundamental Layer
E. Find the **high leverage points** to make those loops go dominant		Raise general ability to detect political deception (aka political truth literacy) from low to high.	Correctness of goals for artificial life forms. These must align with the goal of *Homo sapiens*.	Raise maturity of the political decision-making process from low to high.	Allow firms to appear to lower transaction costs for managing common property sustainably.	Fundamental Layer
3. Solution Convergence		Nine sample solution elements	Corporation 2.0, *Corporatis publicus*	Politician Decision Ratings	Common Property Rights	
4. Implementation		No policy recommendations yet since process execution is incomplete.				

(1) to the environmental sustainability problem. (2) aka low political truth literacy. (3) aka *Corporatis profitis* has the wrong goal of short-term maximization of profits.

Figure 7. SIP summary of analysis results. Results of conventional modeling approaches are confined to the superficial layer of subproblem D, indicated by the gray box.

Conclusion 1. These are the right subproblems.

These four subproblems, or ones like them, in one stroke transform the sustainability problem from insolvable to solvable, because they allow radically more productive lines of analysis and solution strategies. This decomposition (and

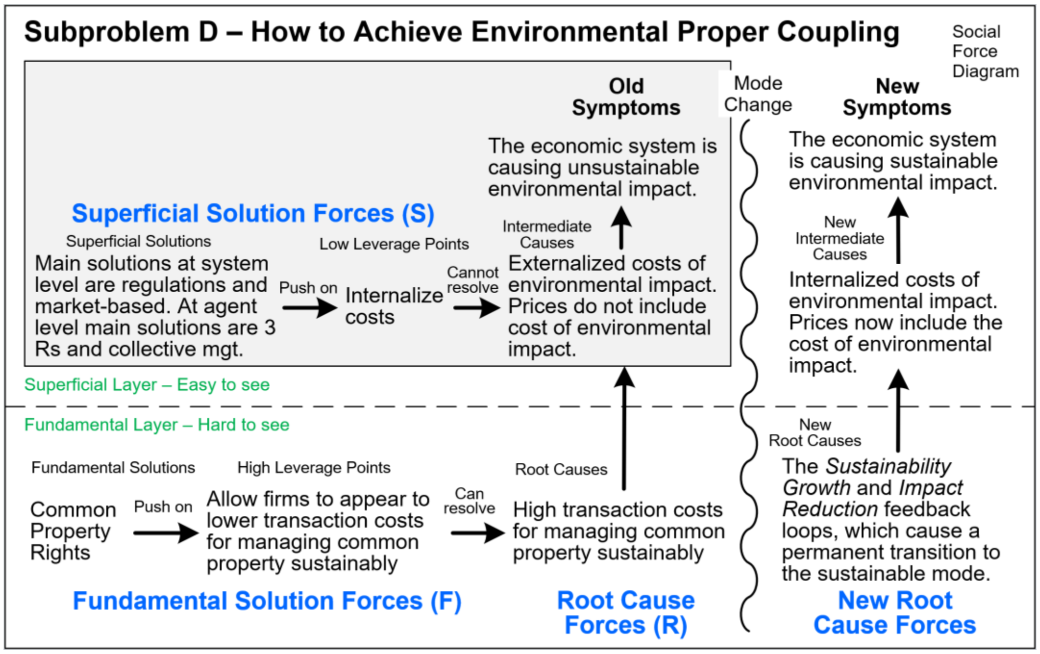

Figure 8. Social Force Diagram for subproblem D. The gray box is all that problem solvers using conventional modeling approaches can see.

simultaneous development of the three subproblems found in all difficult social problems) consumed more analysis time than anything else.

Subproblems A and C are standard subproblems. B and D are proper coupling subproblems. One additional subproblem beyond the three standard subproblems was found: subproblem B. The original problem is subproblem D.

