thwink.org

All problems arise from their root causes.

Root cause analysis as a foundational tool for sustainability science

Jack Harich[1], Montserrat Koloffon Rosas[2,3], Michael Hoefer[4]

[1]Thwink.og, Atlanta, USA. jack@thwink.org. Corresponding author.

[2]Vrije Universiteit Amsterdam, Amsterdam, Netherlands.

[3]Thwink.org, Atlanta, USA, montse@thwink.org.

[4]University of Colorado Boulder, USA, michael.hoefer@colorado.edu.

Abstract

Despite immense attention from scholars and others, solution strategies have failed to address the sustainability challenge, particularly the environmental pillar. We propose the central reason is that due to the extreme dynamic complexity of the problem it cannot be solved without root cause analysis (RCA), which was not used to develop past solutions. While RCA has long been a core tool for solving difficult business/engineering problems, application to social problems remains hindered because no suitable version of the tool exists for difficult social system problems, which differ radically from non-social problems. How then can RCA be adapted to solve difficult social problems, particularly environmental sustainability? To address that question our research iteratively developed an RCA-based process for difficult social problems, while simultaneously applying the process to the environmental sustainability problem and developing what we found to be the fundamental laws of RCA. We conclude this adaption can be accomplished by any RCA-based process incorporating these laws in a tightly integrated manner and offer suggestions for further research.

1. Introduction

Ever since classic works like *Silent Spring* (Carson 1962) and *The Tragedy of the Commons* (Hardin 1968) brought the environmental sustainability problem to the world's attention and *The Limits to Growth* (Meadows et al. 1972) defined the problem in sufficient detail using a series of stunning simulation scenarios, scholars have moved to increasingly sophisticated problem-solving methods. These include a long history of integrated global modeling (Costanza et al. 2007), ecological economics for balancing the eco/economic relationship (Costanza et al. 1997; Daly and Farley 1997), world system analysis (Hornborg and Crumley 2006), resilience theory as the basis for automatic adaptive governance (Folke et al. 2010), the many frameworks of sustainability transitions (Markard et al. 2012), the single research framework of earth system

governance (Burch et al. 2019), and proposals to structure sustainability science research itself (Jerneck et al. 2011). Eight Earth Summits from 1972 to 2019 culminated first in the Brundtland Report's widely accepted definition of "sustainable development" in 1987 (World-Commission 1987) and later the solution mechanism of governance by goal-setting (Biermann et al. 2017), with adoption of the Millennium Development Goals in 2000, followed by transition to the Sustainable Development Goals (SDGs) in 2015.

While there have been some gains, such as in local pollution and stratospheric ozone depletion, "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). Such lack of progress indicates something in these methods, and hence the solutions they produce, is flawed.

In an increasingly urgent effort to find those flaws and correct their methods, scientists closed ranks and began building the new field of sustainability science (Kates et al. 2001; Takeuchi and Komiyama 2006; Clark 2007). As Kates announced, "A new field of sustainability is emerging that seeks to *understand the fundamental character of interactions* between nature and society," with the intent of developing "society's capacity to guide those interactions along more sustainable trajectories."

We propose that understanding can be achieved by taking the transdisciplinary shortcut of adapting a *business* tool to fit *social* problems. A widely used, proven choice is available for understanding the fundamental interactions of any causal problem: root cause analysis (RCA). RCA can potentially provide sustainability science with the knowledge structuring, problem-solving orientation, and generic research platform identified by Jerneck et al. (2011) as critical for the field to have the capacity to solve the sustainability challenge. Miller et al. (2014) contend that "sustainability science must link research on problem structures [which this paper calls essential problem structure] with a solutions-oriented approach." RCA provides the missing methodology for that link.

However, RCA was developed by business to solve difficult business and engineering problems. No suitable version exists for difficult social problems, which differ so radically from non-social problems that they are wickedly difficult and "seem to defy conventional strategies for public policy interventions designed to address them" (Newman and Head 2017). Consequently, to our knowledge RCA has never been effectively applied to difficult social problems. This offers a clear, unifying explanation of why past solutions to the sustainability problem have largely failed: None were based on a suitable version of RCA, so the solutions were unknowingly directed toward intermediate rather than root causes. In this paper, difficult social problems are those that have remained unsolved after continued solution attempts for a generation (twenty-five years) or more and are large-scale (macro), involving social systems of millions of people.

That no suitable version of RCA exists for difficult social problems, particularly the sustainability crisis, reveals an enormous gap and an equally enormous opportunity for establishing a workable foundation for sustainability science. The research question is precisely this: How can the powerful *business* tool of root cause analysis be adapted to solve difficult *social* problems, particularly environmental sustainability?

This paper reports on our work on this question. Over a seven-year period a generic process based on RCA for solving difficult large-scale social problems, the System Improvement Process (SIP), was iteratively developed while simultaneously applying the process to the environmental sustainability problem and identifying the fundamental laws of RCA. The paper is organized into a short review of RCA, the laws of RCA, the key features of SIP, process application results, and our main conclusions.

2. The essence of root cause analysis

RCA originated with the "King of Japanese Inventors," Sakichi Toyoda, in the early twentieth century when he formalized how he applied the method with the justly famous Five Whys, where starting at the symptoms one asks "Why does this occur?" until the root causes are found (Imai 1986, p. 50; Ohno 1988, p. 77).

Today, RCA serves as the foundational paradigm of widely used, highly refined business processes with high process maturity like the ISO 9000 family of international quality standards (Tummala and Tang 1996), lean production (Womack et al. 1990), and Six Sigma (Pande et al. 2000). The ubiquitous leader is Six Sigma, used by 100% of aerospace, motor vehicle, electronics, and pharmaceutical companies in the Fortune 500 and 82% of all companies in the Fortune 100 (Marx 2007).

Industrial RCA revolves around the concepts of defects and root causes. RCA is used to maximize the quality of solutions to customer's problems. Anything that displeases the customer is a defect. Defects arise from root causes. Six Sigma, an RCA-based process for radical improvement of core business processes, routinely cuts defect rates by an astonishing three orders of magnitude, from roughly 6,210 defects per million transactions to 3.4, as process maturity rises from a typical initial level of sigma 4 to a final level of 6 (Pyzdek 2003, pp. 5 & 60). RCA has become so central to quality management and problem solving that "Root cause analysis is an essential process for any organization that wants to continue to improve and is willing to engage in serious introspection and analysis" (Dew 2003).

The RCA paradigm rests on several core concepts. Drawing from a diversity of sources, e. g. (Ishikawa 1986; Pyzdek 2003; George et al. 2005; Tague 2005; Andersen and Fagerhaug 2006; Okes 2019), a root cause is the deepest cause in a causal chain (or the most basic cause in a feedback loop structure for more complex problems) that can be resolved. 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/organization problems like criminal investigation, and puzzle solving. All causal problems arise from their root causes. The sustainability problem is a causal problem. It can therefore only be solved by resolving its root causes, whether root cause terminology is used or not. RCA employs hundreds of supporting tools and techniques. RCA is generic and for difficult problem use must be wrapped in a process tailored to the problem class.

From the vantage point of quality management, where all problems are seen as forms of unacceptable quality of solution of a customer's problem (note that citizens are customers of their governments), the business/engineering world has concluded that RCA

is the only known core method for solving difficult causal problems reliably and efficiently, e. g. (Tague 2005 pp 338-47, The Quality Improvement Process). Other core analytical methods, such as experimental trial and error, forms of statistical analysis like comparative and factor analysis, and simulation modeling, can sometimes eventually solve difficult causal problems. But they cannot do so reliably and efficiently, because unless RCA is combined with these methods the full causal structure of the problem remains hidden.

