The Dimensions of Systems Thinking

An Approach for a Standard Language of Systems Thinking

A Dissertation

Presented to

the faculty of the School of Engineering and Applied Science

University of Virginia

---

in partial fulfillment

of the requirements for the degree

Doctor of Philosophy

by

Nelson Peter Whitehead

May

2014

APPROVAL SHEET

The dissertation
is submitted in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy

AUTHOR

The dissertation has been read and approved by the examining committee:

William T. Scherer

Advisor

Garrick S. Louis, Chair

K. Preston White

Michael C. Smith

Timothy Beatley

Accepted for the School of Engineering and Applied Science:

Dean, School of Engineering and Applied Science

May
2014

The Dimensions of Systems Thinking

An Approach for a Standard Language of Systems Thinking

A Dissertation

Presented to the Faculty of the School of Engineering and Applied Science

The University of Virginia

In partial fulfillment

Of the requirements for the degree of

Doctor of Philosophy in Systems Engineering

N. Peter Whitehead

May 2014

Approval

This dissertation is submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Systems Engineering

____

N. Peter Whitehead, Author

The dissertation has been read and approved by the examining committee:

____

Garrick E. Louis, Committee Chair

____

William T. Scherer, Advisor

____

K. Preston White, Committee Member

____

Michael C. Smith, Committee Member

____

Timothy Beatley, Committee Member

Accepted for the School of Engineering and Applied Science:

____

Dean, School of Engineering and Applied Science

May 2014

Abstract

The concept of systems thinking (and its embodiment in the systems approach, systems science and systems engineering) dates from the historical origins of engineering, policy and philosophy. However, unlike mathematics, physics, biology and other fields with similar histories, systems thinking lacks a common, foundational language that facilitates transparent communication. If language is the manifestation of thought per Chomsky, then systems thinking can be succinctly expressed via its underlying language. Examples from the author's research and the literature show that the practice of and research in systems approaches would benefit from a common language and foundation of systems thinking.

This thesis proposes a common, foundational language to express any systems approach. The author derives this foundation through building a definition of systems thinking from the respective definitions of systems and critical thinking. This definition is then expanded into a foundational working lexicon of systems thinking - the Dimensions of Systems Thinking (DST). To reduce ambiguity and fill gaps, key concepts are introduced including the observer effect of systems thinking, the difference between the scope of the analysis and the boundaries of the system and the distinction between metrics and indices of performance of a system. Case studies demonstrate the development and application of the foundational elements in practical analysis. Liquid biofuel, healthcare and science policy are each considered and system improvements recommended through the application of the Dimensions of Systems Thinking.

The thesis then develops a method of analytically identifying the level of systems thinking in a document. In doing so, it considers the statistical semantic characteristics of term frequency and inverse document frequency, cosine similarity and Naïve Bayes classifiers with

supervised learning such as Rocchio classifiers and quadratic discriminant analysis. A proof-of-concept study then tests the proposed approach. The study successfully demonstrates the analytical assessment of the systems thinking quality of each document in a learning/training corpus and a corpus of unread research studies on life cycle assessment. It also shows that an analytical relation between the specific components of the Dimensions of Systems Thinking and a document can be established - a capability that will be useful for improving the quality of systems approaches.

The way forward will be to discuss and debate the elements of the language of systems thinking with the goal of codifying the concept, to continue refining and testing the analytical capability and further testing of this new methodology on case studies.

Acknowledgement

As of this date, portions of Chapters 1,2 and 3 have been approved for publication with revisions in the IEEE Systems Journal; portions of Chapter 4 were presented at the IEEE Green Technologies Conference in May 2010 and published in the proceedings; portions of Chapter 5 were presented at IEEE Syscon in March 2013 and published in the proceedings; portions of Chapter 6 were developed and presented at the invitation of the President's Office of Science and Technology Policy; and portions of Chapter 7 will be submitted to the IEEE Systems Journal for publication as a follow-on to the earlier ISJ paper. My thanks to the peer reviewers and editors who provided insight and guidance on behalf of those publications.

I could probably fill 200 pages acknowledging the kindness and support without which this thesis would not have been possible.

Bill, you've been oh so patient with me these many years. You never should have given me an A in SYS601, it only encouraged me.

Garrick, Mike, Pres, Tim – Thank you for your wisdom and your guidance.

Support at many levels came from AAAS, Sue Kemnitzer, Dominique Dagenais, Paul Collopy, the Division of Electrical, Communications and Cyber Systems, the Division of Civil, Mechanical and Manufacturing Innovation and the Directorate of Engineering at the National Science Foundation.

Susan, you are my rock, now it's your turn.

Louis and Beau – thanks for keeping me humble.

Matt Burkett, Steve Yang and Tipan Verella – I owe you beer.

Jayne and Jennifer – you two are amazing. Thank you for all the smiles.

Yasu Imao – I've never met you, but thanks for your help.

If you want to see different approaches to systems thinking, grade a few thousand SYS6001 and SYS 2001 submissions.

Lastly, I dedicate this thesis to George E.P. Box, who passed away on March 28, 2013.

"Essentially, all models are wrong, but some are useful."

Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Motivation

Consider two anecdotes. The first involved a conversation at the National Science Foundation between some Program Directors involved in funding systems research. They pointed out that every department that they know of defines systems engineering differently – and there isn't even consistency in the names of the departments. Electrical and computer engineering doesn't feel the need to self-distinguish this way – probably because the foundations of electrical engineering are agreed upon across the discipline.

Next, a conversation with the Director (2014) of DARPA. She intoned that systems engineering has let down the Department of Defense in program after program so why should they continue funding it. Legions of contractors have billed DoD for countless hours of systems effort, but they have failed to provide the improvement promised by the systems approach.

Those are two of many similar incidents in the author's career that indicate a problem for the systems approach and those engaged in and studying the field of systems thinking. This problem isn't new. Many in the field have written about it over the years. After co-authoring with C. West Churchman a book that defined the field of operations research, Russell Ackoff wrote, *"Despite the importance of systems concepts and the attention that they have received […], we do not yet have a unified or integrated set (i.e., a system) of such concepts. Different terms are used to refer to the same thing and the same term is used to refer to different things. […] I feel benefits will accrue to systems research from an evolutionary convergence of concepts into a generally accepted framework."* Despite the passage of time and the efforts of many scholars and practitioners, a unified framework of fundamental systems thinking concepts remains elusive, as will be shown in the literature survey as well as through consideration of the following motivating examples [1], [2].

1.2 Motivating Examples

Chapter 4 of this thesis describes a systems thinking case study of biofuel systems and the lifecycle assessments used to rank them. It found the life cycle, benefit/cost ratio to be an inadequate – though widely accepted – evaluation approach for comparing the value of energy systems. The study shows that the ISO and EPA standards for life-cycle assessment were vague enough to allow the establishment of arbitrary and inconsistent system boundaries. It found indices of performance that were based upon metrics with common names but different definitions being used to empirically compare fuel & energy systems. Policy decisions were made at very high levels of government and industry based upon these flawed systems analyses. Economic and environmental damage might have been avoided had there been more commonality and transparency in the systems approach [3].

Chapter 5 of this thesis reports on a systems thinking case study of the healthcare system in the United States. It shows different objectives for different stakeholders: optimal wellness is the objective for the population; high national rankings are the objectives for the schools in the medical education system and optimal revenue is the objective for the providers and insurers. Moreover, within the provider community, clinicians (physicians and other medical specialists) have incentives that differ from those of the systems where they practice. Often, the stakeholders leading these systems become the default critical decision makers through their financial influence of the policy structure. Performance indices show a system operating with very high revenues yet providing markedly poor performance as measured by many indicators versus other national systems. Indices of performance include life expectancy, infant mortality, nosocomial infections and medical error rates [4].

The medical establishment reacted to these and other systems failures in the 1990s with the establishment of Systems-based practice (SBP). Our research into SBP included extended interviews with several leading medical educators and researchers in the field of systems-based medicine. It showed that systems thinking within graduate medical education and medical practice had developed organically, with virtually no influence from the greater systems community and shared very little in terms of methodology or language with other practitioners of systems thinking. While it would be difficult to conclude that this disconnect is the unique reason for the on-going systems failures in healthcare, it is clear that the work to improve the U.S. healthcare system is hindered by the isolation created by this linguistic and methodological schism. We show, using the Dimensions of Systems Thinking, where key leverage points lie in the U.S. healthcare system and recommend options to correct them [4].

Chapter 6 summarizes a case study wherein the foundation developed in this thesis was applied to quickly and effectively assist the development of national laboratory policy in the President's Office of Science and Technology Policy.

In recent history, several prominent programs sought to incorporate systems methodology in the development process with disappointing results. The Joint Strike Fighter program was plagued with technical problems, is delayed and over budget [5]. The Army's Future Combat System (FCS) was described as "irrevocably damaged" by "poor systems engineering," despite the original intent that it be a model of taking a systems approach to the objectives of a modern army [6]. The rollout of the web access portal for the Affordable Care Act experienced major systems problems [4], [7]. Most of the corporations involved in these efforts have proprietary policies and guides for systems engineering and systems integration with no effort to establish commonality or transparency between them. Some of these corporations even lack a common internal systems language due to mergers and independent initiatives.

My own experience working for the federal government and with some of the corporations involved in systems thinking for the government has shown me first-hand how energy is wasted and errors made due to this lack of commonality in systems thinking. It makes sense that where transparency is lacking, solutions will be harder to derive - but there is also a second reason to consider the benefits of a foundational lexicon. In general, where systems thinking fails - such as a mismatch between indices and metrics, incorrect system boundaries, incorrect stakeholders, mismatched mental models - it is often due to a failure to consider all the Dimensions of Systems Thinking – a lack of fluency. The failure exists because we don't have all the right dimensions in our systems approach.

1.3 Systems

By thinking in systems, the practitioner considers the broadest possible aspects of a system with the goal of innovating change and focusing on optimal solutions that achieve the system objectives. The systems approach comprises the methodologies and tools that manifest most obviously in systems analysis, systems design and systems engineering. The systems approach and research in systems science and systems engineering are of little worth if not based on a foundation of systems thinking. Necessary and sufficient conditions for successful systems, therefore, are to have a sound systems approach methodology supported by an equally sound systems thinking perspective.

The term *systems analysis* is sometimes applied to the development and analysis of systems models where little systems thinking takes place. The paradigm of this thesis, however, is that systems analysis be considered a consulting style practice of analysts as advisors and managers. Systems thinking, per se, would define the broader philosophy that expands beyond the definition of systems analysis. Systems thinking is reflected more in a systemic approach versus a systematic approach. In the authors' experience, frequently what is referred to as a "systems approach" is not systems thinking, but a systematic process often applied mechanistically or built around a specific concept, algorithm or model - a hammer looking for a nail. That hammer might be SysML, SQL, Six Sigma, Arena, UML, IDEF0, DoDAF – or any number or combination of well developed analysis tools or frameworks. As quoted in the dedication of this dissertation, economist George Box wrote, *"Essentially, all models are wrong, but some are useful"[8].* Analytic tools that simulate, optimize and rank systems and decisions can only be effective in conjunction with sound systems thinking. For without sound systems thinking, models and simulations will have little bearing on problem solving.

Consider the article *Systems thinking/system dynamics: Let's just get on with it* by Barry Richmond (1994). This is a systems analysis approach through system dynamics – with the goal of employing the Stella software tool. While a valid approach to many analyses, the stock & flow modeling approach developed by Forrester, it is one approach to analyzing systems, but it is not comprehensive systems thinking [9], [10].

1.4 Thesis Statement

The goals of this thesis will be to 1) re-establish the need for a common framework of language for researchers and practitioners of systems thinking; 2) propose a foundational common language framework; 3) assess this foundational approach by applying it to case studies; and 4) develop a method for quantitatively assessing the level of systems thinking in an analysis and correlate it to the foundational language.

This dissertation describes the development of a comprehensive foundation for systems thinking. Through research, case studies and the experience of the author it shows the lack of such a foundation in the field and the potential benefits from such a foundation. This dissertation also shows the lack of, benefits from, and methodology for an analytical approach to assessing systems thinking. This thesis will significantly enhance the field of systems engineering.

1.5 Organization of the Dissertation

The sections are organized as follows:

This introduction providing the motivation for the work and the thesis definition

Chapter 2, containing a literature survey and further motivation for the thesis

Chapter 3, describing the foundation of the thesis: the Dimensions of Systems Thinking

Chapters 4 and 5, describing case studies of the Dimensions of Systems Thinking in biofuel systems and healthcare systems, respectively

Chapter 6, describing a real-world application case study of the Dimensions of Systems Thinking in U.S. national science policy

Chapter 7, showing the development and testing of an analytical approach to assessing a study in terms of the Dimensions of Systems Thinking

Chapter 8, presenting a summary, review of contributions and suggested opportunities for future work

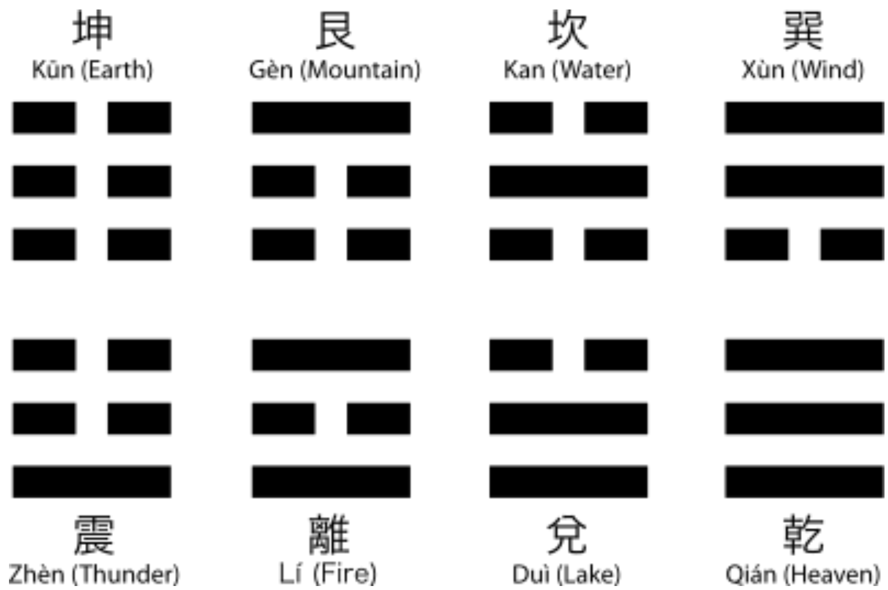


Fig. 1. The eight trigrams of the I Ching

Chapter 2: Background

2.1 History – The Foundations of Systems Thinking

Systems thinking dates to ancient times, manifested in the development of human language, mathematics, philosophy and divination systems such as the I Ching. Thousands of years before Christ, Chinese philosophers were using the tenets of the I Ching to classify, order and assess the elements of systems and to model future behavior. Ancient engineering feats and the construction of societal monuments such as the man-made wonders of the ancient world required the development of an early systems approach to construction and system complexities on a grand scale. Iteration of large-scale construction projects helped create efficiencies and advanced systems that evolved during the development of evolving civilizations. Indus Valley, Greek, Mesopotamian, Roman and Mayan cities and the economies they controlled were complex systems, adapting and improving through history. Systems thinking manifested itself in the Inca Empire and Angor Wat along with the construction of the great cathedrals of Europe at the heart of mega-cities such as Paris, Rome, Cologne and London. These efforts were the metaphorical Apollo space programs of their respective civilizations and as such, required systemic approaches to accomplish. Still, these systems took many generations to reach maturity and were mainly static. It took the industrial revolution to bring large-scale dynamic systems to humanity and the appropriate advances in systems thinking.