Proper coupling occurs when the behavior of one system affects the behavior of one or more other systems in a desirable manner, using the appropriate feedback loops, so the systems work together in harmony in accordance with design objectives. In subproblem B, the two dominant life forms in the human system, *Corporatis profitis* (large for-profit corporations) and *Homo sapiens*, are improperly coupled. This causes the subproblem symptoms of “Large for-profit corporations are dominating political decision making destructively.” In subproblem D, the economic system is improperly coupled to the greater system it lives within, the environment. This causes the subproblem symptoms of “The economic system is causing unsustainable environmental impact.”

The reason we feel these are the right subproblems is each is a distinct complex system in itself, has a main root cause, and three of the subproblems work together to produce the fourth, as explained later. This provides a clear explanation of the entire problem and how to solve it.

Conclusion 2. Conventional modeling approaches are confined to the superficial layer of subproblem D.

This area of confinement is indicated by the gray box in Figures 7 and 8. This serves as a third example of how a model can endogenously replicate reference mode behavior “for the right reasons” and yet not contain the root causes.

The paradigm of how system dynamics can be applied to the environmental sustainability problem was established in Forrester's (1971) World2 model. The model pioneered use of an integrated system model (ISM) approach, using sectors for population, production capital, natural resources, and pollution. Sectors like these are an IPAT equation approach (Chertow, 2001). Forrester saw the environmental sustainability problem as only the proper coupling problem: "The battle between the forces of growth [the economic system] and the restraints of nature [the environment] may be resolved in a number of ways" (p2). This paradigm of how the problem should be modelled continued with the three successive editions of World3 and the *Limits to Growth* books.

Many more ISMs appeared and the IPAT-based paradigm continued. 36 years after World2, Costanza et al. (2007) reviewed the state of ISM modelling by examination of seven leading models: World3, IMAGE, IMAGE-2, IFs, DICE, TARGETS, and GUMBO. Table 2 compared how they handled 13 sectors: atmosphere, water cycle, land, demographic, political, development, cultural values, economics, land use, pollution, energy, agriculture, and freshwater. Political included factors like government spending by sector, democracy failure, and state failure. These sectors all correspond to the PAT factors in the IPAT equation. Pedercini et al. (2020) recently reviewed the use of ISMs for Sustainable Development Goals achievement. The pattern set by the early models has continued.

Let's examine how the IPAT paradigm led to confinement in the gray box.

Chertow (2001) related how "In the early 1970s Ehrlich and Holdren devised a simple equation in dialogue with Commoner identifying three factors that created environmental impact. … Commoner, Ehrlich, and Holdren have been extremely influential environmental thinkers for a generation." The three disagreed on which factor is "the dominant reason for environmental degradation."

The perspective of which factor is the dominant reason became the driving research question, and led to focusing on modeling the IPAT equation by increasing sector detail and adding more related sectors, in order to find the dominant factors where policy change could most efficiently solve the problem. This caused model size and complexity to grow.

Because the main focus was on modeling impact caused by IPAT factors, and because ISM models were seen mainly as integrating the economic and environment systems, problem symptoms were seen as "The economic system is causing unsustainable impact," as diagramed in Figure 8. The cause of that was seen to be the "Externalized costs of environmental impact. Prices do not include the cost of environmental impact." Because this was the cause, there was no need to dig any deeper or search for additional subproblems, as we have done with RCA. *This led to further research being confined within the gray box.*

That externalized costs are the most basic cause of public interest problems is central to academic research. For example, *The Stern Review* (Stern, 2006), a book-length study of the climate change problem, stated that: (italics added)

> In common with many other environmental problems, human-induced climate change *is at its most basic level an externality*. Those who produce

> greenhouse-gas emissions are bringing about climate change, thereby imposing costs on the world and future generations, but they do not face directly, neither via markets nor in other ways, the full consequences of the cost of their actions.

If the most basic cause of unsustainable environmental impact is externalized costs, then the solution strategy is obvious. Those costs must be internalized, represented by "Internalize costs" on the diagram.