3.   The fundamental laws of RCA for difficult causal problems

The scientific rationale behind SIP stems from a set of laws (aka critical success factors) created by long study of the business/engineering RCA literature as SIP was developed. These are laws rather than principles since each describes "a stated regularity in the relations or order of phenomena in the world that holds, under a stipulated set of conditions, either universally or in a stated proportion of instances" (Editors 2014). The laws systemize the core strategy of the RCA paradigm as is practiced on difficult business problems, and as RCA can be practiced on difficult social problems. All must be followed to reliably achieve success.

Clark and Dickson (2003) characterized the emerging field of sustainability science as a field in its prescience stage when they described it as "not yet an autonomous field or discipline, but rather a vibrant arena that is bringing together scholarship and practice, global and local perspectives from north and south, and disciplines across the natural and social sciences, engineering, and medicine." In the terminology of Kuhn (1996), *prescience* practitioners operate under no uniformly accepted paradigm, with no standard set of methods and much unstructured activity and disagreement. They encounter mostly steady failure on solving the field's major problems. Sustainability science is clearly in prescience, as seen in the decades of failure noted earlier by Howes et al. (2017) and the many competing methods listed in the beginning of the Introduction. After discovery and acceptance of a single central paradigm that works reliably, the field enters its *normal science* stage, where research is firmly based on that paradigm. Henceforth major problems of an escalating degree of difficulty are routinely solved.

Scientific paradigms consist of a comprehensive foundation of laws, principles, theories, exemplars, and replicable methods that form "an acceptable model or pattern." (Kuhn 1996, p. 23) At the core of this foundation lie the fundamental laws governing how the crucial aspects of the paradigm work.

The goal of sustainability science is to solve the causal problem of sustainability. *We therefore propose a foundational tool for sustainability science can be most efficiently built by extracting the fundamental laws of RCA for difficult causal problems as practiced in industry, and wrapping those laws in a process tailored to fit difficult social problems.*

After describing a similar extraction project to demonstrate the strength of this proposal, the remainder of this section describes the laws. The first eight were found in highly mature processes used to solve difficult business/engineering problems. Particular attention was given to global exemplars like lean manufacturing, Six Sigma, and the Toyota Production System, e. g. (Womack et al. 1990; Pyzdek 2003; Liker 2004).

The ninth law was added to accommodate social problems and has been somewhat proven by examination of historical cases where mode change accompanied solution of a difficult large-scale social problem, with Figure 2 showing two cases. This addition appears to make the set of laws sufficiently complete for difficult social problems, allowing the set to serve as a starting point for further process improvement. What the laws were did not become fully clear until SIP was fully constructed, as its evolution and study of the RCA literature was highly iterative.

3.1. A similar extraction to create a needed process

In the late 1980s a similar extraction project was performed to create a needed process: lean production. 25 years later, based on an exhaustive literature review of 4,130 lean publications, Samuel et al. (2015) appraised the project as having had such successful results that it catalyzed a worldwide paradigm shift from mass production to lean production. Lean production centers on continuously reducing waste of all kinds (hence the name "lean") by finding its root causes and implementing countermeasures to resolve them, all for the purpose of delivering optimum quality/cost to the customer.

In the 1970s and 1980s the auto industries of North America and Europe were rapidly losing market share to Japanese imports, which offered higher quality at lower prices. To close the gap, in 1985 the International Motor Vehicle Program at MIT initiated a major research project, with the mission of distilling the essence of the Japanese approach into a comprehensive, documented, generic process suitable for manufacturing and service industries of any type, especially auto manufacturing. This mission closely parallels that of our own project, to determine how to distill the essence of industrial RCA into a generic process suitable for difficult social problems, especially sustainability.

Five years later three directors of the program published research results in the aptly named bestseller *The Machine that Changed the World: The Story of Lean Production* (Womack et al. 1990). The book launched the lean revolution in Western industry and concluded that "the principles of lean production can be applied equally in virtually every industry across the globe," (p8). Because Toyota invented and exemplified lean production (Liker 2004, p. 4) the primary source of study was the Toyota Production System. Holweg (2007) describes how a "key driver" behind the book's success was "the readable, non-technical style of the book. The book was not geared at academics, but directed towards senior executives and government officials."

The Machine covered a vast amount of material. Our own similar report/book, *Cutting Through Complexity: The Engineer's Guide to Solving Difficult Social Problems with Root Cause Analysis*, available at Thwink.org, is also written for a general audience and covers a similar amount of material. This includes full description of the laws of RCA, SIP, process application results, analysis simulation models, twelve sample solutions elements, and an empirical study on the effectiveness of Truth Literacy Training, a solution element. This paper reports only a brief summary of research highlights. For further detail the reader is referred to the book as supplementary material. However, compared to *The Machine* we view our work as preliminary rather than definitive.

3.2. Laws 1, 2, and 3. The three laws of causal structure.

1. The first law is axiomatic and defines the very core of the RCA paradigm: *All causal problems arise from their root causes.* Find the root causes, resolve them, and the problem is fully and relatively permanently solved. We define RCA as the systematic practice of finding, resolving, and preventing recurrence of the root causes of causal problems. The literature offers many formal definitions, such as by Okes (2019, p. 77): "[RCA is] the generic steps involved in (1) identifying a problem, (2) performing a diagnosis, (3) selecting and implementing solutions, and (4) leveraging and sustaining results."

2. *Finding and resolving root causes for difficult causal problems requires understanding their essential causal structure, using some form of the Five Whys (described in section 2) and a strong definition of root cause*. We define *essential causal structure* as the nodes, relationships, and interacting feedback loops that provide a sufficiently complete model of how problem symptoms arise from their root causes and where the high leverage points are for effective solutions.

Section 4.5 provides a strong definition of root cause. This is required to avoid confusing root causes with intermediate causes or just as misleading, "common causes," which Shewhart (1931) defined as causes of acceptable variation, as opposed to the unacceptable variation arising from "special causes," also called root causes.

3. *Identifying the essential causal structure of problems with high dynamic complexity requires feedback loop simulation modeling.* This law avoids the trap of modeling the causal structure of the problem with a model incapable of being sufficiently correct.

The sustainability problem exhibits very high dynamic complexity, making "the fundamental character of interactions between nature and society" (Kates et al. 2001) enormously difficult to understand. Sterman (2000, p. 22) lists ten reasons dynamic complexity can arise in social systems. All are present to a high degree in the sustainability problem:

1. The system is constantly changing.
2. Tight coupling.
3. Agent behavior is governed by a multitude of feedback loops.
4. System behavior is nonlinear.
5. System behavior is history-dependent.
6. Self-organizing behavior.
7. Adaptive agent behavior.
8. Counterintuitive behavior.
9. Policy resistance.
10. Interventions lead to trade-offs.

Sterman then explains how feedback loop simulation modeling is required to correctly understand system behavior when dynamic complexity is high. The unaided human mind lacks the capacity to mentally identify, organize, and simulate the very complex causal structures involved.

Yet the sustainability problem *has* been extensively modeled with feedback loop integrated global models. Costanza et al. (2007) reviewed seven of these models, which

are met to "investigate what might happen if policies continue along present lines, or if specific changes are instituted." Integrated global models are widely used for scenario analysis in global environmental assessments to develop response options (van Vuuren et al. 2012)

What's missing in these models? Why have they not led to successful solutions?

A clue to what's missing lies in the intent of these models. Their goal is only to simulate probable system behavior under different policies, as the three editions of *The Limits to Growth* did with their twelve, thirteen, and ten scenarios (Meadows et al. 1972, 1992, 2004).

Missing in these models, as well as the other methods listed in the beginning of the Introduction, is *essential causal structure*. Lacking that, these models and methods can only understand the superficial layer of the sustainability problem, where the easy-to-find intermediate (proximate) causes may be found. Without a correct model of the problem's full causal structure, intermediate causes are assumed to be root causes and solutions are based on that (erroneous) assumption. The first law tells us causal problems can be solved only by resolving their root causes. It follows that if analysis of a causal problem lacks the correct root causes, analysis users will be unable to reliably solve the problem.