In the early 18th Century, pioneering economist Adam Smith applied systems thinking in his study of efficiencies in the manufacturing of metal pins. Considered by many to be the Father of Operations Research (and the father of the mechanical computer), Charles Babbage studied efficiency in the Royal Mail in the early 19th Century. Babbage found that the cost of sorting exceeded the cost of transportation. His recommendations resulted in the uniform postal rate structure commonly known as the Penny Post, adopted by postal systems world-wide. Frederick Winslow Taylor developed the field of scientific management – increasing the efficiency of human laborers and machines by monitoring and timing their movements and interactions. This systematic approach to labor caused friction when the human subjects did not appreciate being considered as machines themselves, influencing the new field of industrial psychology. It was around 1930 that psychologists discovered human engineering, and engineers discovered industrial psychology the later motivated in part by the expenses attributed to a dissatisfied workforce and the cost of labor turnover. A.P. Rowe went beyond operations research as war clouds approached Britain in the late 1930s. His concept of a defense-warning network called **CHAIN HOME** protected the UK before and during WW II. Rowe's systems thinking approach included a network architecture that emphasized robustness and fault-tolerance, thus minimizing the effects of battle damage from Nazi bombers (and later appropriated by ARPA to create a nuclear war tolerant network we now call the Internet). World War II saw the large-scale adoption of operations research and systems approaches to war, logistics and development programs including the Manhattan Project. After World War II, the RAND Corporation and others were engaged by the U.S. Government to apply these new skills in systems thinking to large problems such as space exploration. They built on German and other concepts to lay the systems thinking foundation for the Apollo program in 1946 [11]–[18].

2.2 Literature Survey - Systems Dynamics and Computer Modeling

In the 1950s, electrical and computer engineer Jay Forrester founded a systems analysis field known as system dynamics. Forrester's goal was to simulate the interactions between objects in dynamic systems. According to Lane (2000), system dynamics modeling employs three key characteristics in order to replicate the function and interactions of the system over time and predict the function of the system in the future. Information feedback loops replicate the state of the system and the influencing actions that change the system over time. These causal links – the first characteristic of system dynamics – are also known as stock and flow models. Simulation models using stock & flow diagrams became the hallmark of the Forrester system dynamics approach and led to the modeling of economics, social systems (e.g.: urban dynamics) and ecological systems using computer simulation – the second key characteristic of system dynamics. Due to lags in the system model and the non-linear nature of the feedback links, humans lack the cognitive ability to deduce the behavior of the system over time without the assistance of computers. Causal effects lead to different parts of the system becoming dominant over time with interesting and counter-intuitive results. Forrester insists that the insight of system dynamics explains exactly why policies sometimes produce results contrary to those desired [19]–[23].

The third key characteristic of systems dynamics according to Lane is the need to engage with mental models in the context of a decision maker's comprehension, inference, and consciousness as described by Philip Johnson-Laird [24]. A systems analyst must realize that the inherent complexity of a system is not written down. These mental models are complex and full of quantitative information as well as axiological (value-based) components. They include the judgmental and subjective aspects that fall within the system boundaries but too frequently not within the scope of the analysis. Lane states that it is through eliciting, debating and facilitating change in the mental models that improvements to the management of a system can be derived. An analyst must, therefore, engage the system and the decision makers at close proximity [23].

Forrester expanded the concept of system dynamics until the system boundaries of his model encompassed the entire world and everything in it. He grew so confident in his approach that he stated, "To reject this model because of its shortcomings without offering concrete and tangible alternatives would be equivalent to asking that time be stopped."[20] But Lane criticizes Forrester's approach and points out that the *"various descriptions of [system dynamics] seem extreme, naïve or simply confusing to system (and social) scientists. Many of the hard/deterministic criticisms would not have arisen if the field had been a little more judicious in its language. Some sensitivity towards the concerns of other systems thinkers and a better command of the terminology would be an aid"* [23].

A student of Forrester, Dana Meadows describes the models of systems dynamics through what she called *The System Lens*. In her posthumously published book, she introduces with the fable of the blind men and the elephant to describe her perspective on thinking in systems – "*the behavior of a system cannot be known just by knowing the elements of which the system is made*"[25]. Meadows proceeds, however, to summarize the structure of a system as its interlocking stocks, flows and feedback loops. She acknowledges the limitations summarized by Box: *"We can improve our understanding [through models], but we can't make it perfect. I believe both sides of this duality because I have learned much from the study of systems"*[25]. Meadows' definition of systems thinking (along with Forrester and Richmond) can be summarized as the conjunction of the models of stocks, flows and feedback with the output of such models. If one can understand the connection between the events (model) with the behavior (output) – one is engaged in systems thinking. A critical point that Meadows identifies is that of the leverage point. In her terminology, the mental model underlying the system is the paradigm and the ultimate leverage points can be used to change the paradigm – or even transcend the paradigm [25], [26].

In his tome on dynamic systems, David Luenberger defines the systems approach as: *"…a recognition that meaningful investigation of a particular phenomenon can often only be achieved by explicitly accounting for its environment… Meaningful analysis must consider the entire system and the relations among its components"*[27]. Of course, Luenberger was referring to the mathematical relations in a dynamic system as expressed through a combination of vector algebra and differential or difference equations. The mathematical approach of dynamic systems modeling is critical to assessing a system and modeling potential outcomes, but this 'hard' approach must always be considered in the subjective context of systems thinking for the model to have value. The environment that Luenberger refers to is really the environment of many factors including nature, thought, belief and aesthetics - not just the environment of mathematics and computation.

2.3 The Systems Approach

Russell Ackoff wrote that no amount of [mechanical] analysis of American and British cars could discern why the steering wheels are on opposite sides. He stated, *"Not all ways of viewing a problem are equally productive, but the one that is most productive is seldom obvious. Therefore, problems should be viewed from as many different perspectives as possible before a way of treating them is selected. The best way often involves collaboration of multiple points of view, a transdisciplinary point of view.[2]"*

C. West Churchman describes the system approach in terms of its purpose, not its mathematical structure. The first chapter of his seminal book is entitled *"Thinking"* where he describes four disparate factions of managers in a debate over what constitutes the best approach to systems analysis. The four groups are: the advocates of efficiency in the image of Babbage; the advocates of science who take an objective approach; the advocates of human feelings who take a values-driven approach; and finally the anti-planners that espouse experience and intuition as the hallmarks of good management [28].

All four bands of decision makers, according to Churchman, are deceived in various ways into believing that their approach is correct. The ideal systems approach is therefore based both in an understanding of the ways that humans can be deceived about their perspective and their world - and in the interactions between the four different approaches. In the ancient texts of the I Ching, Churchman finds the ideal systems approach to decision making: a dynamic balance of opposites, the evolution of events as a process and the acceptance of the inevitability of change. Remarkably, the I Ching exhorts the benefits of systems modeling two millennia BC and the need for an expert to develop and to interpret the model [29], [30].

Churchman subsequently identifies the *enemies* of the systems approach: politics, morality, religion and aesthetics. [He includes ignoring history as an adjunct enemy.] With each enemy, the approach to understanding life (Forrester's world) is not comprehensive – none of them accepts the reality of the whole system. Yet Churchman doesn't devote his approach to defeating the enemies of the systems approach, but rather to dealing with them through comprehending them – and thus including their perspective – their mental models - in systems analysis [30]."

Churchman is considered by some to be the grand philosopher of the soft systems approach and was nominated in 1984 for a Nobel Prize in the field of social science. Robert Flood and others succeeded Churchman in examining the distinction between hard systems thinking involving well-defined, quantifiable technological systems and soft systems thinking involving such fuzzy considerations as human beings and belief. Flood and Ewart Carson refer to the soft approach as *systems science*. Underlying systems science is general systems theory (GST), based on fundamental systems concepts that transcend all disciplines. Flood states "*systems thinking is a framework of thought that helps us to deal with complex things in a holistic way. Giving an explicit, definite and conventional form to this thinking is what we have termed systems theory (i.e. theory is the formalization of thinking)*"[31].

Peter Checkland draws the distinction of hard and soft in the approach, not the system. The hard perception sees distinct systems that can be engineered. The soft perception sees a less distinct, more complex world in which the analyst can organize exploration via a learning system. In the hard approach, the world is systemic. In the soft systems approach, the process of inquiry is systemic [32].

Peter Senge defines systems thinking as the cornerstone of five disciplines that make up a learning organization [personal mastery, mental models, building shared vision, team learning and systems thinking.] You can only understand the system by contemplating the whole, not any individual part. *"Systems thinking is a conceptual framework, a body of knowledge and tools ... to make the full patterns clearer and to help us see how to change them effectively"*[33]. Senge employs causal loop sketches reminiscent of Forrester's stock and flow models to show the interrelations of system components resulting in a blend of the Churchman and Meadows approaches to systems analysis.

Over the years, the application of systems thinking in design and analysis came to be known as the field of systems engineering. The term "Systems Engineering" can be traced to Bell Labs in the aftermath of World War II but Bell Labs didn't invent the concept; they just gave it a label. We have seen that the concept existed for thousands of years. Bell Labs, however, recognized the need for a new field of engineering when dealing with complex systems because the correct discrete components frequently did not integrate into the correct system. Andrew Sage provides a clear and concise definition of Systems Engineering: *"We use the word* **systems** *to refer to the application of systems science and methodologies associated with this science of problem solving. We use the word* **engineering** *not only to mean the mastery and manipulation of physical data but also to imply social and behavioral considerations as inherent parts of the engineering process. Thus by systems engineering we refer not only to physical systems and devices but to human and social systems as well."* Sage proceeds to critique the approach of Forrester and his disciples, questioning the system boundaries in Forrester's models and pointing out the subjective nature of his modeling. Changing the parameters within Forrester's model structure, as well as changing the structure itself, produces different simulated behaviors. Forrester's method might be improved through incorporating a game theoretic approach. Sage tacitly agrees with critics of Forrester for developing models with built-in bias, for not explicitly stating a value system and for making potentially invalid assumptions. Sage's point is not to discount Forrester's methodology but to insist that it, and all models, must be explained in context - the more complex the model, the more complex the context. The model is a part of the systems analysis, not the entire systems analysis [34], [35].

Dennis Buede cites ten different definitions of systems engineering, starting with MIL STD 499A, ending with the **AMERICAN HERITAGE DICTIONARY**[1] and concluding with his own: *"[An] engineering discipline that develops, matches and trades off requirements, functions and alternative system resources to achieve a cost-effective, life-cycle balanced product based upon the needs of the stakeholders"*[36]. Buede's emphasis is a framework and tool-centric systems approach including discrete and some stochastic mathematics - but he builds it on a solidly systems thinking approach that includes the importance of considering the entire system life-cycle, the objectives of the stakeholders and identifying the type of system early on in the analysis. Buede reinforces Sage's criticism of Forrester and those who rely overly on system simulation: *"…we must always remember that any quantitative model is developed via a mental process of one or more people and is the product of their mental models. Therefore, it is a mistake to ascribe objectivity to models. Complex mathematical models often have subjective assumptions throughout their equations and data"*[36].

---

[1] *"The application of scientific and mathematical principles to practical ends such as the design, construction and operation of efficient and economical structures, equipment and systems"*[36].

[2] Brazil has also created an extensive infrastructure to support pure ethanol as a transportation fuel.

[3] ISO 14041 as quoted in the EPA LCAP&P

[4] Argonne NL Transportation Technology R&D Center, http://www.transportation.anl.gov/modeling_simulation/GREET/

[5] $(S\&T)^2$ Consultants, http://www.ghgenius.ca/

[6] National Resources Conservation Service, http://www.nrcs.usda.gov/TECHNICAL/maps.html

[7] Envergent is a Canadian/U.S. joint operation of UOP Honeywell and Ensyn, the owner of the intellectual property rights of the rapid thermal processing (RTP™) pyrolysis technology.

[8] The details of the RTP technology are proprietary and, though requested from the source, were not made available.

Similar to Buede, Mark Maier and Eberhardt Rechtin fill an appendix with varying definitions of systems architecture, pointing out that: *"an inordinate amount of time can be spent arguing about fine details of definitions."* They include their own: *"Architecture: The structure (in terms of components, connections, and constraints) of a product, process, or element,"* but conclude with some insight to the defense industrial systems approach in what they call *"Maier's tongue-in-cheek rule of thumb… An architecture is the set of information that defines a systems value, cost, and risk sufficiently for the purposes of the systems sponsor [37]."*

John Gibson, Bill Scherer and William Gibson bring together the systems thinking definitions of Senge and Churchman with the methodologies of Sage, Forrester, Luenberger, Buede and others to establish a primer in systems analysis with an emphasis on systems thinking. Their work forms a significant portion of the foundation of this thesis [38].

Beyond mental models, the metathinking study of systems thinking considers language as an expression of thought. We look to language scholar Noam Chomsky who writes on how we structure thought: *"Nevertheless, all facts are not born free and equal. There exists a hierarchy of facts in relation to a hierarchy of values. To arrange the facts rightly, to differentiate the important from the trivial, to see their bearing in relation to each other and to evaluation criteria, requires judgment which is intuitive as well as empirical. We need meaning in addition to information. Accuracy is not the same as truth."* This systemic approach to how we structure thought became the theory of generative grammar [39].

Derek Cabrera, et.al. provide us with: "*Thinking about systems is an ad hoc, primarily informal process that each of us does on a daily basis. In contrast, systems thinking is a more formal, abstract, and structured cognitive endeavor. While not all systems are complex, all thinking is complex, and as such, the process of thinking in a systemic way is complex. Systems* *thinking is also based on contextual patterns of organization rather than specific content. For example, systems thinking balances the focus between the whole and its parts, and takes multiple perspectives into account"*[40].

Finally, Churchman best describes systems thinking as "playing it hot" with the enemies of the systems approach: "*Accept the fact that 'application' is the biggest problem we face, compared to which population modeling, energy modeling, educational modeling are simple games. Start work on incorporating politics, morality, religion, aesthetics into the systems approach; do not believe the feeling types when they scream at your inhumanity nor the thinking types when they scorn your softness[41]*

Chapter 3: A Framework

3.1 Chapter Summary and Introduction

The previous chapter showed the history of systems thinking back to ancient times. Systems thinking developed alongside mathematics and engineering, but unlike mathematics, physics, biology and other fields with similar histories, systems thinking lacks a common language that transcends disciplines and applications. Such a language would form the foundation of systems thinking much as the symbols of the languages of mathematics and chemistry form the foundation of those fields.

This chapter presents a metathinking – thinking about systems thinking -- approach to a standard foundational language of systems thinking - the Dimensions of Systems Thinking (DST). This chapter introduces key concepts including the observer effect of systems thinking; the delineation between the scope of the analysis and the boundaries of the system; and the distinction between metrics and indices of performance of a system. It defines all of the elements in detail and considers how the system thinking process flows. It starts with some fundamental concepts of language.

3.2 Lexicology

The schools of linguistics that are founded upon Chomsky's theory of generative grammar use the term *language* to refer to a hypothesized, innate module in the human brain that allows people to undertake linguistic behavior. This view, however, does not necessarily consider that language evolved for communication in particular. They consider instead that it has more to do with the process of structuring human thought. The reference from Chomsky in the previous section illustrates how language supports systemic thought: a hierarchy of facts (evaluated alternatives) in relation to a hierarchy of values (system objectives). The functional theories of grammar posit that language emerged as a communication system to support cooperative activity and extend cooperative networks.

It is in these contexts that this thesis presents a defining foundation of systems thinking in a form based upon language, to facilitate communication in cooperative networks of systems thought and that transcends individual thought processes and approaches [39], [42]–[44].

The applications of models and methods derived in operations research, systems engineering and economics are a key part of systems analysis – but not themselves a manifestation of good systems thinking. Neither is the succinct expression of a relevant aphorism – brilliant though it may be. Systems thinking must demonstrate a tool agnostic, transparent thought process through language that delineates a progression to solutions. In this context of metathinking, we undertake the challenge of proposing and describing a lexicon to populate a common systems thinking framework across multiple domains and disciplines.

3.2.1 Systems Thinking

To derive a lexicon of systems thinking, this thesis starts with two fundamental concepts: that of a system and that of thinking. We will start with the definition of a system:

A system is a set of elements so interconnected as to aid in driving toward a defined goal[38].

Next, we consider the definition of thinking, defined by Myers as critical thinking:

Critical thinking examines assumptions, discerns hidden values, evaluates evidence and assesses conclusions[45].

Then, this thesis adds a third key concept: While not all systems are complex, all thinking is complex, therefore thinking in a systemic way is complex [40]. *Systems thinking* describes an evolving structure, a thought process capable of changing and reorganizing its component parts to adapt themselves to new information and new issues. It is *error embracing and iterative. Systems thinking* therefore constitutes an adaptive system and thus*, systems thinking* is, itself, a complex adaptive system.

Therefore, the definition of systems thinking at the cornerstone of the foundation is: *A thought process through which assumptions are examined about a set of interconnected elements that drive toward a common goal with the objective of discerning hidden values and evaluating evidence in order to assess conclusions.* We add the metathinking aspect where we turn systems thinking on itself and conclude that: *Systems thinking is a complex adaptive system.*

This last aspect is integral to a metathinking definition of systems thinking. Solutions and alternatives conceived in the system survive – or not - based on their interactions with other alternatives and the system – while the system itself may be changing. This survival of the fittest harkens to Darwin's original concept of evolution. It establishes a notable parallel between systems thinking and organic complex adaptive systems such as ecosystems, immune systems and the brain [46].