An army of solutions to internalize costs have been tried. The main solutions at the system level are regulations and market-based instruments, like carbon taxes and tradable permits. Regulations internalize costs via fines for unsustainable behavior or prescription of the best practices required for sustainable behavior. The cost of those practices is born by the offender. Market based instruments rely on the power of free markets to cause the desired sustainable behavior, either directly via pollution taxes, or indirectly by devices like tradable permits. The main solutions at the individual agent level are the Three Rs of reduce, reuse, recycle, and collective management.

However, these solutions have had little effect because they are superficial and exclude the other three subproblems.

Conclusion 3. An explanation of why past solutions failed.

Superficial layer results reveal why the sustainability problem remains unsolved. Without realizing it, problem-solvers have been pushing on low leverage points (Figure 7, row "Low leverage points") with superficial solutions. All large-scale solution efforts that we have examined fall into this pattern. For example, the Sustainable Development Goals, as well as earlier regimes like the Kyoto Protocol, are goal-based regulations (even if voluntary) and thus fit in superficial solutions for subproblem D. Misinformation correction, such as with fact checks and news/articles pointing out the truth, fits in with "more of the truth" superficial solutions for subproblem A.

Conclusion 4. High leverage point solutions can rapidly succeed.

A welcome surprise appeared when we uncovered the fundamental layer. If these or something like them are indeed the main root causes (Figure 7, row C), then pushing on these high leverage points (row E) will lead to rapid solution of the sustainability problem due to transformational global mode changes for each of the four subproblems. Unlike the many solutions pushing on the low leverage points, there are no large-scale solutions pushing on any of the high leverage points, suggesting that once problem solvers shift to RCA-based processes, the sustainability problem may be much easier and faster to solve than presently assumed. This is crucial for avoiding ecological tipping points related to climate change.

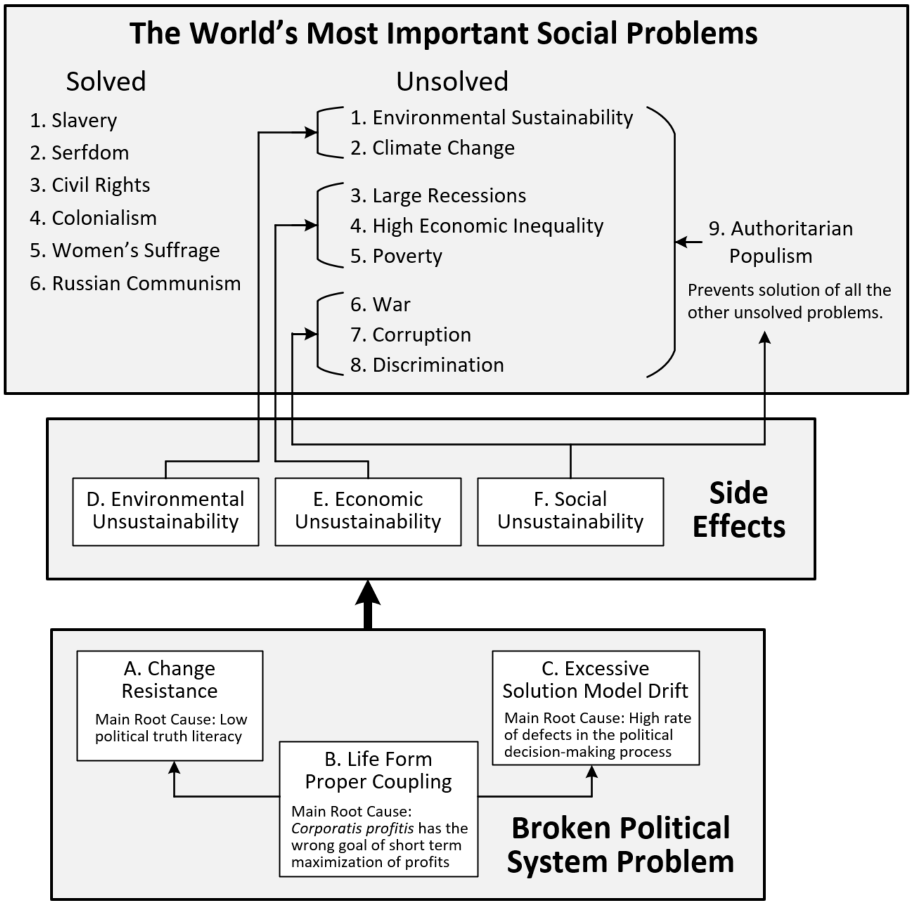

Figure 9. High-level causal diagram of the Broken Political System Problem and its consequences. Subproblems E and F have been added to give all three pillars of sustainability. The lists of problems are not complete or definitive.