3.3. *Laws 4, 5, and 6. The three laws of causal forces.*

These laws employ the terms and relationships shown in the standard social force diagram of Fig. 1c and explained in section 4.1. The key abstraction is the three main forces found in all difficult problems. Force R is the root cause forces causing the problem. Force S is the superficial solution forces that attempt (in vain) to resolve the intermediate causes. Force F is the fundamental solution forces that can resolve the root causes.

4. *Superficial solutions fail because S < R,* since force S is directed at an intermediate cause. Force S is always less than force R, because root causes exert much more force on intermediate causes than superficial solutions ever can. This explains why low leverage points exist.

5. *Fundamental solutions can succeed because they can be designed such that F > R,* since force F is directed at a root cause. This explains why high leverage points exist.

6. *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 one knows exactly why it cannot be solved and will not waste any more effort on solving it.

Laws 4, 5, and 6 work together. In easy problems RCA is not needed to find the root causes because they are relatively obvious. But in difficult problems approached without a suitable RCA-based process, solutions are directed toward low rather than high leverage points, since the root causes remain hidden by problem complexity. The analysis results of Fig. 4 found this to be the case for the environmental sustainability problem. Law 4 explains why these solutions tend to fail. But with awareness of laws 5 and 6, that wasteful effort can be halted and solutions can be directed toward high leverage points.

3.4. Law 7. Avoiding the One Subproblem Trap.

Difficult large-scale problems have multiple root causes and therefore require proper decomposition into subproblems to analyze correctly. This law avoids the One Subproblem Trap, which occurs when problem solvers assume the only subproblem to solve is the original problem. Without proper decomposition, problem complexity will obscure the full essential causal structure and make correct analysis impossible because the analysis is attempting to solve multiple problems and resolve multiple root causes without realizing it.

To avoid the One Subproblem Trap and radically improve process efficiency, many industrial RCA processes offer standard subproblem sets, such as the Four Ps of marketing: Product, Place, Promotion, Price (McCarthy 1960) and the original Four Ms of manufacturing: Materials, Methods, Machines, Measurement (Ishikawa 1986, p. 19). SIP offers three standard subproblems as described later.

3.5. Law 8. Continuous process improvement for high process maturity.

Achieving the ability to solve difficult problems reliably and efficiently requires relentless continuous process improvement, in order to reach and maintain the high level of process maturity required for high quality solutions. This law encapsulates 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." The key to success lies in cultivating an organizational philosophy that is kaizen and process oriented, rather than innovation and results oriented (Imai 1986, p. xxix).

3.6. Law 9. Escaping mode lock-in.

Due to mode lock-in, difficult social problems can be solved only by correctly engineered mode changes. A mode is a general pattern of system behavior and is the same as a system state, rather than the more complex terms and definitions used in systems engineering specifications, such as described by Olver and Ryan (2014).

In difficult 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 system's dominant feedback loops. The desired mode change requires reengineering the system's structure such that when force F is applied, a new force R is created, and the system's current dominant feedback loops are replaced by new ones, causing the mode change to occur.

Earlier we stated that the gap identified by Kates (2001), the need "to understand the fundamental character of interactions between nature and society," could be filled "by taking the transdisciplinary shortcut of adapting a *business* tool to fit *social* problems." The list of laws shows how large that shortcut is. Only the ninth law needed adding to adapt RCA to fit social problems. This suggests the resulting paradigm, while radically new to most sustainability scholars, is a routine incremental adaptation to experienced RCA analysts.

4. A method for understanding fundamental interactions

This section describes SIP, a generic RCA-based process suitable for difficult large-scale social problems, particularly sustainability. SIP incorporates all nine laws of RCA in a tightly integrated manner that encourages successful application of the process.

A note of caution: The results reported here should not be interpreted as *the* laws of RCA, or *the* process, or *the* analysis, but as a meticulously built, sufficiently correct first iteration demonstrating the potential of an RCA-based process to allow solution of difficult social problems. RCA, like all tools, is not a panacea and requires thoughtful, skillful application.

With this caveat in mind, the first component of SIP is:

4.1. Social force diagrams

Multimedia research has shown that textual description of a cause-and-effect explanation alone results in 50% to 75% less learning than text combined with an appropriate visual diagram (Mayer 1997). The complex cause-and-effect behavior of quantum field reactions is impossible for most physicists to grasp without using Feynman diagrams for organizing calculations (Wuthrich 2010). Of the seven basic quality control tools and the seven new tools, only one, check lists, is not a visual diagram (Shahin et al. 2010). Accordingly, we gave considerable attention to developing a strong visual representation of the core of the SIP analysis step, and settled on a variation of the cause-and-effect diagram (Fig. 1a), one of the seven basic quality control tools, combined with the quantum transition (mode change) feature of Feynman diagrams (Fig. 1b).

To make finding the essential causal structure (law 2) of a problem as systematic and reliable as possible, subproblem analysis starts by creating a cause-and-effect diagram called a "social force diagram," using the standard format of Fig. 1c. Social force diagrams show at a glance the high-level causal structure of a problem and the desired mode change. The tool provides a standard vocabulary and analytical framework especially suited for RCA of difficult social problems. Social force diagrams serve as roadmaps to the much more complex feedback loop models behind them.

Social force diagrams simplify difficult social problems to their three main forces. The first is the *root cause forces* (force R) causing the problem. In difficult problems this systemic force is so strong it causes current mode lock-in and inherent high resistance to mode change. A mode is a general pattern of system behavior. Mode change occurs when the new mode differs distinctly from the old mode, such as when a person has recovered from an illness or a nation has industrialized. Systemic means "originating from 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)
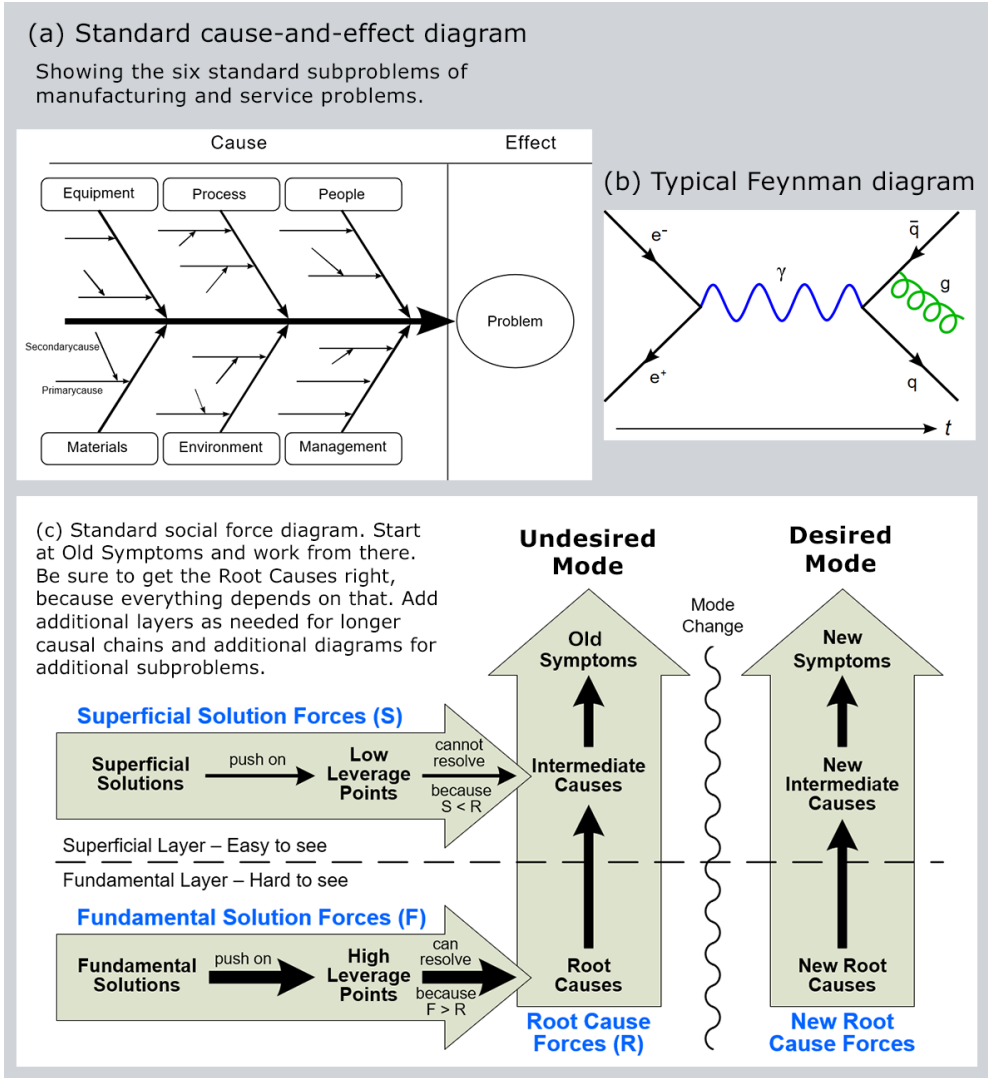