At this point we have established the two upper levels of the hierarchy of the lexical dimensions, shown by the two left columns of the mapping in Fig. 2 on page 24. At the top of the second column are the system dimensions, the bottom are the thinking dimensions and at this level, the clarity between the two is obvious. The systems dimensions would include the abstraction of system models of domain specifics including the idea that we can usefully model elements and interactions from individual cases and find recurrent patterns. The thinking dimensions include the separation of values of alternatives and in the middle we place the reflexive concept that systems thinking is a complex adaptive system. Together, this column delineates what we consider to be a best and minimal description of systems thinking – but not a working level lexicon that can be readily reflected in practice.

In order to derive a working-level set of lexical components, the literature references were mined for key concepts and additional phrases and meanings were designed to resolve certain conflicts in the terminology. The resulting twenty dimensions are mapped to the definition derived above in Fig. 2 to show the direct correlation of the set to the components of the original definition.

Observe that all of the dimensions on the right half of the figure map to both the *systems* and the *thinking* aspect of the definition and that as the dimensions progress from top to bottom the level of the *thinking* aspect increases.

3.2.2 Mapping the definition of systems thinking to the Dimensions of Systems Thinking and vice versa

In taxonomic form, the twenty lexical components of the Dimensions of Systems Thinking are as follows:

1. Descriptive scenario
    a. System boundaries
    b. System stakeholders
    c. Scope of the analysis
    d. Type of system
        i. State of system
        ii. Life cycle of system
    e. Metrics
    f. Axiological components
    g. Observer effects
2. Normative scenario
    a. Objectives
3. Indices of performance
4. Develop alternatives
    a. Outscope
    b. Evaluate & rank alternatives
        i. Iterate analysis
        ii. Interactions
    c. Leverage points
5. Recommendations

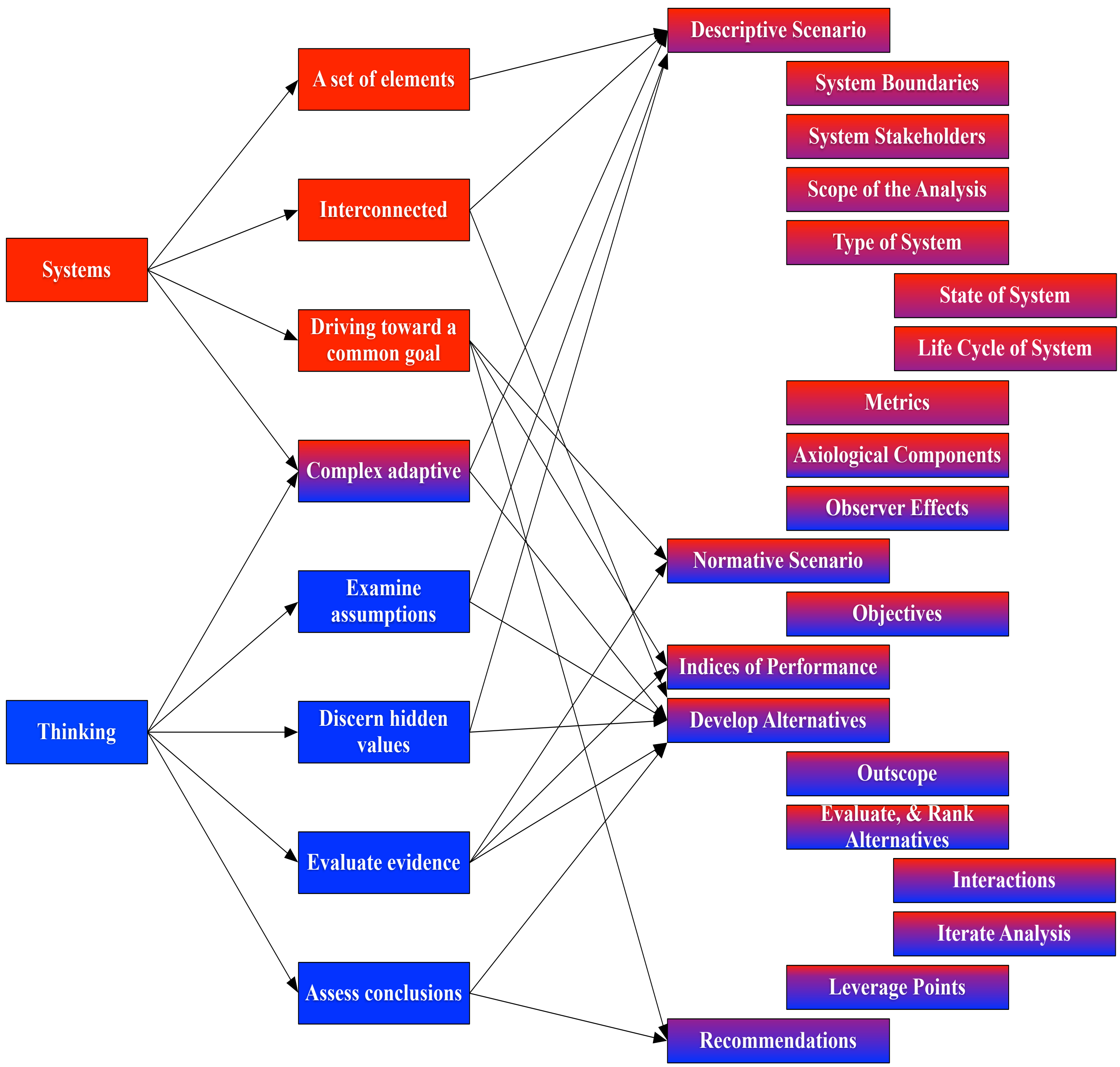


Fig. 2. Mapping of the definition of systems thinking to the Dimensions of Systems Thinking showing the correlation of the systems and of the thinking aspects with each of the five taxonomically higher dimensions

Fig. 2 shows graphically the mapping of the definition of systems thinking to the higher taxonomic Dimensions of Systems Thinking and vice-versa. For clarity, the lower order taxonomic elements are not graphically mapped, but their correlation to the definition is as follows:

- *A set of elements* maps to:
  - The Descriptive Scenario including system boundaries, system stakeholders, the scope of the analysis, the type of system, the state of the system, the life cycle of the system, the axiological components and the metrics.
- *Interconnected* maps to:
  - The Descriptive Scenario including system boundaries and the type of system.
  - Develop Alternatives including interactions, iterate analysis and leverage points
- *Driving toward a common goal* maps to:
  - The Normative Scenario including objectives,
  - Indices of Performance
  - Recommendations
- *Complex adaptive* maps to:
  - The Descriptive scenario including the scope of the analysis, axiological components, the observer effects and the state of the system.
  - Develop Alternatives including outscope, interactions and iterate analysis
- *Examine assumptions* maps to:
  - Descriptive Scenario - all dimensions
  - Develop Alternatives including outscope and iterate analysis.
- *Discern hidden values* maps to:
  - Descriptive Scenario - all dimensions
  - Develop Alternatives including outscope, interactions and leverage points

- *Evaluate evidence* maps to:
    - The Normative Scenario including objectives
    - Indices of performance
    - Develop Alternatives - all dimensions
- *Assess conclusions* maps to:
    - Develop alternatives including evaluate and rank alternatives and leverage points
    - Recommendations

The twenty working-level elements that make up the Dimensions of Systems Thinking lexicon are presented alphabetically below in Section 3.3. The listing includes a definition of the lexical component in the context of systems thinking; an explanation of why this is an important factor of systems thinking; the difficulties associated with this aspect of systems thinking; a brief example of this facet of systems thinking being done well (generally from engineering or analysis); and another brief example of this facet of systems thinking gone wrong.

This list of foundational dimensions was developed to be as complete as possible in the sense that the expression of any systems thinking process could be described using these twenty lexical components – but just as new genus and species are added to the hierarchy of biological classification and new elements are added to the periodic table, new elements will undoubtedly be added to this list as discussion and the development of systems thinking progresses. The list expresses a baseline of a lexicon. In language, there are multiple ways to express an idea and appropriate synonyms exist for every term in the list. This is a non-unique set and other spanning lexicons certainly exist.

For example, consider the lexical component *Objectives.* This term was selected as representational in the dimensions where other terms are interchangeably used in the literature. Some approaches delineate that *goals* are subjective and *objectives* quantifiable. Ackoff delineated a hierarchy of *goals* leading to *objectives* leading to *ideals*.[2] Gibson, Scherer and Gibson write of a hierarchical *objectives* tree being a graphic display of the *goals* of the system [38]. We all may understand the terms *requirements, goals, objectives, ideals, targets, ambitions* and *key performance parameters*, but consider that these terms delineate different hierarchies in different contexts. Systems engineering must be goals driven, so this lack of clarity in the very definition of what drives our work should be a prime matter for discussion and resolution.

As with objectives, there are hierarchies within many of the aspects of a systems approach. The objectives would be determined from the normative scenario and delineated into a hierarchical objectives tree then cross-correlated with a hierarchical outline of the stakeholders. Each stakeholder has mental models that may be dynamic, requiring some iteration of the objectives. A hierarchical delineation of possible solutions makes-up the core of the recommendations. The interim thought process is largely devoted to the iterative development and assessment of that hierarchical set of solutions to achieve the hierarchical set of objectives.

3.2.3 Descriptive scenario and the development of alternatives

The *descriptive scenario* presents the current system/design/problem/issue as described and agreed upon by the primary stakeholder(s). It is commonly derived through observation, research, meetings and interviews. Ten lexical components derive from and affect the delineation of the descriptive scenario as the syntax flows from descriptive scenario to develop alternatives: *system stakeholders, system boundaries, metrics, type of system, axiological components, the observer effect*, *the scope of the analysis, the life cycle of the system, the state of* *the system* and *outscope.* The last term, *outscope*, is a critical component in the transition from *descriptive scenario* to *development of alternatives*.

System stakeholders and *system boundaries* are considered early in a systems analysis. Few systems truly count all living things as stakeholders and the universe and time as we know it as boundaries., The *scope of the analysis* represents practical limits of the analysis within the *system boundaries*. The analyst still needs to be aware of the system boundaries and be prepared to adjust when *outscoping*. The practical limits on the scope of the analysis may be driven by data availability, cost, available time, policy, access and other practical limits.

Metrics are not necessarily *indices of performance*. While the former describes the state of the system in terms of what we can observe and measure, the latter is a relevant quantitative measure to *evaluate and rank alternatives* for achieving the system *objectives*. The metric that the car is red will not be a performance index if the objective is speed, but will if the objective is sales.

Axiological components and *observer effects* are two key lexical components often overlooked in systems thinking. There is always a snail darter, hidden burial ground or nut allergy to be considered, so the thought process must consider the axiological early and often. Planning early for the axiological aspects can become a temporal leverage point [38]. Axiological considerations found late can cause disproportionate delays. It may not matter if a bad bearing or an unmapped pipe cause a tunneling machine to stop, but planning ahead for such an axiological contingency reflects a sound systems thinking approach: how the tunneling machine would be removed from the hole if it should stop functioning for whatever reason. Nothing is unsinkable. Similarly, getting minority stakeholders invested in the system early can avoid problems and delays later.

Consideration of *observer effects* means the final analysis must have none of the prejudices of the analyst and only the perspective and values of the stakeholders. This must be balanced with the knowledge that key stakeholders are frequently too close to the problem to fully understand it. The analyst must judiciously leverage her/his own outside perspective to help the key stakeholders understand the true descriptive scenario.

In the physical sciences, especially quantum physics, the term observer effect is used to describe how the act of experimentation, measurement or observation changes the subject system. For example, if you measure the current in a wire, your instrument infinitesimally reduces that current. Thus, the system will have different characteristics when under observation (analysis) versus when not under observation. In systems analysis, this effect may manifest itself in several ways. It is not difficult to conceive of someone under scrutiny performing differently if they know they are being observed. Consider also the observer forgetting that she/he is not a decision maker and allowing personal prejudice to influence perception. The observer effect can also be positive in the case where the analyst objectively reveals the true nature of a problem to a stakeholder who is too close to it to see it clearly. (The observer effect is sometimes confused with the uncertainty principle in physics)

Understanding the *type of system* includes understanding the *life cycle of the system* and *the state of the system*. Buede lists the following example types of systems:

- *Natural vs. man made*
- *Closed vs. open*
- *Static vs. dynamic*
- *Simple vs. complex*
- *Reactive vs. non-reactive*

- *Precedented vs. unprecedented*
- *Safety-critical vs. not safety critical*
- *High reliability vs. not high reliability*
- *High precision vs. not high precision*
- *Human-centric vs. nonhuman*
- *High durability vs. not high durability* [36]

Magee and deWeck classify types of systems with a two by two matrix: On the X-axis: Matter (M), Energy (E), Information (I) and Value (V). On the Y-axis: Transformation or Process (1); Transport or Distribute (2); Store or House (3); Exchange or Trade (4) and Control or Regulate (5). In the paper referenced in Section I, Ackoff also derived a system of systems concepts for describing the type and state of the system being considered [2], [47].

The *life cycle* of the system is not a life cycle assessment of the system. The latter is a metric. The life cycle is a description of the dynamic nature of the phases of the system lifetime expressed in terms of lust-to-dust, well to wheels, plow to pedal, cradle-to-grave, or cradle-to-cradle context. Analysis must begin with the origins of the concept and continue through the re-use and retirement of the system. The *state of the system* similarly describes the system in terms of its level of evolution, technology readiness or current position in the life cycle. The Department of Defense devised the Technology Readiness Level (TRL) metric and other metrics for cataloging the state of the system.

Outscope describes the systems analysis process of systems decomposition followed by recomposition of the system with a broad perspective so that every contingency and possible stakeholder are considered - break the system down to its core component parts and then reconstruct it while considering alternatives. Systems analysts need to be big-picture, outside the box thinkers, while rooted in the foundation of the quantifiable and practical. [36].

3.2.4 Objectives, the normative scenario and the evaluation of alternatives

The ten lexical components described in the previous section form the flow from *descriptive scenario* to the *development of alternatives* in a systems approach. The *normative scenario* projects the descriptive scenario into a future, desired state where the *objectives* have been achieved. Developed from the normative scenario, the system objectives describe a hierarchical delineation of goals derived from a deep understanding of stakeholder needs and values. The ability of the alternatives to fulfill the objectives and achieve the normative scenario – the key analytic component of a systems approach – is included in the lexical component *evaluate and rank alternatives*. The analytic tools – many of which pass for an entire systems analysis elsewhere – reside in this component. Modeling (physical, quantitative, qualitative, mental), system dynamics, game theory applications, design of experiments, statistical analysis and inference, simulation, market research, trade study techniques, optimization and optimization tools, sensitivity analysis, decision analysis, financial analysis, utility functions and many other functions of systems engineering and operations research make up the taxonomy of this component.

Included in the analytical aspect of evaluating alternatives is the validation and verification of the assumptions and trade-offs that occur in the analytical part of any systems approach. For example, in determining the scope of the analysis, certain assumptions are made regarding the significance of factors known to be inside the systems boundaries but outside the scope of the analysis. Verifying these and other assumptions goes hand-in-hand with the validation of evaluating and ranking alternatives. Transparency and the validity of the approach demand that this be done clearly and prominently in the process.

3.2.5 Recommendations

Alternative solutions are developed, evaluated and ranked in their ability to achieve the objectives. During the progression of the systems thinking process, the analytic tools such as system dynamics modeling reveal *interactions* in the system, sensitivity and instabilities. Different alternatives and perhaps different indices of performance are considered through *iteration* of the analysis. Iteration is a notable concept in systems thinking and encompasses the notion that systems thinking is error embracing and iterative – we learn more about the system and then re-apply that knowledge to our approach in order to improve our thinking and thus improve the system. Error embracing and iterative can also mean either reducing the error through higher resolution analysis or learning things along the way that illuminate an important consideration that had been omitted. In iteration, the systems thinker should take care to consider the mental models involved including the danger of designer bias – the observer effect.