Conclusion 5. There is a deeper problem to solve.

As analysis proceeded a striking pattern emerged. The environmental sustainability problem was not the only large social problem society has been unable to solve. There are many more, as the 17 Sustainable Development Goals suggest. There are also many problems society *has* been able to solve. The pattern is that all of these problems would benefit the common good if solved, but yet some invisible force was causing one group of problems to be solved and the other group not solved. Patterns this strong do not happen by chance. What could explain this phenomenon?

Further application of the process led to an answer (Figure 9). The diagram explains why society has been unable to solve so many common good problems. The root cause forces of subproblems A, B, and C combine to form a deeper problem, the Broken Political System Problem. Its side effects are that all three pillars of sustainability are weak. *Therefore, the Broken Political System Problem is the real problem to solve.*

The ideals of democracy and pursuit of the common good pervade the planet, even in China (Wang, 2007). In theory the world's nations *should* be intently focused on solving the eight unsolved problems and mostly succeeding, but yet in practice they are not, due to the Broken Political System Problem. The problem is so systemic it causes extraordinarily high change resistance to solving any problem that runs counter to the goal of what has become the dominant life form (Beder, 2006; Korten, 2015; Shamir, 2005) in the human system, *Corporatis profitis*, better known as the large modern for-profit corporation. Like the way *Homo economicus* models the behavior of humans (a genetic species) as consistently rational, optimal agents in pursuit of self-interest and serves as a cornerstone component of economic theory (Ng and Tseng, 2008), *Corporatis profitis* models the way large for-profit corporations (a memetic species) behave and serves as a key component of the analysis theory.

The main root cause of subproblem B is that *Corporatis profitis* has the wrong goal of *short-term maximization of profits*. (As identified in Figure 7, subproblem B, substep 2C.) This incentivizes the corporate hegemony (Levy, 1997) into leading the charge against solving the environmental sustainability problem, though that effort is masked by clever deception (Beder, 2006, 2002; Hoggan, 2009). This works due to the main root cause of successful change resistance: *low political truth literacy*. (Figure 7, subproblem A, substep 2C.) Truth literacy is the ability to tell truth from deception, i.e., to be able to "read" the truth. Political truth literacy is the ability to vote correctly, given the level of truth of political statements.

Because political truth literacy is low, corporate deception works and has become the cornerstone strategy for achieving the interests of *Corporatis profitis*. The more acceptable term for corporate deception is public relations (PR), which works as follows: (Dinan and Miller, 2007, pp. 11 & 12)

> Public relations was created to thwart and subvert democratic decision making. It was a means for 'taking the risk' out of democracy. The risk was to the vested interests of those who owned and controlled society before the introduction of voting rights for all adults. Modern PR was founded for this purpose and continues to be at the cutting edge of campaigns to ensure that liberal democratic societies do not respond to the will of the people and that vested interests prevail. PR functions, in other words, as a key element of propaganda managed democracy. … [PR] is overwhelmingly carried out for vested powerful interests, mainly corporations. … It characteristically involves deception and manipulation.

As numerous scholars have phrased it, "democracy is broken", e.g. (Freeman, 2017; Lukensmeyer and Brigham, 2002; Norris and Inglehart, 2019; Panagopoulos and Weinschenk, 2016). Figure 9 explains why. Instead of working for the common good, too many political systems are working for the uncommon good of large for-profit corporations, and to a lesser extent authoritarian populism leaders like Putin, Trump, Erdogan in Turkey, Bolsonaro in Brazil, and Modi in India, a "terrifying" trend with widespread popular support and destructive consequences for environmentalism (McCarthy, 2019).