Fig. 1. Three visual tools for taming the complexity of cause-and-effect behavior. Source for diagram a: https://commons.wikimedia.org/wiki/File:Ishikawa_Fishbone_Diagram.svg. Source for diagram b: https://en.wikipedia.org/wiki/Feynman_diagram#/media/File:Feynmann_Diagram_Gluon_Radiation.svg

The central role of lock-in (law 9) 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." Lock-in occurs in all difficult systemic social problems. An unsolved problem is locked in the undesired mode, while a solved problem has switched to the desired mode. Non-difficult problems, like local pollution or susceptibility to flooding, usually require no mode change, making them much easier to solve.

Working backward from the old symptoms, research in the social sciences has traditionally identified what is believed to be the causes and then develops solutions based on that assumption. If it's a difficult problem the solutions fail because they are *superficial solution forces* (force S) attempting (in vain) to resolve intermediate causes. This is the second type of force.

Using traditional methods, only the superficial layer of the sustainability problem has been uncovered. By contrast, with RCA-based methods problem solvers can penetrate to the fundamental layer and see the problem's complete causal structure, which contains the root causes and their high leverage points. This allows sustainability scientists "to understand the fundamental character of interactions between nature and society," which, we argue, has the potential to change the sustainability problem from insolvable to solvable.

Once the root causes are known the third type of force can be employed. *Fundamental solution forces* (force F), if properly designed, resolve the root causes by changing the feedback loop structure of the system such that a new homeostasis (dynamic equilibrium) becomes more attractive. If the altered system lies within the basin of attraction created by force F, lock-in to the present mode ends, causing the system to quickly and automatically transition to the desired new mode (Sterman 2000, p. 351). The system stays locked into the new mode due to the new root cause forces arising from the new feedback loop structure introduced by the fundamental solution forces. If analysis and solution convergence testing are done well, the solution force will solve the problem rapidly and relatively permanently, in the same predictable engineering manner by which so many difficult business/engineering problems have been solved using RCA.

Superficial solutions work only partially, temporarily, or not at all because the superficial solution forces can never exceed the root cause forces. Fig. 1c shows this law of system behavior with $S < R$. The equation means "S is always less than R." (law 4) By contrast, fundamental solution forces work because $F > R$, meaning "Fundamental solutions can succeed because they can be designed such that $F > R$." (law 5)

These two equations arise from the laws of nature. The simulation models behind social force diagrams contain equations that duplicate the way physical forces cause change to occur in the real world. The way change occurs arises from Newton's three laws of motion, evolution's law of survival of the fittest, etc. Here S, F, and R summarize the forces that model nodes exert on other nodes. Due to the laws of nature, $S < R$ and $F > R$.

4.2. Two social force diagram examples

To illustrate how social force diagrams work, consider one of history's most intractable problems: autocratic rule by countless warlords, dictators, and kings. The Autocratic Ruler Problem was eventually solved by invention of modern representative democracy (Stasavage 2020). This took thousands of years and much painful trial and error because the root cause was not clearly known. Now it is, allowing the upper diagram in Fig. 2 to be constructed.

The upper 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). 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 has begun to do since 2000 due to backsliding to authoritarian rule (Mechkova et al. 2017).
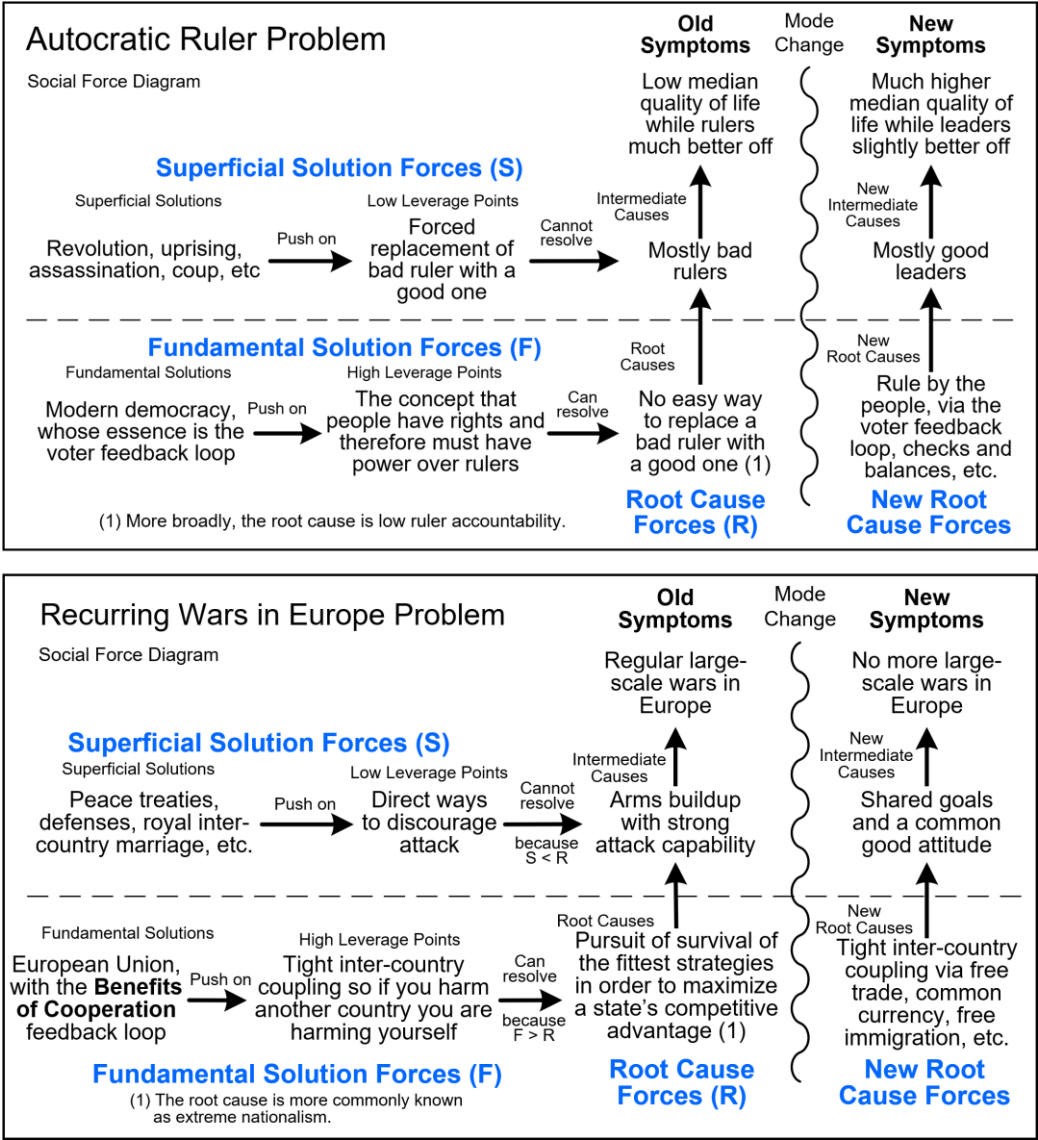

Fig. 2. Two retrospective social force diagrams.