Leverage points - places in the system where a small change could lead to a large shift in system behavior – are identified through the evaluation and ranking of alternatives including statistical regression, sensitivity analysis, analysis of interactions and analysis iteration. The leverage points in a systems analysis will be system specific, but an excellent example (in system dynamics terms) can be gleaned from a paper by Dana Meadows, listed here in reverse order as they were originally published:

12. Numbers: Constants and parameters such as subsidies, taxes, and standards

11. Buffers: The sizes of stabilizing stocks relative to their flows

10. Stock-and-Flow Structures: Physical systems and their nodes of intersection

9. Delays: The lengths of time relative to the rates of system changes

8. Balancing Feedback Loops: The strength of the feedbacks relative to the impacts they are trying to correct

7. Reinforcing Feedback Loops: The strength of the gain of driving loops

6. Information Flows: The structure of who does and does not have access to information

5. Rules: Incentives, punishments, constraints

4. Self-Organization: The power to add, change, or evolve system structure

3. Goals: The purpose or function of the system

2. Paradigms: The mindset out of which the system—its goals, structure, rules, delays, parameters —arises.

1. Transcending Paradigms [26]

The optimum alternatives – including leverage points – and the analysis results to support them - become the core of the *recommendations,* - the conclusions derived from systems thinking. An approach can be computationally correct and provide recommendations that solve the stakeholders' problems, but still fail if the information in the recommendations is not presented systemically. The work done to understand the observer effect must factor into the presentation of the recommendations. Failure to consider such factors as the mental model, the mindset and knowledge of the stakeholders vs. that of the analyst and the time limitations on someone at the decision-making level of authority can doom an otherwise good analysis. Brevity is a friend. So is accuracy.

3.2.6 Metathinking

In the metathinking context, all of this is centered on several global constructs that inform each action, including an explicit recognition of the iterative nature of systems thinking: we learn as we think and we modify our priors as we learn, resulting in deeper understanding and more complete picture of both current and desired future states. We also are on constant lookout for opportunities for those elements that offer leverage for significant movement toward the desired future state – policy, technology, strategic investments, skills, etc. In addition, we are aware that systems thinking always has a temporal dimension and requires consideration of long-term effects – throughout the life cycle of a product or service, including the effects of the system on observers who are outside the designated boundaries of the system of interest.

3.3 The Dimensions of Systems Thinking (DST)

The following list details alphabetically each of the foundational lexical dimensions of the language of systems thinking.

3.3.1 Axiological components

3.3.1.1 Definition

Factors not necessarily obvious at first examination of the system, particularly to the decision makers; axiological components frequently involve the underlying values (including feelings and beliefs) or agendas behind the mental model and the willingness of stakeholders to accept change. [see: *Outscope*] [28], [38]

3.3.1.2 Why Important

The latent axiological components of a scenario may lead to conflicts that hinder the resolution of the problem; identifying and resolving these conflicts may be the only way to truly solve the problem and achieve the normative scenario.

3.3.1.3 Why Difficult

The axiological facet can involve deeply set feelings and may include partisan, belief or political overtone; trying to discuss them may make the stakeholders feel attacked, possibly making them defensive and less cooperative.

3.3.1.4 Positive example

A systems analysis of the transportation system in Canada that considers the lifestyle and desires of citizens as well as the political mores of the key decision makers [48].

3.3.1.5 Negative example

An aid program that delivers a water purification system to a village to help eradicate childhood diarrhea but ignores practicalities and the local beliefs and sensibilities [49].

3.3.2 Descriptive scenario

3.3.2.1 Definition

An illustration of the current state of the system; may include diagram(s) and a taxonomy to describe the system/problem and its environment; considers the functional, physical, allocated and interface architectures of the system; describes the situation as it is and how it got to be that way (See also *Type of System.)* [36], [38]

3.3.2.2 Why Important

The systems thinking analyst must have a comprehensive understanding of the system - without being a subject matter expert - in order to properly plan and conduct the systems analysis

3.3.2.3 Why Difficult

The systems analyst is not a subject matter expert and therefore must rely on their own ability to learn the subject quickly while relying on SMEs. The experts that are already engaged with the system are likely too close to it to see the problem clearly

3.3.2.4 Positive example

Farmers addressing the causes more than the symptoms of soil erosion in Zambia [50]

3.3.2.5 Negative example

The Renewable Fuel Standard 2 (RFS2) (U.S. Environmental Protection Agency) directed the production of 15 billion gallons of corn ethanol annually to be blended with gasoline for use in internal combustion engines. Data now show that the descriptive scenario was incorrect and the maximum amount of ethanol that could be consumed would be less than 13 billion gallons; ethanol production surpassed consumption and new plants were shut down.[51]

3.3.3 Develop Alternatives

3.3.3.1 Definition

Different routes to achieve objectives or perhaps improve upon the normative scenario; Tools to aid the development of alternatives may include: brainstorming, brain writing, dynamic confrontation, Zwicky morphological box, options analysis, Delphi [38].

3.3.3.2 Why Important

This is the creative aspect of systems thinking where good outscoping can make the difference in a systems analysis by illuminating new options for system improvement; the systems thinking approach can result in recommendations that lie far from the original concept of the decision makers.

3.3.3.3 Why Difficult

All stakeholders will have ideas for how to improve a system, the analyst must filter carefully to avoid excessive analysis and frequently derive original options based on the systems thinking approach.

3.3.3.4 Positive example

Considering teleworking in a transportation/energy use study [52]

3.3.3.5 Negative example

A surgeon who fails to consider alternatives to surgery when treating a patient - in this case performing an unnecessary hysterectomy [53]

3.3.4 Evaluate & rank alternatives

3.3.4.1 Definition

The application of systems engineering tools to score and rank the indices of performance of alternatives; tools may include: modeling (physical, quantitative, qualitative, mental), operations research techniques, game theory applications, design of experiments, statistical analysis, simulation, market research, trade study techniques, optimization tools, decision analysis, financial analysis and utility functions [35], [36], [38].

3.3.4.2 Why Important

Decision makers want factual, quantitative analysis to support their decisions; they also want valid options, particularly options they had not previously considered.

3.3.4.3 Why Difficult

Sensitivity analysis plays a key role in identifying options and critical metrics. Weightings can then be modified to study optional scenarios [see: *Indices of Performance*, *Leverage Points, Iterate Analysis*].

3.3.4.4 Positive example

Base re-alignment and closure office - BRAC, evaluated all U.S. military installations and facilities with the objective of reducing the footprint and base costs of DoD [54].

3.3.4.5 Negative example

BRAC (Bitburg, Germany air base was closed in 1993 BRAC and all aircraft relocated to Spangdhalem 10 miles away. Two + 1/2 years later, Bitburg was leased back & reactivated at considerable expense so that the runway could be resurfaced at Spangdhalem) [55].

3.3.5 Indices of performance

3.3.5.1 Definition

Criteria for ranking alternative solutions to the problem must be: meaningful, consistent, understandable, related to individual objectives and determined from defined metrics (see: *metrics*) using system modeling, statistical analysis, datamining, trade studies, house of quality, hierarchical decision tools, financial analyses, etc. [38].

3.3.5.2 Why Important

A quantitative, logical ranking of alternatives is the basic result of a systems analysis; this ranking is supported by the IPs and generally includes the option to make no change – retain the baseline scenario.

3.3.5.3 Why Difficult

The systems thinker must avoid performing unnecessary analysis, using inappropriate analysis tools, over-complicating or over-simplifying the analysis or omitting verification and validation of assumptions made in the analysis.

3.3.5.4 Positive example

Decision trees with probabilities derived from statistical analysis that are used by doctors when performing differential diagnosis [56].

3.3.5.5 Negative example

More accurate forms of statistical regression not used because they may be harder to understand or compute (e.g.: support vector machines used in place of artificial neural networks because ANN was determined to be more difficult to use) [57].

3.3.6 Interactions

3.3.6.1 Definition

A systemic consideration of the interrelations between goals, activities, constraints, resources, stakeholders and other system interactions [10], [28], [38].

3.3.6.2 Why Important

Illustrating systemically the interrelations of a system can reveal key cause/effect relationships including nonlinearities and feedback loops that may not be otherwise be evident but should factor in the analysis.

3.3.6.3 Why Difficult

System complexity can make charting interrelations daunting, automation can alleviate much of the task; unexpectedly high levels of causality can lead to a re-definition of system boundaries

3.3.6.4 Positive example

Correctly modeling the integration and correlation of energy and agricultural markets resulting from US corn-based ethanol policy [58]

3.3.6.5 Negative example

Failure to correlate prior to the decision to invade Iraq what the consequences in term of global terrorism might be [59]

3.3.7 Iterate analysis

3.3.7.1 Definition

Repetition of part or all of the systems approach in order to consider modifications to the scenario such as alternatives [38].

3.3.7.2 Why Important

Systems analysis tools allow the consideration and evaluation of many options as the analyst modifies the scenario(s) to accommodate new ideas including changes derived from the original analysis such as changes to leverage points identified in the sensitivity analysis of a simulation.

3.3.7.3 Why Difficult

Frequently the scope of the analysis will limit the number of options and iterations

3.3.7.4 Positive example

Total-system performance assessment for Yucca Mountain - second iteration considers effects of climate change and other new factors [60]

3.3.7.5 Negative example

Poor business decisions that can result when management fails to iterate through all the possibilities - Bob Rice **THREE MOVES AHEAD: WHAT CHESS CAN TEACH YOU ABOUT BUSINESS [61]**

3.3.8 Leverage Points

3.3.8.1 Definition

Focus points in the system where a small change to the system could lead to a large reaction [20], [21], [25], [26].

3.3.8.2 Why Important

Identifying leverage points allows the systems analyst to study optimal mechanisms for systems change as well as potential systems vulnerabilities.

3.3.8.3 Why Difficult

Leverage points, particularly in complex systems, tend to be counterintuitive. Engaging the leverage point incorrectly will degrade the state of the system quickly so careful analyses must be brought to bear.

3.3.8.4 Positive example

Royal Dutch Shell analysts identifying in the early 1970s the risk and potential effect of an Arab oil embargo and planning accordingly. **THE ART OF THE LONG VIEW** - Peter Schwartz [62].

3.3.8.5 Negative example

Forrester's study of urban dynamics (1969) showing that subsidized urban housing is a leverage point - the less of it there is, the better off a city is, including low-income residents [as cited in **THINKING IN SYSTEMS: A PRIMER**, D. Meadows, 2008] [25].

3.3.9 Life cycle of system

3.3.9.1 Definition

Temporal description of the life of a system (may include temporal system boundaries); the lifecycle considers what comes before the system and what comes after in a cyclical concept to retirement (aka: cradle to grave or cradle to cradle) context [36], [38].

3.3.9.2 Why Important

Considering the cyclical nature of a system vs. the linear approach is a hallmark of systems thinking. All systems can trace a beginning and no system will continue forever.

3.3.9.3 Why Difficult

Developers of simulation models like to focus on linear segments of the life cycle - because it's easier and sometimes that's enough, but doing the extra work to outscope and consider the entire system life cycle can reveal important aspects of the system and lead to better solutions.

3.3.9.4 Positive example

Life cycle comparison of paper vs. plastic disposable grocery bags that shows plastic has less environmental impact [63].

3.3.9.5 Negative example

Modern industrialized agriculture that took the traditionally cyclical system of agrarian society and replaced it with a linear industrial system without consideration of the system lifecycle [64].

3.3.10 Metrics

3.3.10.1 Definition

The data used to determine system performance; must be: measurable, objective, nonrelativistic; may be from existing data, survey data, data collected from a correctly designed experiment or similar sources.

3.3.10.2 Why Important

Metrics form the core of any systems analysis. If they are incorrect, the analysis is invalid.

3.3.10.3 Why Difficult

Fitting the analysis to the data instead of obtaining correct data must be avoided; the data delivered by the key decision makers may not be useful, but omitting them may cause offense; the existing data may not be valid or missing critical variables thus overlooking key information. Metrics may be confused with indices of performance.

3.3.10.4 Positive example

Consistently reliable and transparent OECD metrics for main economic indicators [65].

3.3.10.5 Negative example

The use of data from extreme weather events such as high snowfall or increased tornados to negate or support climate change analysis [66].

3.3.11 Normative Scenario

3.3.11.1 Definition

The description of the system in the optimal, desired state as agreed upon by the key decision makers and as the ultimate outcome of specific proposed alternatives. Should be a clear, measurably quantitative change from the descriptive scenario [28], [38].

3.3.11.2 Why Important

The normative scenario must thoughtfully consider the needs of and impacts to all stakeholders and their respective mental models. Outscoping plays a key role in understanding the real normative scenario - the problem the client may not see.

3.3.11.3 Why Difficult

The key decision makers may not understand what the actual goals of their system may be and therefore may be focused on a solution that may not be optimal.

3.3.11.4 Positive example

Defining a comprehensive energy system scenario in Copenhagen, Denmark that reduces consumption, produces minimal pollution and waste while approaching sustainability [67].

3.3.11.5 Negative example

U.S. Army effort (2003-2009) to develop an integrated Future Combat System based on a flawed perception of future threats and future technologies [68].

3.3.12 Objectives

3.3.12.1 Definition

Clarification of the normative system scenario in a hierarchical manner that sets the stage for the rest of the systems thinking process; the objectives include the sub-goals required to solve the problem, i.e.: to get from the descriptive to the normative scenario; the objectives tree starts with the principal objectives and branches out to the sub-objectives required to progress toward the superior objectives. Terms used to describe objectives include: goals, ideals, requirements and key performance parameters [28], [38].

3.3.12.2 Why Important

A well-described, hierarchical objectives tree becomes a clear definition of the problem and a framework for a systems solution to the problem. Practical aspects of working toward the solution such as indices of performance, metrics and requirements definitions are derived from the objectives tree..

3.3.12.3 Why Difficult

The objectives tree requires the input of subject matter experts who may not fully understand the problem but are capable of in-scoping the problem analytically to make the sub-objectives practical; the level of granularity of the sub-objectives can omit key characteristics if too broad or bog-down the analysis if too fine (see Scope).

3.3.12.4 Positive example

Fitch's 8 goals for an urbanizing America [69].

3.3.12.5 Negative example

Failure to develop a clear objectives tree for the Future Combat System - the objectives were vague and centered around technology risk reduction [70], [71].

3.3.13 Observer Effects

3.3.13.1 Definition

Observation affects the system so the observation and the observer must be considered as parts of the system being observed. The systems thinker must correctly position him/her self within the system as an observer and source of recommendations, not a decision maker.

3.3.13.2 Why Important

Unless a system is 100% automated, the act of systems analysis will have some impact on the system. A correct systems thinking process must take this effect into consideration and account for it in areas including the sensitivity analysis and the recommendations. A systems approach that introduces bias from the analyst will not reflect the correct system objectives and requirements.

3.3.13.3 Why Difficult

The primary decision makers are immersed in the system and frequently do not understand the systems aspect of the problem. The analyst must always be cognizant of the primary decision makers and not confuse roles. Recommendations must suit the normative system – the system that does not contain the analyst.

3.3.13.4 Positive example

A retail firm engaged a systems analysis firm to provide a staffing simulation model. The analyst correctly brought to bear an outside-the-system perspective and determined that the problem was not staffing but store layout – resulting in a valid systems analysis. [38].

3.3.13.5 Negative example

An analyst at an FFRDC working on a simulation project said, “I don’t have a client, only a sponsor.” He had confused roles making himself the primary decision maker and without input from the actual primary decision maker. The project failed. [38].

3.3.14 Outscope

3.3.14.1 Definition

An expanded generalization of the problem and the system in which it exists beyond the original problem description to add insight (limited by practical concerns, see *scope of the analysis*) [38].

3.3.14.2 Why Important

Outscoping is a key factor of systems thinking - the ability to step back from the system and see it with systems eyes allows better problem definition and leads to better solutions; outscoping can produce both blue-sky alternatives as well as revised value for the option to do nothing.

3.3.14.3 Why Difficult

Outscoping can be one of the hardest things for experienced engineers and professionals to consider; they know their subject matter much better than the analyst, but this focus prevents them from viewing the problem through systems eyes. To outscope all judgment and criticism must be suspended.

3.3.14.4 Positive example

The Department of Defense directing that managers must open teleworking to as many employees as possible (30 percent by 2020) to improve quality of life, reduce traffic congestion & pollution [72]

iPod ecosystem & a thermostat "Steve had a way of scoping the problem bigger. He could just look at a problem and find the solution by thinking larger." [73].

3.3.14.5 Negative example

Citizens (Atlanta, Ga) voting against a one-cent sales tax hike to improve transit when they spend, on average, 127 minutes of every day stuck in traffic [74].