Corporatis profitis is dead set against solving the environmental sustainability problem and is winning, because of its overwhelming control of the human system, superior financial power compared to mere citizens, and its obsessive goal of short-term profit maximization. This goal conflicts with the goal of *Homo sapiens*, which is the long-term optimization of quality of life for people. These goals are mutually exclusive. Because *Corporatis profitis* dominates the system, its goal prevails and has become *the wrong implicit goal of the system*. As Peter Senge (1990, p. 88) warns us when this occurs, “The resistance is a response by the system, trying to maintain an implicit system goal. Until this goal is recognized the change effort is doomed to failure.” Donella Meadows (2008, p. 113) phrases her warning differently: “Such resistance to change arises when goals of subsystems are different from and inconsistent with each other.”

The wrong implicit goal has caused high systemic change resistance to solving problems whose solution would reduce short term profits. The result is the eight unsolved problems of Figure 9 and more not listed. The ninth unsolved problem, authoritarian populism, is a deception strategy blending authoritarian values with populist rhetoric to create a cult of fear, driving citizens into supporting only what an authoritarian leader wants, even if this requires sacrificing personal freedom (Norris and Inglehart, 2019).

While it took time and some struggle, the reason the six problems on the left of Figure 9 were solved was low change resistance. Solving these problems did not pose much of a threat to *Corporatis profitis*.

Integrating RCA into the system dynamics modeling process

The rich and productive conclusions of applying SIP to the sustainability problem, one of which explained why ISMs have been confined to the gray box and have thus failed to generate workable policies, lead us to believe that RCA can be successfully integrated into a system dynamics modeling process suitable for difficult problems. The target problem type is not just the difficult large-scale social problems ISMs model, but any problem so difficult it requires a customized form of RCA that cannot be found in existing processes.

As we see it, the task is to integrate three processes (Table 1) into a single process. We chose Toyota's practical process rather than Toyota's A3 Report process, since that is a lower-level shop floor version of the practical process. We chose the Sterman process as it is productive, well described, well organized, and being so widely taught, is the present de facto standard (Sterman, 2000, p. 86).

Table 1. Main steps in the three problem-solving processes to integrate. The second row is the most common problem type the process was designed for.

Toyota's practical problem-solving process (Figure 3)	**System Improvement Process (Figure 4)**	**Current system dynamics modelling process (Sterman)**
Manufacturing and service process improvement problems	Difficult large-scale social problems	Business client problems
Initial problem perception	Problem definition	Problem articulation
Clarify the problem	Problem decomposition	Formulation of dynamic hypothesis
Locate area/point of cause	Subproblem analysis using the five substeps	Formulation of a simulation model
Five Why investigation of the root cause	Solution convergence	Testing
Countermeasure	Implementation	Policy design and evaluation
Evaluate		
Standardize		

The resulting synthesis is outlined in Table 2.

Table 2. Integrated RCA-based system dynamics modeling process for difficult causal problems

1. Problem Articulation

A. Initial problem perception: Study the large, vague, complicated problem. Develop an understanding of what the problem is and why it's a problem.

B. Collect problem clarification data: Collect the information required for the next step.

C. Formal problem definition: Define the problem using the standard format: Move system A under constraints B from present state C to goal state D by deadline E with confidence level F. Modify the format as necessary to fit the problem. This step defines the original subproblem.

2. Formulation of the Static Hypothesis

A. Begin detailed data collection: This continues throughout the process as necessary.

B. Problem decomposition: Decompose the one big problem into the standard subproblems for the problem type, plus additional subproblems as needed. Innovate as necessary.

C. Social Force Diagrams: Develop an SFD for each subproblem.

D. Explanation of the Gestalt Whole: Arrange the SFDs into a single high-level causal diagram, with optional feedback loops, that explains the problem as a cohesive whole.

3. Formulation of the Dynamic Hypothesis

A. Subproblem structure: Develop a causal loop diagram (CLD) for each subproblem, starting with its SFD and using the five substeps of analysis. The CLD must be endogenous and may be a hybrid with stocks.