The lower diagram shows traditional solutions to the Recurring Wars in Europe Problem didn't work because they didn't resolve the root cause. A numerous historians such as Dinan (2014) have recounted, after the horrors of two successive world wars on European soil, problem solvers said never again and intuitively looked deeper for the root cause and its high leverage point. The resulting solution, the European Union, caused a permanent mode change. Today no member of the union would even consider war against another member since that would be terribly self-destructive.

The superficial solutions failed because they pushed on a low leverage point. All those peace treaties, military defenses, royal marriages between countries, and so on did little to resolve the root cause. The drive to maximize a state's competitive advantage was a much stronger force than the superficial solutions, due to $S < R$.

The fundamental solution worked because it pushed on a high leverage point, where $F > R$ was possible. This resolved the old root cause forces and created new root cause forces, which emanated from the Benefits of Cooperation loop, now so strong that as Dinan states, European integration has become synonymous with peace and prosperity.

Social force diagrams are part of:

4.3. The System Improvement Process (SIP)

SIP is a comprehensive method for applying RCA to difficult social problems. 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.

Fig. 3 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 defines the problem in step 1. Step 2 decomposes the one big problem into carefully identified 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:
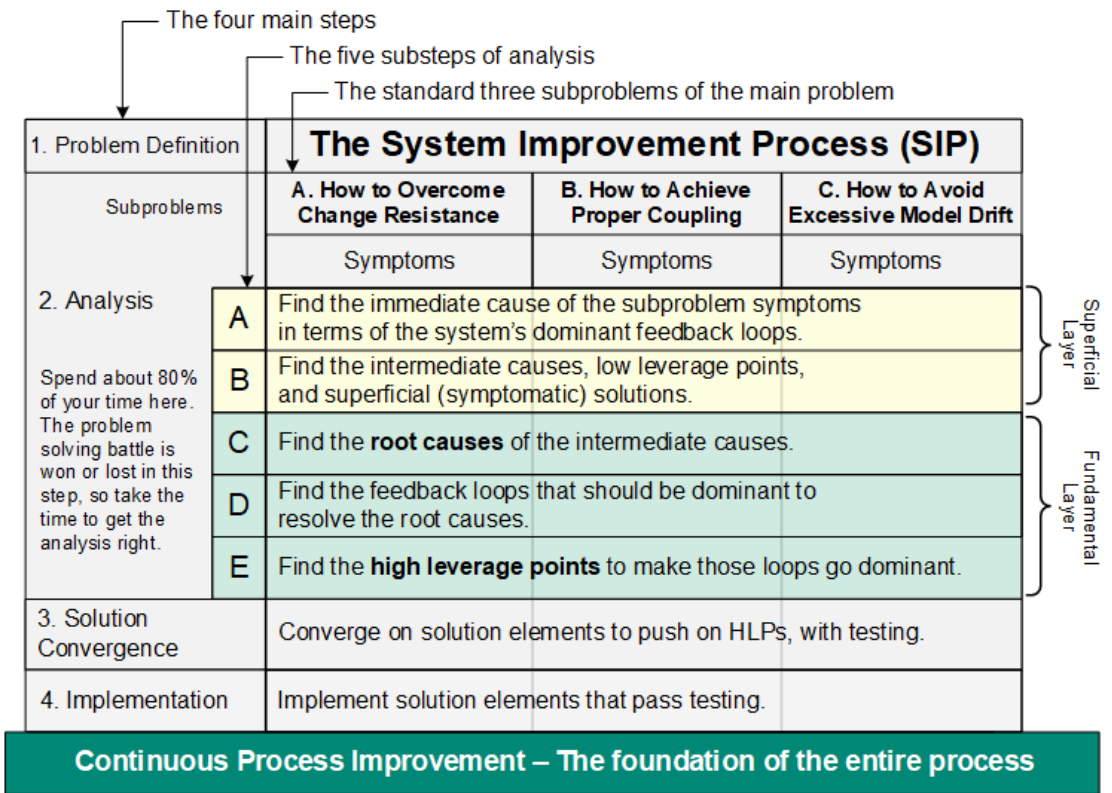
Fig. 3. The SIP matrix. Each subproblem employs a social force diagram and necessary models.

4.4. Step 1. Problem Definition

This defines the problem using a standard format: 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 (law 9). SIP treats difficult social problems as social systems stuck in the wrong mode.

4.5. Step 2. Analysis

Following law 7, avoiding the One Subproblem Trap, this step begins by decomposing the original 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. During our research we found that without the right decomposition the sustainability problem was impossible to analyze.

A standard decomposition allows problem solvers to work much more efficiently, by what we estimate is several orders of magnitude. The three standard subproblems are:

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 particular 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." Change resistance is the most important

14

subproblem to solve (in the short term) and must be solved first if possible, a conclusion also reached in a prior work (Harich 2010).

B. *How to achieve proper coupling.* 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. The original problem to solve is, we suspect, always a proper coupling problem. In the Autocratic Ruler Problem citizens were improperly coupled to their rulers. In the Recurring Wars in Europe problem a collection of states were improperly coupled to each other.

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. This 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 may eventually be overwhelmed by multiple problem recurrence.

These three subproblems are present in all difficult large-scale social problems: (A) High successful change resistance is present because prior solutions have failed. (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).

Change resistance differs from lock-in in that change resistance is to particular solutions, as seen in the symptoms for subproblem A in Fig. 4. In mode lock-in, the feedback loop structure of the system locks the system into a particular mode of behavior, where certain agents behave in a similar manner and find it hard to behave otherwise. An undesirable mode creates a problem to solve, as seen in the symptoms for subproblems B, C, and D, and in the analysis model for subproblem A, whose structure causes lock-in to particular behavior.

After problem decomposition each subproblem undergoes the five substeps of analysis. The substeps serve as a "cookbook" procedure for achieving a solid first iteration of a subproblem's essential causal structure. This lays the groundwork for what is typically the toughest part of the entire process: cutting through the fog of complexity to synthesize *only* the essential feedback loop structure of the subproblems while ignoring everything else. By modeling *only* the loops related to the intermediate and root causes, and the low and high leverage points, the "DNA" of a problem can be identified exactly, closely examined, and then reengineered to achieve the desired mode change. By doing this in a standardized engineering manner, much less modeling expertise is required.

As analysis proceeds a social force diagram and feedback loop model of the subproblem are constructed. A simulation model rather than a causal loop diagram is preferred (law 3), though the latter will suffice for simple subproblems. Model simulation allows rapid theoretical testing of the analysis via scenarios that would be slow, expensive, or impossible to test in the real world. For simulation modeling we recommend system dynamics due to its elegant simplicity, its emphasis on feedback loop structure, and its suitability for qualitative or quantitative modeling (Sterman 2000; Homer 2012).

SIP utilizes a strong definition of root cause (law 2). 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) to be quickly 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)

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 requirements must be supported by a model of the essential causal structure of the problem with all important feedback loops clearly organized and named.

4.6. Step 3. Solution Convergence

Sustainability scholars, e. g. (Fischer and Riechers 2019; Chan et al. 2020; Lam et al. 2020), led by the work of Donella Meadows (1999), have emphasized the importance of high leverage point solutions, and even the need to "engage with the *root causes* of unsustainability" using "a leverage points framework" (Abson et al. 2017). Gooyert et al. (2016) argue understanding of high leverage points is required to elicit the desired mode change, since "A *sustainability transition* [which we call the desired mode change] can be understood as a transformation in a complex system consisting of several feedback loops. With this understanding, successfully managing a sustainability transition becomes a matter of identifying *high leverage points* in those feedback loops that can support the progression of the transition, thereby overcoming policy resistance". However, scholars have been unable to provide an effective method for finding a problem's correct high leverage points. Substep 2E fills that gap.