3.3.15 Recommendations

3.3.15.1 Definition

Provide results in a language that the key decision makers can understand. May also include system requirements and/or a system design; recommendations are clear, concise, brief and support all statements with results from the system analysis in an executive summary. Follow-up with more depth in a conclusions section at the end of the analysis.

3.3.15.2 Why Important

The best systems approach ever done will be of little worth if the analyst cannot properly communicate the results; Brevity and clarity are critical; high level decision makers presented with a myriad of complex recommendations have precious little time to probe them deeper.

3.3.15.3 Why Difficult

Engineers tend to be proud of their hard work and eager to show it off - but executives want clear, concise answers not volumes of results; great care should be taken in presenting outside-the-box recommendations that they not be dismissed for their seemingly extreme perspective.

3.3.15.4 Positive example

Present recommendations in the form of a clear, easy to understand list as in "Why Invest with Children's Paradise" slide 11 [75].

3.3.15.5 Negative example

Pentagon PowerPoint slide of the integrated defense acquisition life cycle [76].

3.3.16 Scope of the analysis

3.3.16.1 Definition

Limits to a systems approach driven by data availability, cost, available time, politics and other limitations imposed upon the analysis; after outscoping, the scope imposes practical limits that rein-in the effort; [boundaries define system, scope defines analysis].

3.3.16.2 Why Important

Just like system boundaries, limitations to the scope can result in the omission of important system impacts. Assumptions that are made in modeling alternatives are included in defining the scope of the analysis and need to be verified as part of the evaluation.

3.3.16.3 Why Difficult

All systems approaches are limited by their scope but the systems analyst must also use systems thinking to maximize the impact of the analysis given the limitations to the scope.

3.3.16.4 Positive example

A Limited-Scope Reliability-Centered Maintenance Analysis of Wind Turbines that focuses on the most critical subsystems with respect to failure frequency and consequences. [77].

3.3.16.5 Negative example

The model of everything will take forever to build and be of very little practical use [78].

3.3.17 State of system

3.3.17.1 Definition

A categorization of the system in terms of its life cycle and environment, the state can include the technology readiness (TRL), stage of development, position of the system within its life-cycle and the cost to date of the system [36].

3.3.17.2 Why Important

Understanding the state of the system can help determine if the system is ahead of its time, obsolete, an over-extension of current technical capability, overly ambitious, or a breakthrough whose time has come.

3.3.17.3 Why Difficult

The technical assessment of the state of the system may initially come from key decision makers/subject matter experts whose perception may be incorrect; the state of the system may include factors not considered before the systems analysis.

3.3.17.4 Positive example

Introduction of the iPod system at the point where the technology and the customer base were ready for a new medium to store music that interfaced easily with a personal computer [79].

3.3.17.5 Negative example

Thirty years of development and expenditure toward missile defense including high-speed missiles, airborne lasers and space-based interceptors [80].

3.3.18 System boundaries

3.3.18.1 Definition

The definition of the system in terms of what it encompasses: the temporal, spatial, and physical limitations of the system; the system displacement [33].

3.3.18.2 Why Important

A description of the boundaries of a system considers what will be improved, affected or replaced by the system and, conversely, what affects the system under study, as the system changes and is changed by its environment - observing what constitutes that environment helps the systems thinker to define the system boundaries. Incorrect system boundaries can result in the omission of important system impacts.

3.3.18.3 Why Difficult

System boundaries may seem well defined at the initial stage of the analysis but become subject to change as the analysis progresses. Analysts may focus on limited dimensions of the system boundaries, omitting other dimensions and thus omitting important aspects of the system.

3.3.18.4 Positive example

Defining the boundaries of the nitrogen ecology to include the impact of automobile emissions on watersheds [81].

3.3.18.5 Negative example

An auto company that develops an SUV while ignoring the temporal system boundaries of the life cycle in which the cost of fuel may climb to a point where the vehicle becomes unaffordable to the target market [82].

3.3.19 System stakeholders

3.3.19.1 Definition

The human elements and organizations that have an effect on the system and/or are affected by it [38].

3.3.19.2 Why Important

Virtually all systems are evaluated at some level by their impact on the stakeholders; for example, this could be the return on investment for some stakeholders, the political benefit for some stakeholders or the health impact on some stakeholders.

3.3.19.3 Why Difficult

When outscoping the system, stakeholders on the margin may be inordinately affected by the system or have an inordinate impact on the system; analysts tend to focus on the key decision makers and neglect other stakeholders; the term "stakeholder" is undergoing a period as an overused buzzword in some analyses.

3.3.19.4 Positive example

Including considerations of tribal stakeholders regarding a burial ground in a systems analysis of a new building construction [83].

3.3.19.5 Negative example

Corn-ethanol biofuel systems analysis that erroneously omits the millions of stakeholders worldwide who depend on inexpensive American corn for sustenance [84].

3.3.20 Type of System

3.3.20.1 Definition

The type of system will have several descriptors and may include: natural or man-made; closed or open; static or dynamic, simple or complex, reactive or non-reactive [36], [47].

3.3.20.2 Why Important

Categorizing the type of system under consideration is a prerequisite to properly establishing the system boundaries; deciding how to represent or model the system; and considering what nature the solution to the problem will likely take.

3.3.20.3 Why Difficult

It can be more convenient to model one type of system versus another and this can influence an analyst to incorrectly use the tools they have instead of the correct approach.

3.3.20.4 Positive example

Categorizing energy systems as dynamic systems, not the static, closed-cycle systems described in a life-cycle assessment [85], [86].

3.3.20.5 Negative example

In a pollution analysis, incorrectly classifying a production system as a steady-state system instead of a dynamic one [87].

3.4 The dimensions of system thinking as a process

Fig. 3 on page 56 shows how the twenty dimensions may be represented in a process diagram showing some of their interrelationship in practice. In this example, the process begins with the descriptive scenario and the concept of the normative scenario. The descriptive scenario is broken down into the ten dimensions that lead to the development of the alternatives. Simultaneously, the specific system objectives are derived from the normative scenario, which leads to the indices of performance being derived from the metrics. The indices of performance become the lynch pin between the normative scenario and the descriptive scenario through the alternatives. That is to say, the alternatives should be quantifiable with regard to their ability to transform the system from the descriptive to the normative scenario.

This coordination among the dimensions is why a strict, systematic linear progression of process-flow steps is incorrect. The systems thinking approach includes all the steps as it flows from descriptive scenario to recommendations, but is considering many of them simultaneously as it progresses through the evaluation of the alternatives. The entire systems thinking process is error embracing and iterative. Mistakes are made and welcomed as learning more about the system. New information from within or outside the thought process may lead to changes in the process or repetition of the process to include the new information. The complex, adaptive nature of systems thinking targets the complete and systemic conclusions that will be presented in the recommendations.

This complex adaptive thought process makes analytics of DST difficult, but we will consider an approach to measuring DST in Chapter 7.

Now that the foundation of the thesis is established, we consider some case studies of the Dimensions of Systems Thinking.

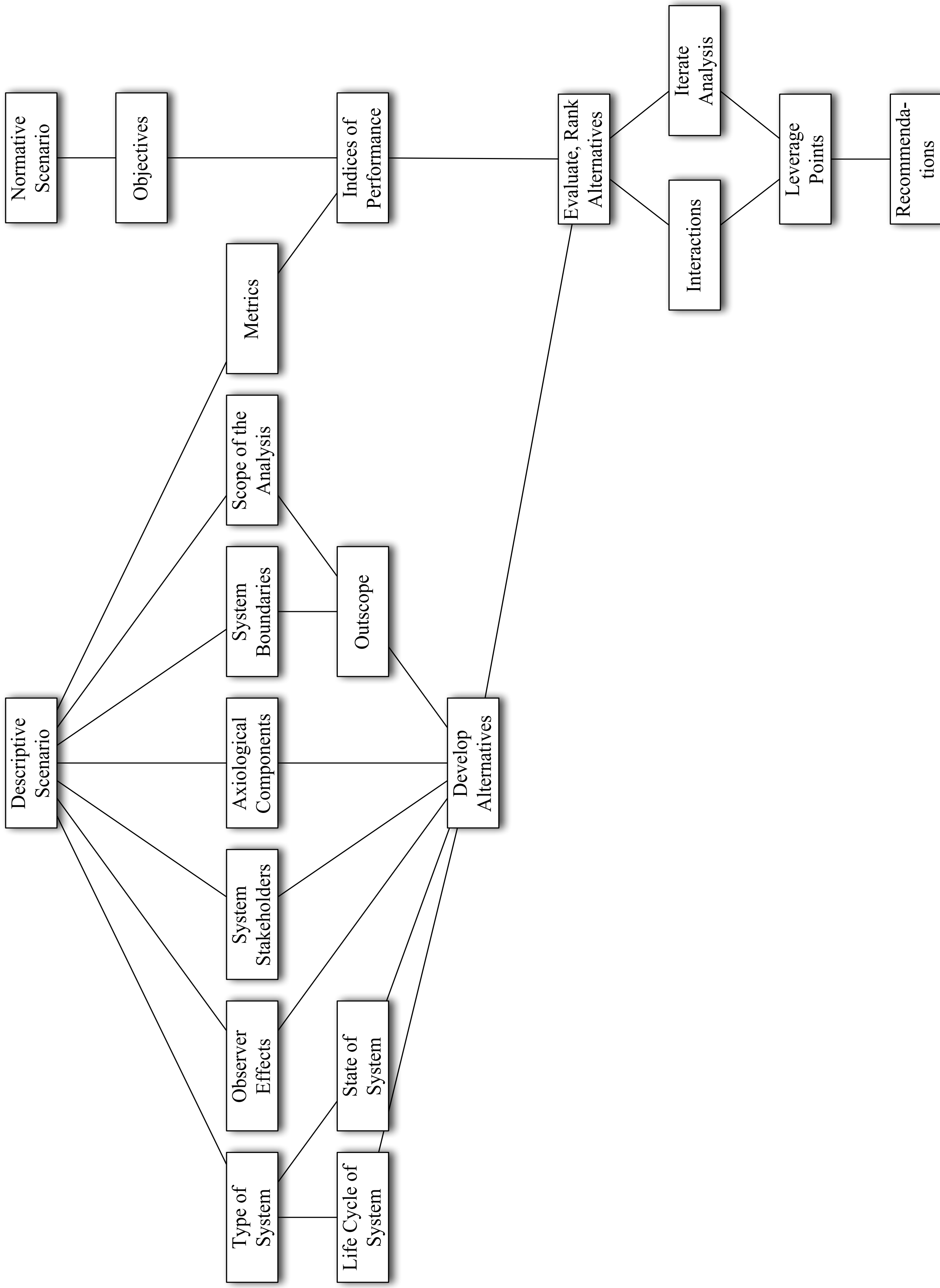


Fig. 3 . A process diagram showing a typical systems approach using the Dimensions of Systems Thinking

Chapter 4: Case Study: Green Energy and the Dimensions of Systems Thinking

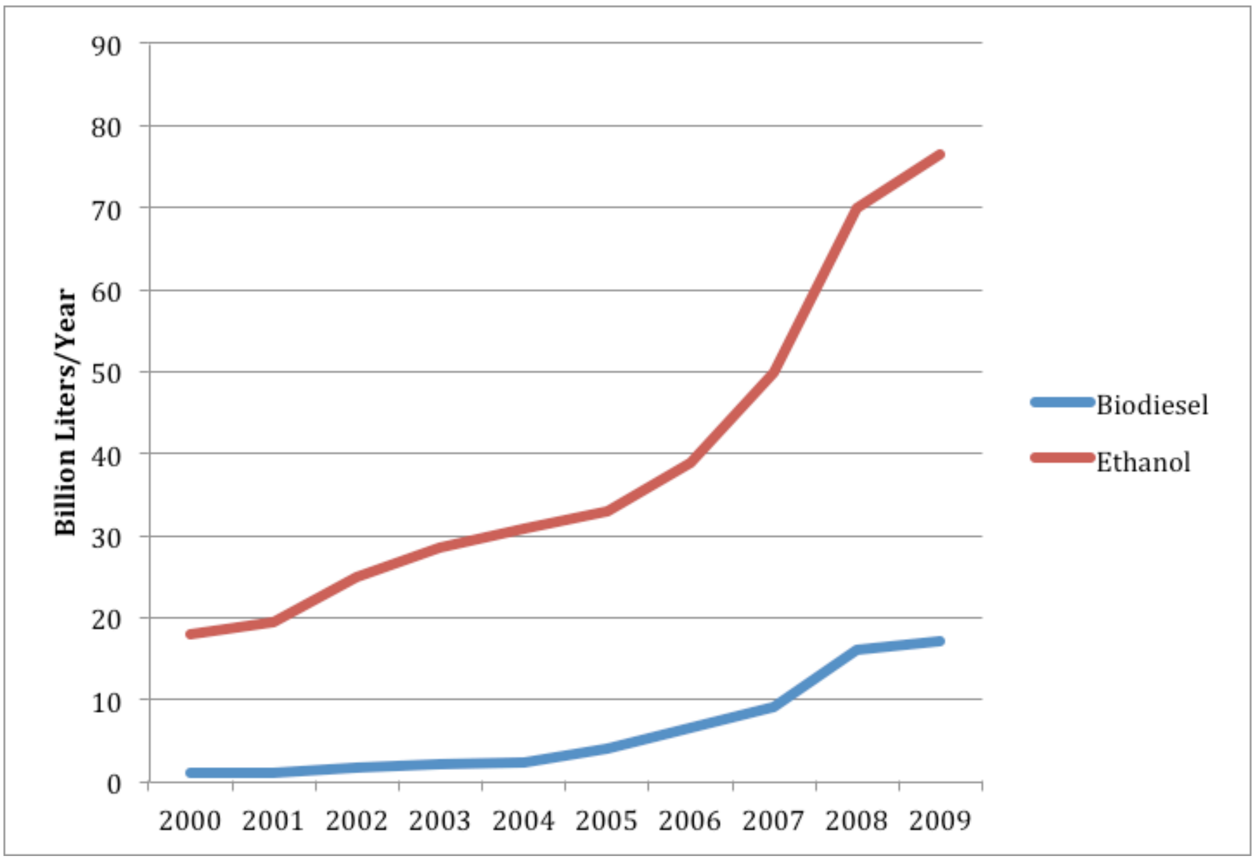


Fig. 4. World production of ethanol and biodiesel 2000 to 2009 (Data: REN 21 Report)

4.1 Introduction and Summary

This case study was presented at the IEEE Green Technologies Conference in 2010 – near the peak of ethanol production in the U.S. At the time, ethanol production was seen by many policy makers as a pathway to energy independence and reduced carbon emissions at the same time.

This case study was authored in late 2009 at the very early stages of the development of the Dimensions of Systems Thinking. It led to the concept of carefully distinguishing between metrics as data about a system and indices of performance as data and calculations relevant to systems thinking. In general, this study considers the foundations of the Dimensions of Systems Thinking as applied to the system of liquid biofuel lifecycle assessments and prompts the development of a new way of approaching the problem.

The history of corn-based ethanol in North America is illustrative of the problematic interdependencies that can arise when decisions about policy are made without sound systems thinking At the direction of Congress the EPA has proposed new standards for renewable fuels to be based on lifecycle assessment (LCA) methodology. At the same time, the European Commission explicitly dictates the use of LCA for biofuel in their Renewable Energy Sources Directive. Likewise, the United Nations Environment Program (UNEP) has directed that biofuel assessment be made based on LCA standards [88]–[94].

Recent lifecycle assessments of complex biofuel systems follow standard methodology such as EPA guidelines and ISO14040 standards, yet there are wide variations in the results. Studies conducted on the same liquid biofuel system reveal diverse and even conflicting results, some showing a net greenhouse gas (GHG) reduction, while others show a net increase for the same biofuel system. The results from these studies, therefore, cannot be considered viable for quantitative system impact comparisons [95], [96].

[While there are solid and gaseous biofuels, this case study focuses on liquid biofuel for simplicity and because of a strong economic need for liquid transportation fuels. The conclusions would apply to all three modes of biofuel.]

Through the Dimensions of Systems Thinking, this study discloses deficiencies in the current approach to biofuel LCA as an index of performance. It approaches the existing methodology with respect to the Dimensions of Systems Thinking and finds inconsistencies in descriptive scenarios, inconsistencies in system boundaries, system boundaries that exclude relevant sub-processes, elements and environmental factors, a lack of standardized units and the reliance of commonly used LCA tools on industry-wide averaged data without regard for relevant impact.