B. Whole problem structure: Integrate the CLDs into a single high-level CLD.

C. Additional mapping: Supplement A and B with additional mapping tools as necessary to reach the point of a solid and clear foundation for the next step.

4. Formulation of a Simulation Model

A. Construct the system dynamics model: Build the model using the above artifacts as input, with emphasis on modeling the causes and leverage points identified on the SFDs. Behavior must arise endogenously from model structure.

B. Qualitative behavior: Tune the model to qualitatively behave realistically in terms of leverage point behavior. Estimation of parameters, equations, and structure is usually required at first, since not all data has been collected and the structure is evolving. Once you are satisfied the model has proper qualitative behavior and structure, move on to the next step.

C. Quantitative behavior: Determine which estimations must be based on real data, collect the data, then change and tune the model to use that to achieve sufficiently accurate behavior.

5. Theoretical Testing of the Low and High Leverage Points

Proceed as in the Sterman Testing step, except emphasis is on leverage point behavior. The reference mode occurs when present superficial solutions are applied. The model should be able to simulate the hypothesized behavior of the SFDs, including mode changes. The model is now theoretically rigorous, in that it reflects real world problem structure and behavior.

6. Policy Design and Evaluation

A. Proceed as in Sterman: Design policies to push on specific high leverage points.

B. Empirical testing of solution elements: In this additional step testing is done empirically in the real world, with laboratory experiments, field experiments, and pilot projects as necessary. This step ends when there is a high probability of solution success. The model and solutions are now theoretically and empirically rigorous, and can be said to be well engineered.

7. Solution Implementation

A. Policy recommendation: Recommended policies are presented and justified. The problem owner(s) has engaged in the process at many points up until now, so this should go well.

B. Policy implementation: The policies are translated to what the problem owner requires for implementation, approved, and then implemented. Due to process design, implementation should go smoothly, in an engineering-like manner with a minimum of surprise and solution adjustment, due to high predictability of how the system will respond.

8. Solution Learning

A. Policy results monitoring: How the system responds is monitored.

B. Learning: There will almost always be some deviation from solution behavior prediction in difficult problems. The monitoring data is evaluated and used to improve what was learned in any of the above steps. If others will use the same process or solutions, they are standardized and improved as more is learned.

The resulting integrated process is a customized version of the Sterman process that fits problems so difficult they require well-structured RCA. The process captures how we approached analysis using SIP and the Sterman process, though we are speculating on how steps 7 and 8 should work. We have learned from experience and are attempting to standardize that knowledge in this paper. This is a starter process, as only continuous improvement can produce a mature process.

Note how the root cause point of view drives the process, rather than the endogenous point of view. This begins in step 1C, *formal problem definition*. The problem is not defined in terms of reference mode behavior, but the gap between the present and goal states. For example, for the climate change problem, temperature rise must be limited to 1.5 degrees Celsius. For a fluctuating inventory problem, fluctuation must be limited to a range of 20%. For the recurring large recessions problem, decline in one year in GDP must not exceed, say 10%. The gap to close and the rest of the standard format is all that's needed to tightly define and focus the problem from a root cause point of view.

The root cause viewpoint continues with use of problem decomposition, SFDs, the five substeps of analysis, and heavy emphasis on leverage point behavior in model construction, testing, and results monitoring. Superficial solutions push on low leverage points (in vain) to resolve intermediate causes. Fundamental solutions push on high leverage points to resolve root causes. Model emphasis always centers on structural explanation of the SFDs.

Difficult problems vary. In step 2B, *problem decomposition*, the analyst should use standard subproblems plus additional ones as necessary for whatever problem type they are working on, or design new subproblems for a unique problem or the first problem in a new domain. The three standard subproblems described in this paper fit only one problem type: difficult large-scale social problems.