In SIP, a high leverage point is a specific place in the causal structure of a problem to change (or "push on") to resolve its connected root cause. Pushing on the high leverage point with solution elements reduces the root cause force to an acceptable level or eliminates it altogether. A high leverage point description, such as "raise political truth literacy from low to high," summarizes a solution strategy that can be realized with one or more solution elements pushing on the same high leverage point.

The convergence step uses that strategy to rapidly converge on the few solution elements that could plausibly work. These become solution candidates and are then tested and improved as necessary. Testing reduces the number of candidates to the selected few that will be implemented. Testing takes many forms, principally simulation model scenarios, laboratory studies on test subjects, and real word studies such as pilot programs. This step ends when there is a high probability the selected solutions will work to initiate the desired mode change scenario.

As solution 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.

4.7. Step 4. Implementation

Here the most promising solutions become policy proposals and 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. Any significant deficiencies in solution success cause iteration to step 2, analysis, where the analysis is first updated to reflect what was learned. The process then proceeds as before.

"An engineering-like manner" refers to achieving system improvement goals within a predictably acceptable range of time, cost, and quality by use of a standard mature process. An example is how in 1983 Toyota replaced the core process in the NUMMI factory in Fremont, California with the Toyota Production System and in three years reduced defects per vehicle from 12 to 1, cut labor per vehicle in half, and reduced

absenteeism from 20% to 3% (May 2007, p. 65). This was the "miraculous transformation" that proved to the West that lean success was not due to "Japanese business culture" but to the inherent superiority of the innovative RCA-based process itself (p61). Similar results have been reported in software development using Capability Maturity Model Integration (Gibson et al. 2006), use of lean Six Sigma in a variety of industries (Dumitrescu and Dumitrache 2911), and conversion to lean production at Wiremold (Byrne 2013, pp. 9–13). All these processes are RCA-based. Each solves problems as they are identified in an engineering-like manner.

A problem stays solved as long as the system remains in the desired mode. If the model drift subproblem is well-solved, future troublesome problem evolution will quickly result in appropriate solution adjustments due to intimate knowledge of how to fine tune the effects of the new root cause forces in order to "steer" the governance system appropriately. Or the solution may be self-managing. This provides the mechanism Young (2017, p. 3) seeks in *Governing Complex Systems*: "The thesis of this book is that solving the problems of the Anthropocene will require the creation and operation of innovative *steering* mechanisms that differ in important respects from those familiar to us from past experience." SIP first solves a problem, then steers the solution so the problem is solved permanently, just as one first builds a ship and then steers it along its journey through time.

4.8. Continuous process improvement

Underneath the four main steps lies continuous process improvement, the most important step of all (law 8). This step has taken SIP and the analysis, as well as countless other processes, to where they are today.

This completes description of SIP. Next, we examine the results of applying it.

5. SIP application results and discussion

5.1. Summary of Analysis Results

SIP was iteratively developed while applying it to the environmental sustainability problem. The matrix of Fig. 3 was expanded in Fig. 4 to show key analysis results. The one big problem of environmental sustainability was decomposed into four smaller subproblems. The original problem is subproblem D. One additional subproblem beyond the three standard subproblems was found: subproblem B. We cannot describe analysis results in detail here, and instead review only our most important insights:

(1) The key insight, the one all the rest depend on, is that 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 simultaneous development of the three subproblems found in all difficult social problems) consumed more analysis time than anything else.

(2) Superficial layer results reveal why the sustainability problem remains unsolved. Without realizing it, problem-solvers have been pushing on low leverage points (Fig 4, row "Low leverage points") with symptomatic solutions. All large-scale solution efforts

fall into this pattern. For example, the SDGs, as well as earlier regimes like the Kyoto Protocol, are goal-based regulations (even if voluntary) and thus fit in symptomatic 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" symptomatic solutions for subproblem A.

(3) A welcome surprise appeared when we uncovered the fundamental layer. If these or something like them are indeed the main root causes (Fig 4, 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

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

1. Problem Definition		How to achieve global environmental sustainability in terms of the desired system goal state			
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
2. Analysis / 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
	Improperly coupled systems	Not applicable	Corporate and human life forms	Not applicable	Economic and environment systems
	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
	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)
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
	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
	Symptomatic 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.
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
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
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.
3. Solution Convergence		Nine sample solution elements (4)	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. (4) One is Truth Literacy Training.

Fig. 4. Summary of Analysis Results.

the many solutions pushing on the low leverage points (where S < R), there are no large-scale solutions pushing on any of the high leverage points (where F > R is possible), suggesting that once problem solvers shift to RCA-based processes, the sustainability problem may be substantially easier and faster to solve than presently assumed.

5.2. A Deeper Problem: The Broken Political System

As analysis proceeded a striking pattern emerged, leading to a fourth major insight. The environmental sustainability problem was not the only large social problem society has been unable to solve. There are many more, as the 17 SDGs 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 (Fig. 5). 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
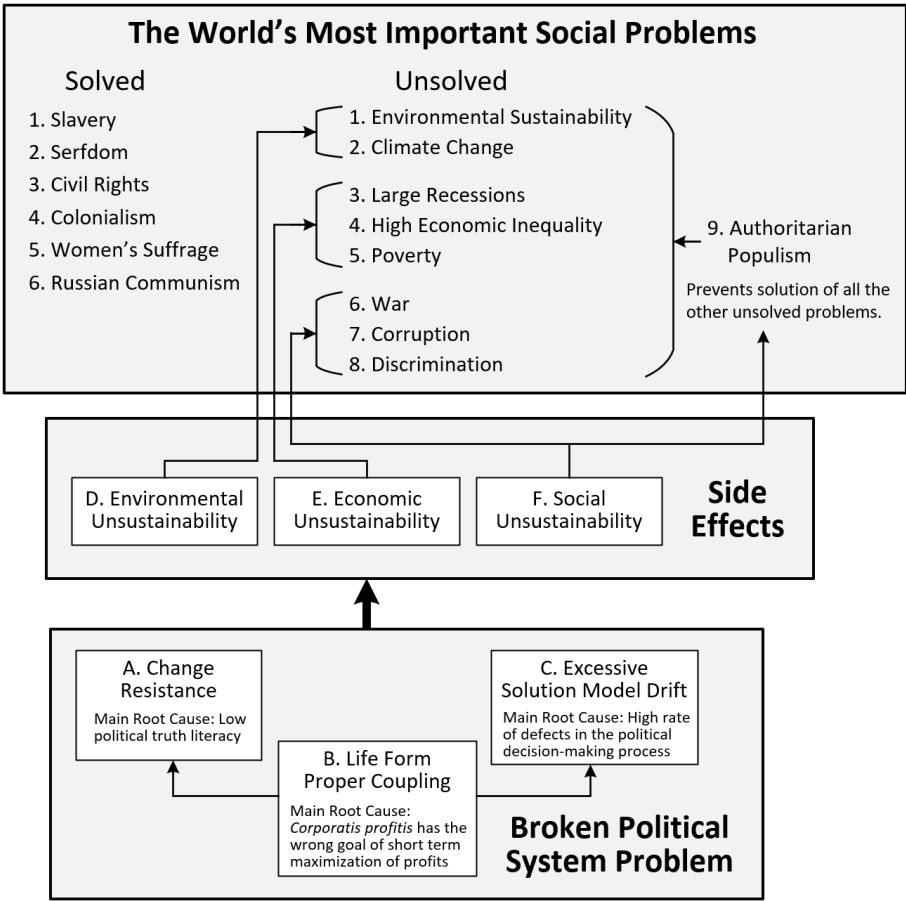

Fig. 5. High-level causal diagram of the Broken Political System Problem and its consequences. Subproblems E and F have been added to give all three pillars of sustainability. The lists of problems are not complete or definitive.