This study concludes based on the DST that improved methodologies of determining system boundaries based on impact are necessary to adequately assess biofuels and their environmental effect. The study proposes a new approach based on an integrated hybrid assessment with unitized impact metrics (Renewable System Impact Rating – RSIR). Correct application of the DST will lead to viable system impact optimization, permitting engineers and farmers to maximize the net energy balance of a biofuel system, while minimizing negative impacts on the environment and on world food supplies.

4.2 Liquid Biofuel for Transportation

Thanks in large part to government promotion; liquid biofuel has been shown to be a viable economic enterprise. Fig. 4 on page **Error! Bookmark not defined.** shows the recent growth in ethanol and biodiesel production. Naturally, an industry that showed this level of growth during the period of a severe economic downturn received significant influx of capital. Unfortunately, policy was not based on sound systems thinking such as the Dimensions of Systems Thinking and, as a result, the future does not look bright for liquid biofuel.

As corn-based ethanol policy was implemented, it was discovered that ethanol has compatibility problems with the existing U.S. fuel infrastructure. It was shown to corrode the existing petroleum infrastructure and strain liquid fuel transportation capacity with small batches of incompatible products. Production of blendstocks containing ethanol has required modification to refining structures and greatly reduced the fungibility of the resulting products [88], [97].

Emissions of GHG including nitrogen, ammonia and sulfur increased with fertilizer use, as did eutrophication and acidification while use of petroleum based pesticides and herbicides increased in proportion to crop acreage for both soy and corn. Finally, the net energy balances of the respective corn-based ethanol and soy-based biodiesel systems weren't adequately modeled and quantified before investment Worldwide, the promotion of corn-based ethanol created an adverse affect on food supplies. In 2007 transportation ethanol consumed 24% of the corn produced in the U.S. and ethanol made up 1.3% of the domestic transportation fuel. Countries of the E.U. produced 80% of the world's biodiesel in 2007 - around 9.6 billion liters, diverting fields from food production to soybeans for fuel[96], [98]–[101].

In 2007, the U.S. President set a goal of reducing gasoline use 20% by 2017. To do this, 15% of the reduction would come from the introduction of alternative liquid fuels - approximately 133 billion liters - and 5% from improving vehicle efficiency. The current administration has taken a more systemic approach to energy that includes alternative energy for transportation and tougher CAFÉ standards. The European Union has also taken a generalized approach to the problem by directing “20 by ‘20” - 20% of the total energy used in Europe must derive from renewable resources by 2020 with targets for individual member nations ranging from 14% to 40% .

Still, liquid biofuels for use as transportation fuels have advantages. These include: a perceived effect on energy security through reduced reliance on petroleum – specifically imported petroleum, general compatibility with the existing liquid fuel infrastructure, the renewability of a fuel product derived from biomass and reduced lifecycle greenhouse gas emissions during the combustion segment of the life cycle. This later property has sparked interest in aviation biofuels on the part of the U.S. Air Force, the U.S. Navy, Virgin Atlantic Airlines, Japan Airlines, KLM and others [102].

The technological advances in biofuel necessitate a categorization of the different products. The generally accepted naming standard is to describe the solid, wood-based biomass as used by humans for heating and cooking fuel as *basic biofuel* and describe the distillation of ethanol, refinement of seed oils for liquid fuel, as *first generation liquid biofuel*. *Second generation liquid biofuels* include bioethanol derived from lignocellulosic biomass and fuels from Fischer-Tropsch type synthesis. *Third generation liquid biofuels* include those from bioreactors such as macro-algae, and fuels derived via pyrolysis,. Research in third generation biomass pyrolysis has demonstrated the commercial scale conversion of cellulosic biomass to liquid fuel at rates as high as 75% by mass. Included in the third generation are algae technologies with the goal of developing strains to serve as bio-reactors for ethanol and green gasoline, also considered to be third generation biofuels [101], [103].

Liquid biofuel offers political benefits since it can be promoted as leading to energy security by reducing the importance of imported petroleum to the domestic economy. Still, the international geopolitical perspective of biofuel reveals drawbacks. Brazil leads the world as an exporter of ethanol[2], and the U.S., despite high import tariffs, is the world's leading ethanol importer. If Brazil were to raise its ethanol price, the cost of gas blends at the pump in the U.S. would go up.

With the significant exception of ethanol, liquid biofuels are largely compatible with the existing technology for transportation and dispensing of fuel. This makes them preferable to hydrogen, LPG, or even electric vehicles. If one percent of the 300 million personal vehicles in the United States were replaced by plug-in electrics overnight, the power grid in its current state could not support them. Replacing one percent of the fuel used in transportation with biofuel has already been accomplished and the current target is several times that in most developed nations [104].

Other perceived advantages of biofuel include reduced emissions. However, complications arise when determining emissions from the entire biofuel lifecycle.

Most biofuels contain more oxygen than the petroleum products they replace. This causes higher combustion temperatures, increased wear on engines and may lead to increased levels of pollutants in vehicle exhausts. The combustion of ethanol (E85) may also lead to increases in certain carcinogens [105].

---

[2] Brazil has also created an extensive infrastructure to support pure ethanol as a transportation fuel.

The processes of land clearing, growth and cultivation, while not factors in the well to wheel analysis of petroleum, must be considered with biofuel due to its significant spatial dependence. Increased levels of NO_X, N_2O and ammonia [NH_3], as well as sulfur in the form of SO_X enter the atmosphere during the growth and cultivation cycles of biomass – also not a consideration with petroleum. N_2O, for example, has the same greenhouse effect as 298 times as much CO_2 by mass. Ancillary environmental effects such as soil depletion, eutrophication and acidification also result from the biomass growing process [96].

Many studies of the conversion of biomass from forestry and organic industrial waste to biofuel negate these factors. In those studies, the environmental/GHG effects of biomass cultivation are part of an already existing system, not the biofuel system, and therefore would already have occurred, regardless of the biofuel system.

Land history is also often overlooked. The land in Brazil where cane is grown as biomass consists largely of former rain forest and peat bog that once absorbed large quantities of carbon from the atmosphere and injected it naturally into the soil. In Southeast Asia, palm oil expansion for food and fuel is the largest cause of rainforest destruction. In Indonesia, two-thirds of the on-going palm-oil expansion will be in converted rain forest, 25% in peat soil. All soils release some GHGs when tilled, but peat soils release very high amounts of damaging GHGs including methane [94].

Finally, biofuel generally lacks the energy potential of petroleum-based fuel. An automobile running on a 10% ethanol, 90% gasoline blend [E10] can count on about a 3% drop in gas mileage. E85 mileage is about 27% less efficient than pure gasoline.

4.3 Lifecycle Analysis

Biofuel LCA studies are intended to generate such metrics as the greenhouse gas balance – generally represented as a change or difference from gasoline or diesel combustion, the net energy balance, and the economics of a biofuel system over its entire lifecycle. Governments have seen the logic in this approach and have mandated the LCA as the foundation of new standards for biofuel. In this light, the U.S. Environmental Protection Agency proposed new renewable fuel standards (RFS2) based on LCA. A key change from the previous standard (RFS1) is the focus on the greenhouse gas impact of renewable fuels from a lifecycle perspective. According to the published RFS2 proposal: "The lifecycle GHG emissions means the aggregate quantity of GHGs related to the full fuel cycle, including all stages of fuel and feedstock production and distribution, from feedstock generation and extraction through distribution and delivery and use of the finished fuel. […] EPA must conduct a lifecycle analysis to determine whether or not renewable fuels produced under varying conditions will meet the greenhouse gas (GHG) thresholds for the different fuel types for which EISA [Energy Independence and Security Act] establishes mandates. […] As mandated by EISA, the greenhouse gas emission assessments must evaluate the full lifecycle emission impacts of fuel production including both direct and indirect emissions, including significant emissions from land use changes."[106]

For simplicity, the EPA proposes assigning fixed GHG and energy values to specific biofuel products such as ethanol from corn. This would ignore the advantages gained by local efficiencies and may reduce the incentives that drive those efficiencies. A tanker full of oil seed-derived biodiesel arriving at Long Beach from Indonesia would be considered to have the same impact and as domestic or European produced biodiesel. – in spite of significant differences in the respective production systems and ignoring changes to metrics from transportation.

The European Commission dictates the use of LCA for biofuel in their Renewable Energy Sources Directive. Likewise, the United Nations Environment Program (UNEP) has directed that biofuel assessment be made based on LCA. The German, Swiss and UK governments have all established the LCA as the standard for assessing biofuel systems As a result, researchers have, over the past few years, produced scores of life cycle studies of biofuel systems [93]–[96].

EPA directs in RFS2 that the standard LCA methodology be: *Life Cycle Assessment: Principles and Practice [LCAP&P*]. This document guides the development of lifecycle assessments (LCAs) in any environmental impact context in order to quantify the environmental aspects and potential impacts associated with a process, product or service [92].

LCAP&P breaks the LCA process down into three stages: goal definition & scope, lifecycle inventory analysis [LCI] and lifecycle impact assessment [LCIA.] The prescribed process is a cyclical one, with the results of each stage intended to be used for the refinement of the overall system through interpretation and iteration. The LCAP&P emphasizes a comprehensive view of the environmental impacts and the environmental trade-offs in product

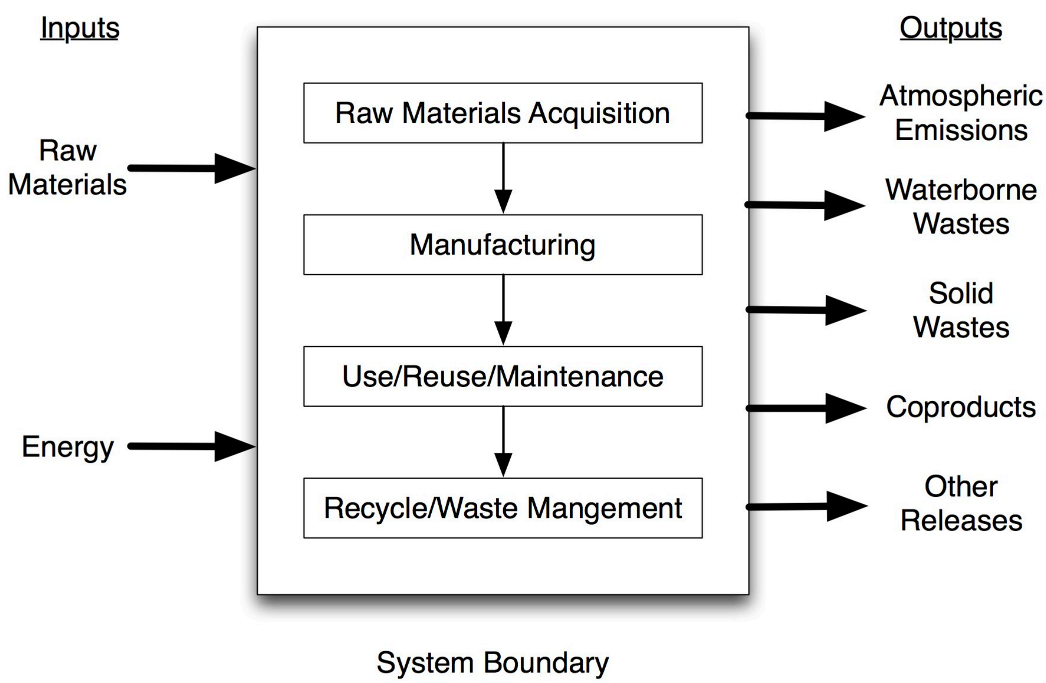


Fig. 5. Life cycle stages (EPA LCAP&P 2006)

and process selection.

LCAP&P defines lifecycle as: "The major activities in the course of the product's life-span from its manufacture, use, and maintenance, to its final disposal, including the raw material acquisition required to manufacture the product." Graphically, it portrays the LCA process as in Fig. 5. This type of approach is known as a process analysis. Worthy of note is the listing of coproducts as an output. In anything but a very simple system, the coproducts and wastes will have their own system lifecycle.

If we consider that the inputs to a biofuel system may be outputs of another system, it would be logical to consider (allocate) none, some or all of the data from the source system in the LCI of the biofuel system and vice versa. Using residual co-products from a lumber system as biomass would be such an example. Those co-products are the result of a process that consumed energy. They might have been disposed of in such a way as to produce more, less or different GHG than its conversion/combustion as biofuel. If the conversion of the lumber process residue to biofuel results in a favorable delta GHG and delta energy balance, it becomes advantageous to the lumber process LCA author to incorporate these data as part of the lifecycle of the lumber. If the ash or residue from a lumber residue combustion system is then used as a coproduct, such as fertilizer, the data from the fertilizer system may also be of interest.

Accounting for the system data may be simplified in the LCI by attributing them or allocating them to a specific input or output product, material or activity. This is known as an I/O based inventory. However, ISO 14041 [quoted below] dictates the avoidance of I/O allocation if at all possible, and the adherence to a model that accurately reflects the physical relationships between inputs and outputs [92].

1. *Step 1: Wherever possible, allocation should be avoided by:*
    a. *Dividing the unit process to be allocated into two or more subprocesses and collecting the input and output data related to these subprocesses.*

b. Expanding the product system to include the additional functions related to the co-products, taking into account the requirements of (function, functional unit, and reference flow).

2. *Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them, i.e., they shall reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system. The resulting allocation will not necessarily be in proportion to any simple measurement such as mass or molar flows of coproducts.*
3. *Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between coproducts in proportion to the economic value of the products.3*

A key reason for avoiding the allocation approach is the difficulty in discerning exactly how much of a value should be attributed to a specific product. In the lumber example, we may need to calculate the amount of energy used in the lumber mill that should be attributed specifically to the co-products versus the primary products. As stated in the ISO, co-products and pollutants should be allocated LCI values based on their properties and inter-relationships including mass, volume, energy, economic value or some other metric and that inter-relationship

[3] ISO 14041 as quoted in the EPA LCAP&P

must remain constant across the LCA. When using historical data, the basis for the LCI allocation may not be known or correctly defined, thus becoming a source of error for many LCAs.

In practice, breaking the system process down into the clear sub-processes of a process-based analysis is not possible and some allocation generally takes place creating a type of hybrid I/O-process based analysis [92], [107].

To facilitate biofuel LCA development, several automated tools for LCA modeling have been developed. In 1996, Argonne National Laboratories first developed the Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) model, a spreadsheet based tool for use in performing lifecycle analysis of biofuels. The current revision of GREET provides simulations based on data for over 100 fuel production pathways and more than 70 vehicle/fuel systems.[4] Canadian researchers employ a similar tool, GHGenius, as a model for lifecycle assessment of transportation fuels.[5] In Europe, a list of similar tools exists including GEMIS, Umberto and GaBi 4. All of these tools depend on expertise of the user to establish the correct system boundaries for the product under evaluation. ISO 14040:2006 and ISO 14044:2006 establish international guidelines, framework and requirements for LCAs, but also leave the exact determination of the system boundaries to the discretion of the analyst.

Reviews have shown a lack of standardized units in the respective studies. Some of the units used in biofuel LCAs include: vehicle-km per hectare, v-km/ha/yr, GJ/ha/yr, GJ saved primary energy/ha x yr, tons saved CO_2 equiv/ha x yr, g saved CO_2 equiv/km, well to wheels energy in MJ/km and well to wheels GHG in g CO_2 equiv/km [95].

[4] Argonne NL Transportation Technology R&D Center, http://www.transportation.anl.gov/modeling_simulation/GREET/

[5] $(S\&T)^2$ Consultants, http://www.ghgenius.ca/

Add to the technical complexity of a biofuel system the socio-economic and geo-political considerations that tend to influence an LCA. For example, corn is well understood as a crop and politically important, but political influence and growing methods differ sharply among regions. It's easy to see the stark contrast of growing maize in sub-Saharan Africa to growing corn on an industrial scale in Illinois, but perhaps less obvious are the equally strong contrasts between mechanized corn production systems in North America and Europe. Agricultural chemical use is significantly different (more fertilizer used in the E.U., more herbicides and pesticides used in the U.S.).

Studies that have compared biofuel LCA results have shown that the results vary a great deal. These LCAs do not offer comparable, standard, quantitative metrics for net energy balance and GHG, but a wide range of values with the truth hopefully hidden somewhere within. Note, for example, the wide range of GHG emission metrics in . A system of bioethanol production and consumption may range from a 72% reduction of net GHG to a 38% increase in net GHG over comparable fossil fuel. Biodiesel from animal tallow may range from an 86% net GHG decrease to a 17% net GHG increase [95], [96], [108].