Conclusions

The paper began with Forrester's question: "Why is there so little impact of system dynamics in the most important social questions?" We found that the main reason for little impact, based on study of RCA in industry, is that the foundation of system dynamics modeling is the endogenous point of view rather than the root cause point of view when working on difficult problems. This suggests that if the field of system dynamics wishes to solve important social problems, it must switch to the root cause point of view, using a suitable comprehensive process.

The payoff to the business world for switching to its own suitable process (the Deming Cycle) was the ability to solve previously insolvable problems, beginning with solution of their own wicked problem: How to consistently mass produce products of very high quality and low cost. RCA is generic and applies to all types of causal problems. Therefore, by integrating an appropriate RCA-based process into the system dynamics modeling process, we can expect the same payoff for wicked social problems, as well as difficult problems in general.

The paper described an example of how this integration can be done. The integrated process works by driving model construction with well-structured RCA.

As one example of the potential benefits of the integrated process, consider humanity's most pressing high-impact problem: environmental sustainability and in particular, climate change. Efforts to solve this problem have failed for decades, due to high change resistance to proposed solutions. Resistance is so high the Paris Agreement is voluntary, as are the Sustainable Development Goals. Progress is so poor that "decades of scientific monitoring indicate that the world is no closer to environmental sustainability and in many respects the situation is getting worse" (Howes et al., 2017).

The principals of the *Limits to Growth* project all pointed out the need to overcome this resistance:

Jay Forrester (2007) argues that finding the answer to "Why is there so little impact of system dynamics in the most important social questions?" requires modeling the root causes of change resistance and how to revolve them: "How often do you see a paper that shows all of the following characteristics?" The last two were: "8. It examines why the proposed policies will be resisted. 9. It recognizes how to overcome antagonism and resistance to the proposed policies."

Donella Meadows (1980, p. 37) stated that "[Policy] recommendations are often politically unacceptable. The problem is intrinsic to the basic paradigm of system dynamics and the nature of public decision making, and will probably always be a factor hindering the practical use of system dynamics in the policy world".

Dennis Meadows (2012) feels that the "political and financial power [of the industries behind unsustainable growth] is so great [that] they can prevent change." He sees no solution. "It is my expectation that they will succeed."

Jorgen Randers (2012, p. 326) reasoned that "solving the climate problem amounts to a minor restructuring of the economy. This can be done without much difficulty—but only if the voters and rulers actually want to do it, which is rarely the case." He repeated this point in a talk commemorating the fortieth anniversary of *Limits to Growth* (Smithsonian, 2012, minute 14:00). One slide stated that "The root cause of current decision delays" was "We know the solution. But we don't like it."

But how exactly does the system dynamics modeler go about finding the root causes of change resistance? On that the field is silent, other than what the endogenous point of view implies: If a model can endogenously reproduce a problem's reference mode "for the right reasons," then it must contain the "causes."

For the climate change problem, lack of a suitable way to analyze and solve resistance to proposed policies has stymied system dynamics modelers. The integrated process eliminates that roadblock by use of RCA and the standardized subproblem of How to overcome systemic change resistance.

Inspection of major ISMs of the sustainability problem (Costanza et al., 2007; Pedercini et al., 2020), beginning with World2 and running up to current ones, shows none incorporate the concept of the change resistance subproblem or RCA. Imagine what will probably happen once current models add a change resistance sector with root causes, run tests to develop practical solutions for resolving those root causes, and include first overcoming change resistance in their policy recommendations.

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Supplementary materials

For additional sections pertaining to this paper please see *Supplementary Sections for The Process Must Fit*. The sections are: Current methods for finding a difficult large-scale social problem's root causes, How we found the root causes, How we developed SIP, Integrated Process Step 6B - Empirical Testing of Solution Elements, and How long will it take system dynamics to accept the Deming philosophy? Step 6B includes a short overview of the Truth Literacy Training study.

For further detail on SIP please see the book *Cutting Through Complexity: The Engineer's Guide to Solving Difficult Social Problems with Root Cause Analysis*, freely available at Thwink.org. The book contains full description of the process, an analysis of the sustainability problem using the process, the Truth Literacy Training study, and twelve sample solution elements.

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