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 (Shamir 2005; Beder 2006; Korten 2015) 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 Fig. 4, 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 2002, 2006; Hoggan 2009). This works due to the main root cause of successful change resistance: *low political truth literacy*. (Fig. 4, 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. (Lukensmeyer and Brigham 2002; Panagopoulos and Weinschenk 2016; Freeman 2017; Norris and Inglehart 2019). Fig. 5 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 Fig. 5 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 Fig. 5 were solved was low change resistance. Solving these problems did not pose much of a threat to *Corporatis profitis*.

6. Conclusions

This paper addressed the research question of how the business/engineering tool of root cause analysis (RCA) can be adapted to solve difficult social problems, especially environmental sustainability. Given the method and results presented here and how well RCA has worked in industry for over a century, we offer these conclusions. All suggest opportunities for further research.

1. Our most important conclusion is that RCA can be successfully adapted to solve difficult social problems, including environmental sustainability, by thoughtful application of any RCA-based process that incorporates the fundamental laws of RCA in a tightly integrated manner. This allows social engineers to implement one of the maxims of industry: "The right process will produce the right results" (Liker 2004, pp. 85–168). SIP can serve as a seed process, as a time-saving starting point for this adaptation.

2. The SIP analysis explains why popular large-scale solutions for solving the environmental sustainability problem have largely failed. All are superficial/symptomatic solutions like those listed in Fig. 4 and thus attempt, in vain, to resolve the easy to find intermediate (proximate) causes rather than the much harder to find root causes. Further efforts should be directed elsewhere, toward solutions designed to resolve specific root causes. For example, the SDGs should be reinterpreted as part of defining the problems to solve, rather than being the leading component of a governance by goals solution strategy, which is a form of regulations and thus pushes on a low leverage point.

3. The analysis found that unlike the many solutions pushing on the low leverage points, there are no large-scale solutions pushing on any of the high leverage points. This suggests that once problem solvers shift to RCA-based processes, the sustainability problem may be substantially easier and faster to solve than presently assumed, and is solvable rather than insolvable. This is especially relevant to the climate change crisis, where we are running out of time on avoidance of ecological tipping points.

4. The analysis found the Broken Political System Problem is the real problem to solve, not its side effects, one of which is environmental unsustainability. This conclusion accomplishes what we see as the first step in solving the core challenge of sustainability science, stated by Kates (2001) as understanding "the fundamental character of interactions *between nature and society*." As Fig. 5 explains, the second step lies in deeper understanding of the interactions *within society itself* (subproblems A, B, and C), such that the human system can be reengineered to solve the Broken Political System Problem and thereby automatically reduce the so-called side effects of environmental, economic, and social unsustainability to acceptable levels. It is to this second step that sustainability scholars should consider shifting their attention.

5. Finally, given the first conclusion and the widespread foundational role RCA has achieved in industry, we see no reason why the emerging field of sustainability science cannot do the same, and adopt a standard process based on the fundamental laws of RCA or their equivalent as one of its foundational tools. The quality and speed of this adaptation could be enhanced by launching an extraction project similar to the one that created the lean production process, using the preliminary work presented here as proof of concept.

Soon, we expect, sustainability science will have more than "a room of its own" (Clark 2007). It will have a seat at the table with the other engineering sciences.

Once the foundation of sustainability science reaches a critical mass of evidence it works, transition from prescience to normal science will begin and history will repeat itself. Switching to RCA-based processes will precipitate a long overdue paradigm shift in social problem-solving methods, solution strategies, and curriculums, and will repeat the same fundamental change industry underwent generations ago when, beginning in post WWII Japan, the RCA-based quality revolution (led by lean production) swept the business world. Gabor (1990, p. 286) describes that transformation (which in the West began largely in the US) and ends his story with this prophetic passage, one that applies to all political systems: "…as Deming's principles [of quality management] are embraced by pioneers in government and education in the 1990s, they could give the United States [and anyone who adopted 'a new belief system that executives and workers of all industries could share'] powerful new tools for tackling the country's *most pressing social problems*."

Acknowledgments

References

Abson DJ, Fischer J, Leventon J, et al (2017) Leverage points for sustainability transformation. Ambio 46:30–39. https://doi.org/10.1007/s13280-016-0800-y

Andersen B, Fagerhaug T (2006) Root Cause Analysis: Simplified Tools and Techniques, Second Edition. ASQ Quality Press

Beder S (2006) Suiting Themselves: How Corporations Drive the Global Agenda. Earthscan

Beder S (2002) Global Spin: The Corporate Assault on Environmentalism, Revised Edition. Chelsea Green

Biermann F, Kanie N, Kim RE (2017) Global governance by goal-setting: the novel approach of the UN Sustainable Development Goals. Curr Opin Environ Sustain 26–27:26–31. https://doi.org/10.1016/j.cosust.2017.01.010

Burch S, Gupta A, Inoue CYAA, et al (2019) New directions in earth system governance research. Earth Syst Gov 1:100006. https://doi.org/10.1016/j.esg.2019.100006

Byrne A (2013) The Lean Turnaround: How Business Leaders Use Lean Principles to Create Value and Transform Their Company. McGraw Hill

Carson R (1962) Silent Spring. Houghton Mifflin Company

Chan KMA, Boyd DR, Gould RK, et al (2020) Levers and leverage points for pathways to sustainability. People Nat 2:693–717. https://doi.org/10.1002/pan3.10124

Clark WC (2007) Sustainability science: A room of its own. Proc Natl Acad Sci U S A 104:1737–1738. https://doi.org/10.1073/pnas.0611291104

Clark WC, Dickson NM (2003) Sustainability science: The emerging research program. Proc Natl Acad Sci United States Am 100:8059–8061

Costanza R, Cumberland J, Daly H, et al (1997) An Introduction to Ecological Economics. St. Lucie Press

Costanza R, Leemans R, Boumans R, Gaddis E (2007) Integrated Global Models. In: Sustainability or Collapse: An Integrated History and future Of People on Earth. p 417

Daly H, Farley J (1997) Ecological Economics, Second. Island Press

Dew J (2003) The Seven Deadly Sins of Quality Management. Qual Prog 36:59–65. https://doi.org/10.1309/lmn5ej2caruo0unt

Dinan D (2014) Europe Recast: A History of European Union. Lynne Rienner

Dinan W, Miller D (2007) Thinker, Faker, Spinner, Spy: Corporate PR and the Assault on Democracy. Pluto Press

Dumitrescu C, Dumitrache M (2911) The Impact of Lean Six Sigma on the Overall Results of Companies. Econ Ser Manag 14:

Editors (2014) Laws of nature. In: Encyclopedia Britannica

Fischer J, Riechers M (2019) A leverage points perspective on sustainability. People Nat 1:115–120. https://doi.org/10.1002/pan3.13

Folke C, Carpenter SR, Walker B, et al (2010) Resilience thinking: Integrating resilience, adaptability and transformability. Ecol Soc 15:. https://doi.org/10.5751/ES-03610-150420

Freeman B (2017) Democracy Rising: Politics and Participation in Canada. Dundurn Press

Gabor A (1990) The Man Who Invented Quality: How W. Edwards Deming Brought the Quality Revolution to America. Penguin Books

George M, Rowlands D, Price M, Maxey J (2005) The Lean Six Sigma Pocket Toolbook. McGraw Hill

Gibson DL, Goldenson DR, Kost K (2006) Performance Results of CMMI-Based Process Improvement

Gooyert V, Rouwette E, Kranenburt H, et al (2016) Sustainability transition dynamics; Towards overcoming policy resistance. Technol Forecast Soc Change 111:

Hardin G (1968) The Tragedy of the Commons. Science (80-) 162:1243–1248

Harich J (2010) Change resistance as the crux of the environmental sustainability problem. Syst Dyn Rev 26:35–72. https://doi.org/10.1002/sdr

Hoggan J (2009) Climate Cover-Up: The Crusade to Deny Global Warming. Greystone Books

Holweg M (2007) The genealogy of lean production. J Oper Manag 25:420–437.

https://doi.org/10.1016/j.jom.2006.04.001

Homer JB (2012) Models that Matter: Selected Writing on System Dynamics from 1985 to 2010. Grapeseed Press

Hornborg A, Crumley C (2006) The World System and the Earth System: global socioenvironmental change and sustainability since the Neolithic. Left Coast Press, Walnut Creek

Howes M, Wortley L, Potts R, et al (2017) Environmental sustainability: A case of policy implementation failure? Sustain 9:1–17. https://doi.org/10.3390/su9020165

Imai M (1986) Kaizen: The Key to Japan's Competitive Sucess. McGraw Hill

Ishikawa K (1986) Guide to Quality Control, 2nd revised edition, edited for clarity. Asian Productivity Organization

Jerneck A, Olsson L, Ness B, et al (2011) Structuring sustainability science. Sustain Sci 6:69–82. https://doi.org/10.1007/s11625-010-0117-x

Kates RW, Clark WC, Corell R, et al (2001) Sustainabilty Science. Science 292:641–642. https://doi.org/10.1126/science.1059386

Korten D (2015) When Corporations Rule the World - Third Edition. Berrett-Koehler Publishers

Kuhn T (1996) The Structure of Scientific Revolutions, Third Edition. University of California Press

Lam DPM, Martín-López B, Horcea-Milcu AI, Lang DJ (2020) A leverage points perspective on social networks to understand sustainability transformations: evidence from Southern Transylvania. Sustain Sci. https://doi.org/10.1007/s11625-020-00881-z

Levy D (1997) Environmental Management as Political Sustainability. Orgasnization Environ 10:

Liker J (2004) The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer. McGraw Hill

Lukensmeyer C, Brigham S (2002) Taking Democracy to Scale:Creating a Town Hall Meetingfor the Twenty-First Century. Natl Civ Rev 91:

Markard J, Raven R, Truffer B (2012) Sustainability transitions: An emerging field of research and its prospects. Res Policy 41:955–967. https://doi.org/10.1016/j.respol.2012.02.013

Marx M (2007) Six Sigma Saves a Fortune. Six Sigma Mag. 3

May M (2007) The Elegant Solution: Toyota's Formula for Mastering Innovation. Free Press

Mayer RE (1997) Multimedia learning: Are we asking the right questions? Educ Psychol 32:1–19. https://doi.org/10.1207/s15326985ep3201_1

McCarthy J (2019) Authoritarianism, Populism, and the Environment: Comparative Experiences, Insights, and Perspectives. Ann Am Assoc Geogr 109:301–313. https://doi.org/10.1080/24694452.2018.1554393

McCarthy J (1960) Basic Marketing: A Managerial Approach. R.D. Irwin

Meadows D (1999) Leverage Points: Places to Intervene in a System. In: Sustain. Inst. http://www.donellameadows.org/archives/leverage-points-places-to-intervene-in-a-system/. Accessed 10 Feb 2016

Meadows D (2008) Thinking in Systems: A Primer. Chelsea Green

Meadows D, Meadows D, Randers J (1992) Beyond the Limits. Chelsea Green

Meadows D, Meadows D, Randers J, Behrens W (1972) The Limits to Growth. Universe Books

Meadows D, Randers J, Meadows D (2004) Limits to Growth: The 30-Year Update. Chelsea Green

Mechkova V, Lührmann A, Lindberg SI (2017) How much democratic backsliding? J Democr 28:162–169. https://doi.org/10.1353/jod.2017.0075

Miller TR, Wiek A, Sarewitz D, et al (2014) The future of sustainability science: A solutions-oriented research agenda. Sustain Sci 9:239–246. https://doi.org/10.1007/s11625-013-0224-6

NASA Safety Center (2013) NASA Root Cause Analysis Tool. http://nsc.nasa.gov/RCAT/. Accessed 16 Feb 2016

Newman J, Head BW (2017) Wicked tendencies in policy problems: Rethinking the distinction between social and technical problems. Policy Soc 36:414–429. https://doi.org/10.1080/14494035.2017.1361635

Ng I, Tseng L-M (2008) Learning to be Sociable: The Evolution of Homo Economicus. Am J Econ Sociol

Norris P, Inglehart R (2019) Cultural Backlash: Trump, Brexit, and the Rise of Authoritarian Populism. Cambridge University Press

Ohno T (1988) Toyota Production System: Beyond Large-Scale Production. Productivity Press

Okes D (2019) Root Cause Analysis: The Core of Problem Solving and Corrective Action. ASQ Quality Press

Olver A, Ryan M (2014) On a Useful Taxonomy of Phases, Modes, and States in Systems Engineering. In: Systems Engineering/Test and Evaluation Conference

Panagopoulos C, Weinschenk A (2016) A Citizen's Guide to U. S. Election: Empowering Democracy in America. Taylor & Francis

Pande P, Neuman R, Cavanagh R (2000) The Six Sigma Way: How GE, Motorola, and Other Top Companies are Honing Their Performance. McGraw Hill

Pyzdek T (2003) The Six Sigma Handbook: A Complete Guide for Green Belts, Black Belts, and Managers at All Levels. McGraw Hill

Rittel HWJ, Webber MM (1973) Dilemmas in a general theory of planning. Policy Sci 4:155–169. https://doi.org/10.1007/BF01405730

Samuel D, Found P, Williams S (2015) How Did the Publication of the Book The Machine That Changed The World change management thinking? Exploring 25 years of Lean Literature. Int J Oper Prod Manag 35:1386–1407

Senge P (1990) The Fifth Discipline: The Art and Practice of the Learning Organization. Currency Doubleday

Shahin A, Mazaher G, Arabzad SM (2010) Proposing an Integrated Framework of Seven Basic and New Quality Management Tools and Techniques: A Roadmap. Res J International Studies-Issue 17:183–195

Shamir R (2005) Corporate social responsibility: A case of hegemony and counter-hegemony. In: Law and Globalization from Below. Cambridge University Press

Shewhart W (1931) Economic control of quality of manufactured product. Van Nostrand Company

Stasavage D (2020) The Decline and Rise of Democracy. Princeton University Press

Sterman J (2000) Business Dynamics: Systems Thinking and Modeling for a Complex World. McGraw Hill, Boston

Tague N (2005) The Quality Toolbox. Quality Press

Takeuchi K, Komiyama H (2006) Sustainability science: building a new discipline. Sustain Sci 1:1–6. https://doi.org/10.1007/s11625-006-0007-4

Tummala VMR, Tang CL (1996) Strategic quality management, Malcolm Baldrige and European quality awards and ISO 9000 certification: Core concepts and comparative analysis. Int J Qual Reliab Manag 13:8–38. https://doi.org/10.1108/02656719610114371

van Vuuren DP, Kok MTJ, Girod B, et al (2012) Scenarios in Global Environmental Assessments: Key characteristics and lessons for future use. Glob Environ Chang 22:884–895. https://doi.org/10.1016/j.gloenvcha.2012.06.001

Wang Z (2007) Public Support for Democracy in China. J Contemp China

Womack J, Jones D, Roos D (1990) The Machine that Changed the World: The Story of Lean Production. Harper Perennial

World-Commission (1987) Our Common Future (The Brundtland Report). Oxford University Press

Wuthrich A (2010) The Genesis of Feynman Diagrams. Springer Science

Young O (2017) Governing Complex Systems: Social Capital for the Anthropocene. MIT Press