LCA studies of Soy Methyl Ester resulted in a variance of results from 75% reduction of GHG to 213% increase of GHG [95].

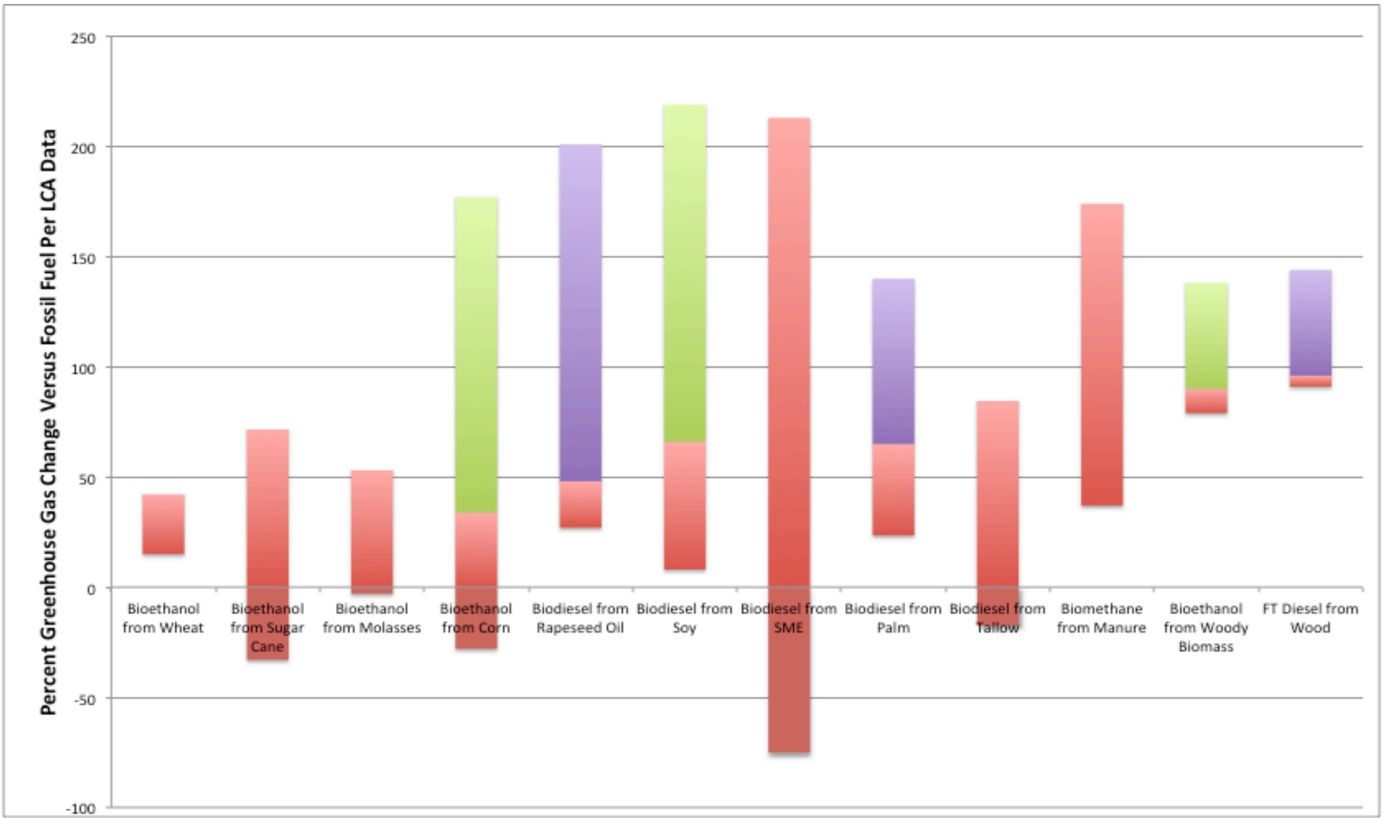


Fig. 6. Estimated percent savings of GHG emissions from biofuels (Gallager 2008, Searchinger 2009, Larson 2006)

The LCAs done on biofuel to date using such modeling tools as GREET rely on industry average data for crop yields per hectare, fertilizer & pesticide use. While using these data simplifies the LCI, it omits the sub-system impact and it may also introduce allocation inaccuracies by not accounting for the local best practices and levels of process efficiency. [For the U.S., more specific historical GIS based cultivation data may be available from sources such as the USDA NRCS and climate.com [6].]

In summary, the principal deficiencies in current biofuel LCA methodology include:

- Inconsistencies in LCA system boundaries
- System boundaries that exclude relevant sub-processes, elements, relative efficiencies and environmental factors

[6] National Resources Conservation Service, http://www.nrcs.usda.gov/TECHNICAL/maps.html

- Lack of standardized units
- Reliance on industry average data without regard for relevant impact

4.4 Looking at Biofuel System Complexity with New Eyes: A Dimensions of Systems Thinking Approach

Research into scores of published life cycle assessments reveals almost universal inconsistency and difficulties in defining the descriptive scenario of the respective systems. Without a standardized approach to defining the descriptive scenarios of the alternative systems being evaluated – such as that in the foundation of the DST - the resulting metrics will fail to be valid indices of performance. They will be invalid for comparing systems. Consider the process flows for select fuel systems – the alternatives that are to be evaluated and ranked by LCA:

As a baseline for greenhouse gas life cycle comparisons, LCAs use fossil fuel process flow cycles. Fig. 7 on page 74 shows a simplified, standard process flows for natural gas and liquid petroleum based fuels. Bear in mind that each step in the processes depicted here is itself a sub-process whose data must be allocated to the process as a whole. Steps where greenhouse gasses are likely emitted are marked with "GHG."

Compare the process flow above with the simplified process flow for corn-based ethanol in Fig. 8 on page 75. This corn conversion process flow example uses a first-generation process to distill ethanol from the corn grain as well as a second-generation process to convert the cellulosic mass of the non-grain parts of the corn plant (the stover and the cob) into ethanol. Before the process even begins, there must be extensive systems in place to provide the seed, pesticides, fertilizer fuel and water required – all of which have their own respective life cycle analyses and greenhouse gas impacts. Converting lignocellulosic mass such as stover or wood into biofuel in second-generation biofuel systems requires stages where chemical or biological enzymes break down the complex organic molecules. The development of the catalysis systems required remains at a low technology readiness level – too low for economically viable production. Many grain or seed-based liquid biofuel processes may simply burn these cellulosic products to provide heat for the process or to generate electricity. Still others may convert the cellulosic material into animal feed or leave it in the field to protect and nourish the soil. [For simplicity, the disposition of the cellulosic material is omitted from subsequent biofuel process flow diagrams for simplicity, but in all cases it should be accounted for in the LCA.] Note the complexity in Fig. 8 relative to Fig. 7 and consider the multiple process stages where liquid fuel may be required such as each transportation stage. Each of those stages represents the introduction of an allocation from another process, either from the primary process itself, resulting in a geometric progression in the assessment, or from a sub-process such as the petroleum fuel process. Note also that there is limited consideration of the land upon which the corn is grown [107], [109].

The initial tilling of untouched land and prior disposition of the terrain is rarely considered in an LCA, but it should be under RFS2. As mentioned earlier, if the land had been prairie, bog or forest before the first tilling, a transition from a GHG absorbing sub-system to a

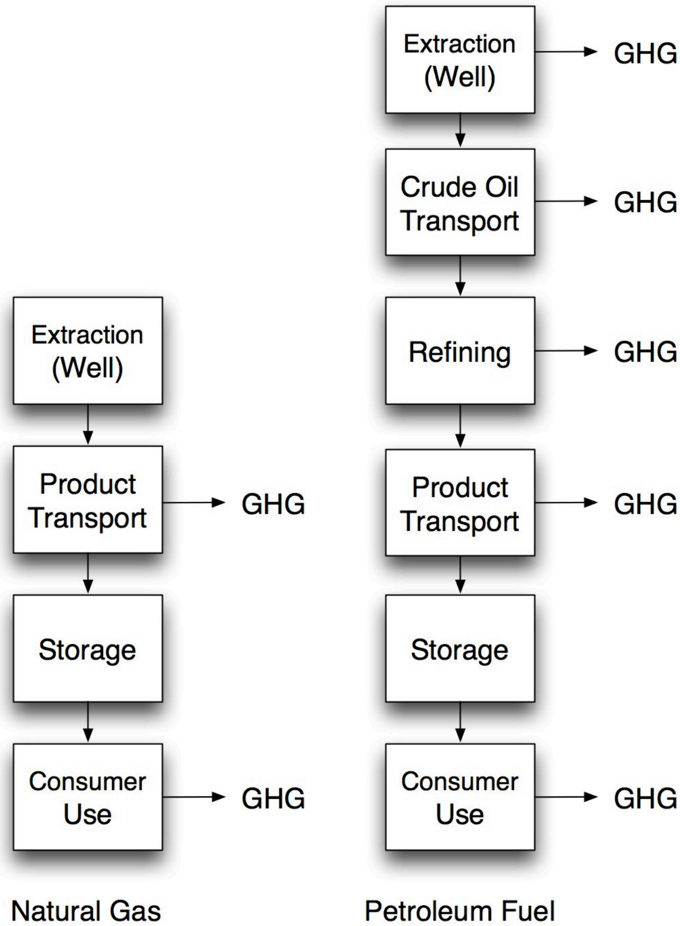


Fig. 7. Natural gas and petroleum fuel process flow diagrams

GHG emitting sub-system takes place. Later, the emitting sub-system may be replaced with another absorbing sub-system if a biomass crop is planted that does not require tilling such as palm trees or prairie grass [106].

Fig. 9 represents a sample LCA process flow diagram for a biodiesel system. Again, the GHG labels indicate sub-processes with greenhouse impact and the flow suffers from the same limited boundaries as above. Note also that the system appears somewhat simpler than the corn-based ethanol system, even when the disposition of the cellulosic material is considered.

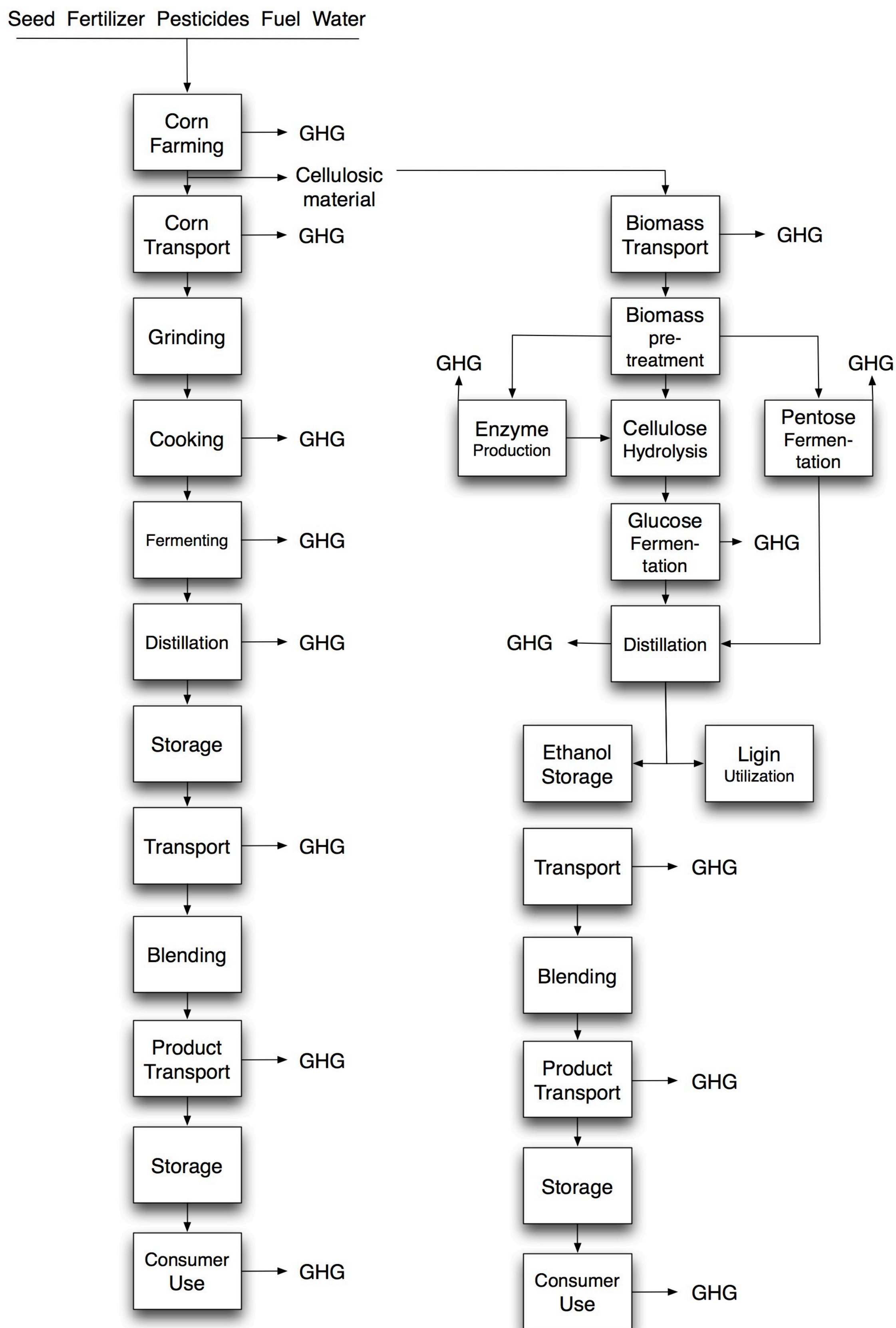


Fig. 8. Corn-based ethanol process flow diagram

Fig. 10 represents the simplified standardized process flow for sugar cane-based ethanol taken from a Brazilian LCA study. It shares much with the corn-based ethanol flow, but in Brazil the infrastructure and many vehicles have been designed or modified to support a pure-ethanol system vs. the blend of ethanol and gasoline in use in the U.S. – thus increasing the overall efficiency of that system [110].

A final example comes from an LCA conducted recently on a third generation biofuel by Michigan Technological University on behalf of Envergent Technologies [7][8]. This study of a pyrolysis oil system followed the ISO 14040 standards and employed SimaPro7.1 LCA modeling software. For impact analysis, the global warming potential (GWP) [9] was modeled by the software on the Intergovernmental Panel on Climate Change (IPCC) accepted values agreed upon in Kyoto [111].

This LCA is a hybrid I/O-process analysis that uses 1MJ of fuel energy as the basis for allocation. Fig. 11 shows the process flow basis for the two LCAs considered – one for conversion of logging residue into pyrolysis based transportation fuel, the other for a system that incorporates the growth of specific crops for conversion, in this case Willow or Poplar trees [111].

---

[7] Envergent is a Canadian/U.S. joint operation of UOP Honeywell and Ensyn, the owner of the intellectual property rights of the rapid thermal processing (RTP™) pyrolysis technology.

[8] The details of the RTP technology are proprietary and, though requested from the source, were not made available.

[9] From Wikipedia: Global Warming Potentials (GWPs) are one type of simplified index based upon radiative properties that can be used to estimate the potential future impacts of emissions of different gases upon the climate system in a relative sense. GWP is based on a number of factors, including the radiative efficiency (infrared-absorbing ability) of each gas relative to that of carbon dioxide, as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of carbon dioxide.

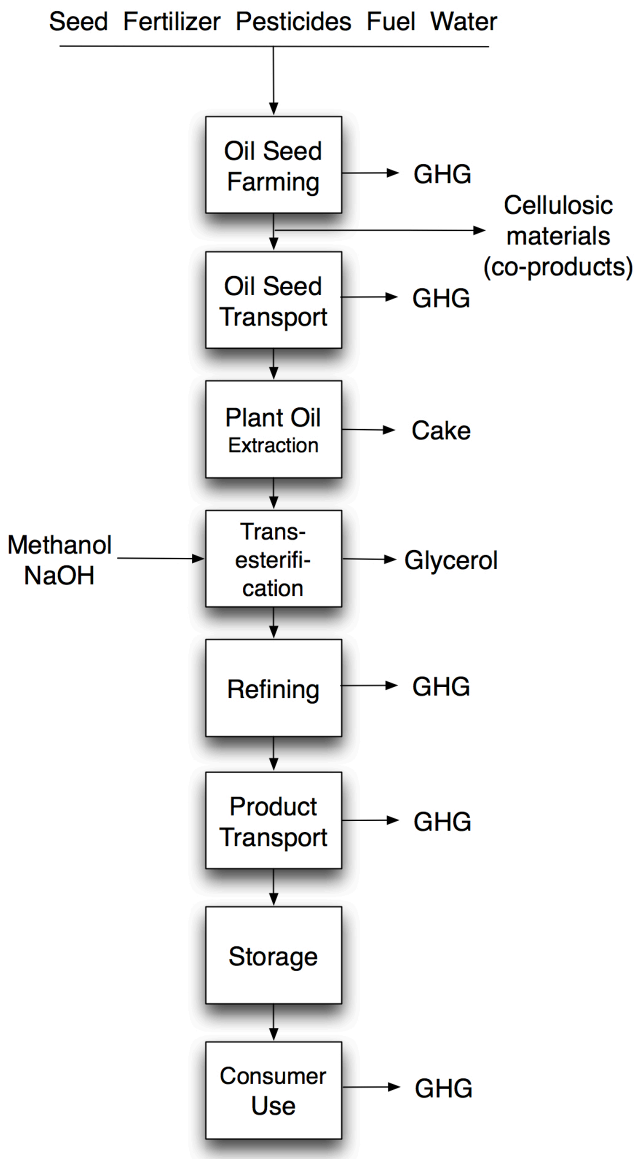


Fig. 9. Biodiesel from seed crop process flow diagram

This LCA is representative of the current state of the art. Allocation breakdowns are provided for some of the representative process flow stages including the GHG contribution by the logging residue stage as compared to the farming of poplar and willow. Note in Fig. 12 and in Fig. 13 the use of CO_2 equivalent as a normalized value for GHG impact over a variety of causes. Note also the limited number of GHGs considered and the apparent lack of any GHG

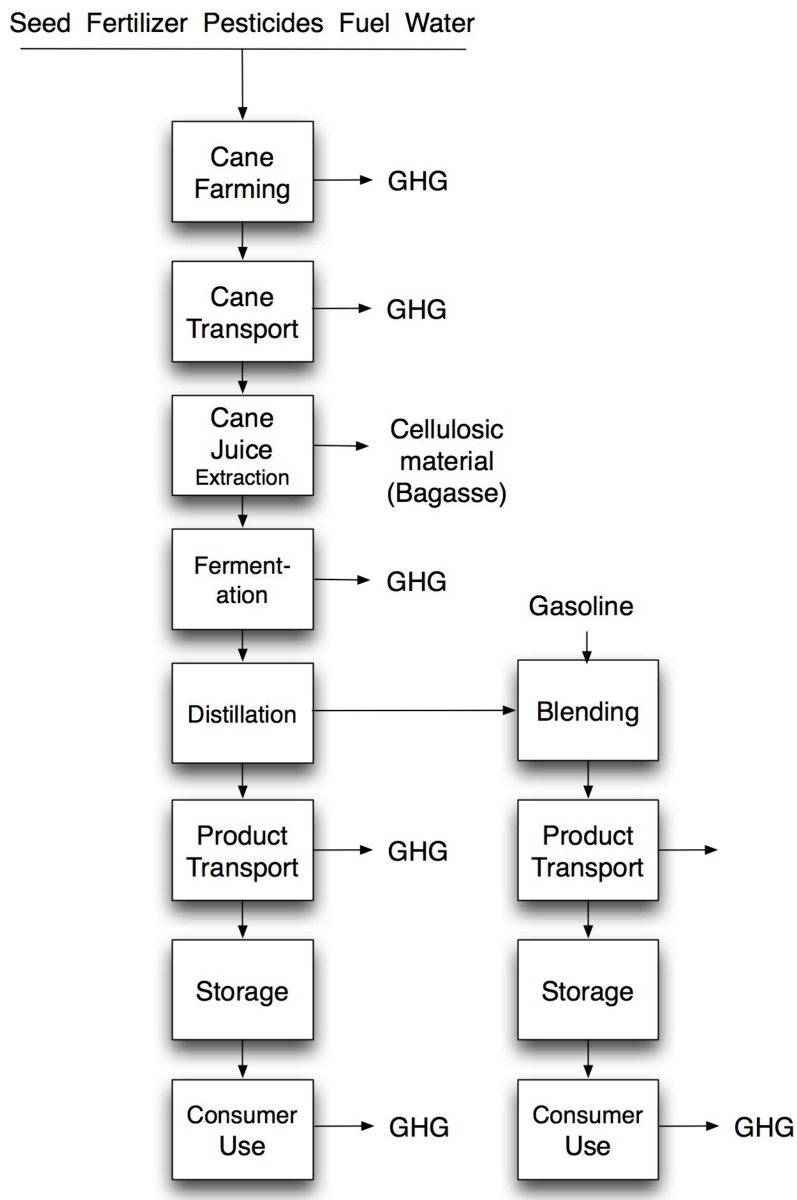


Fig. 10. Sugar cane based ethanol fuel process flow diagram

allocation from the hydrogen production process. This LCA accounts for the differences in fuel efficiency by comparing impacts by fuel energy (MJ) rather than volume or mass of fuel produced. MJ are an excellent index of performance, yet standards neglect to specify such an IP so conversion is frequently necessary. Some objectivity may be lost because the company

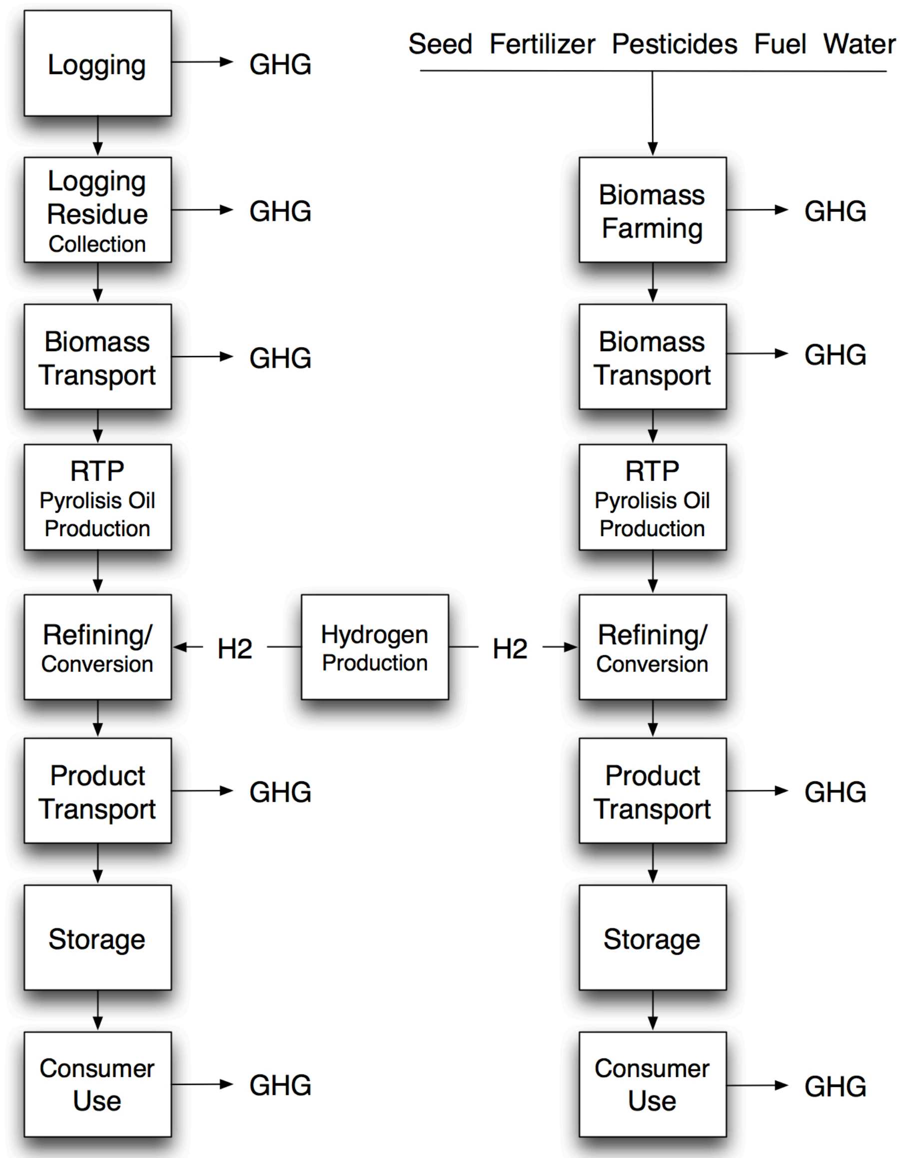


Fig. 11. RTP (pyrolysis) fuel process flow diagram

producing the fuel sponsored the study. Altering the boundaries to include other impacts would probably change the results.

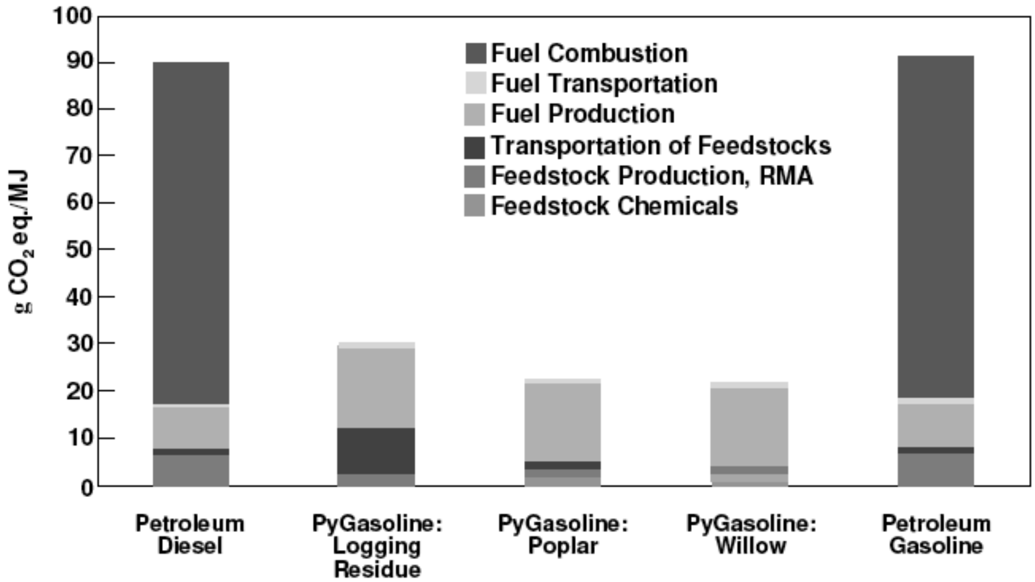


Fig. 12. RTP transportation fuel process GHG emissions by lifecycle stage (UOP Honeywell, 2009)

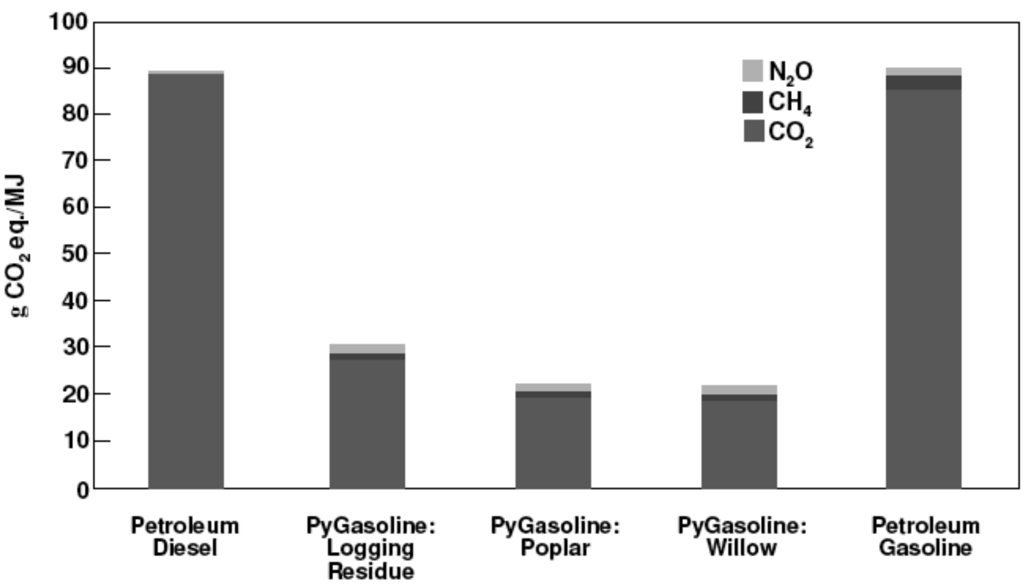


Fig. 13. RTP transportation fuel process GHG emissions by GHG type (UOP Honeywell 2009)

To summarize this section, Biofuel production processes are very complex, very different and therefore, the derivation of the descriptive scenario in a DST approach requires consistency and transparency. Within accepted criteria, the authors of LCAs have used their own knowledge, discretion and mental models to establish the system boundaries (this concept will evolve into the observer effect of the DST). They may have included the entire biomass system from field clearing & seed planting to harvest and transportation, or simply assigned an arbitrary, standardized value to the energy and GHG balance of the biomass as it enters the energy conversion stage. There is motivation to consider the GHG impact of the biomass entering the system to be zero if the opinion – correct or not -- of the analyst is that the biomass would have been produced anyway and thus does not alter the GHG balance.

In general, LCA studies completed to date have fallen short in the Dimensions of Systems Thinking dimension of defining system boundaries. They ignored such system impacts as acidification and eutrophication resulting from the biofuel system under analysis. Likewise, the effect on food cost, supplies and food crops displaced by biomass production have not factored into many biofuel LCA studies. They have also failed in the Dimensions of Systems Thinking concept of delineation between metrics and indices of performance. Index of Performance criteria for ranking alternative solutions to the problem must be: meaningful, consistent, understandable, related to individual objectives and determined from defined metrics. LCA fail in terms of meaning and consistency. In that light, we consider the development of new indices of performance [94].

4.5 Development of a New Impact Metric

Historically, LCA methodologies prescribe the incorporation of system boundaries based on physical, temporal and economic metrics – but without more specific guidelines for doing so. We propose the addition of a new standardized impact metric as an index of performance and the determination of system boundaries based on that metric.

The impact metric would be a measurement of different environmental effects in units of a standardized factor. Employing an integrated hybrid analysis, impact would be assessed and allocated between sub-systems using LCI matrix methodologies - following prior work by Leontief, Heijungs, Suh, Huppes, Moriguchi and others [107].

Since nearly all of the recent LCAs base GHG emissions on equivalent tons of CO_2 in terms of GWP, this will serve as the baseline for a standardized impact unit. This renewable system impact rating (RSIR) metric will be used to account for such impact factors as: land history, water usage, biomass point of origin, food supply displacement, cultivation, eutrophication, harvesting process, biomass transport, biomass processing, acidification, GHG, relative efficiency of the product (liquid fuel energy per land area required) and combustion emissions.

Establishment of standardized RSIR calculations and tools will be the core of the systems analysis effort going forward. This systems approach will involve the engagement of stakeholders including policy makers, subject matter experts and systems analysts. Calculations of the impact in terms of the RSIR units will be established based on temporal, geospatial, physical, chemical and other criteria.

Impacts of the sub-systems will be calculated and then allocated accordingly into the integrated hybrid analysis. System boundaries would then be confirmed based on guidelines for impact analysis. Iterations and sensitivity analyses will be performed to verify these boundaries. An impact threshold will be required, above which a sub-process or element will be required to be included within the boundaries. This impact threshold will become the basis for standardized liquid biofuel LCA boundaries.

The following is a simulation of data from such an impact assessment. Petroleum based gasoline and diesel are presented for comparison and the relative impact is scaled as a factor of a MJ of potential energy.

Fig. 14 illustrates the currently accepted LCA output focusing on the impact of only 3 GHGs, CO_2, N_2O and CH_4. These three GHG factors can be readily compared and linearly added as CO_2 GWP equivalent making them convenient metrics. Fig. 15 portrays the change in information. This new perspective expands the system boundaries and metrics to include perspective that might come from additional impact both the original 3 GHGs as well as CFCs, HCFCs, HFCs and other factors as RSIRs. For example, liquid biofuel product B uses 3 times as much water during cultivation as Product C, thus creating 3 times the system impact from water use. Product B is also shown to have four times the methane emissions when the LCA

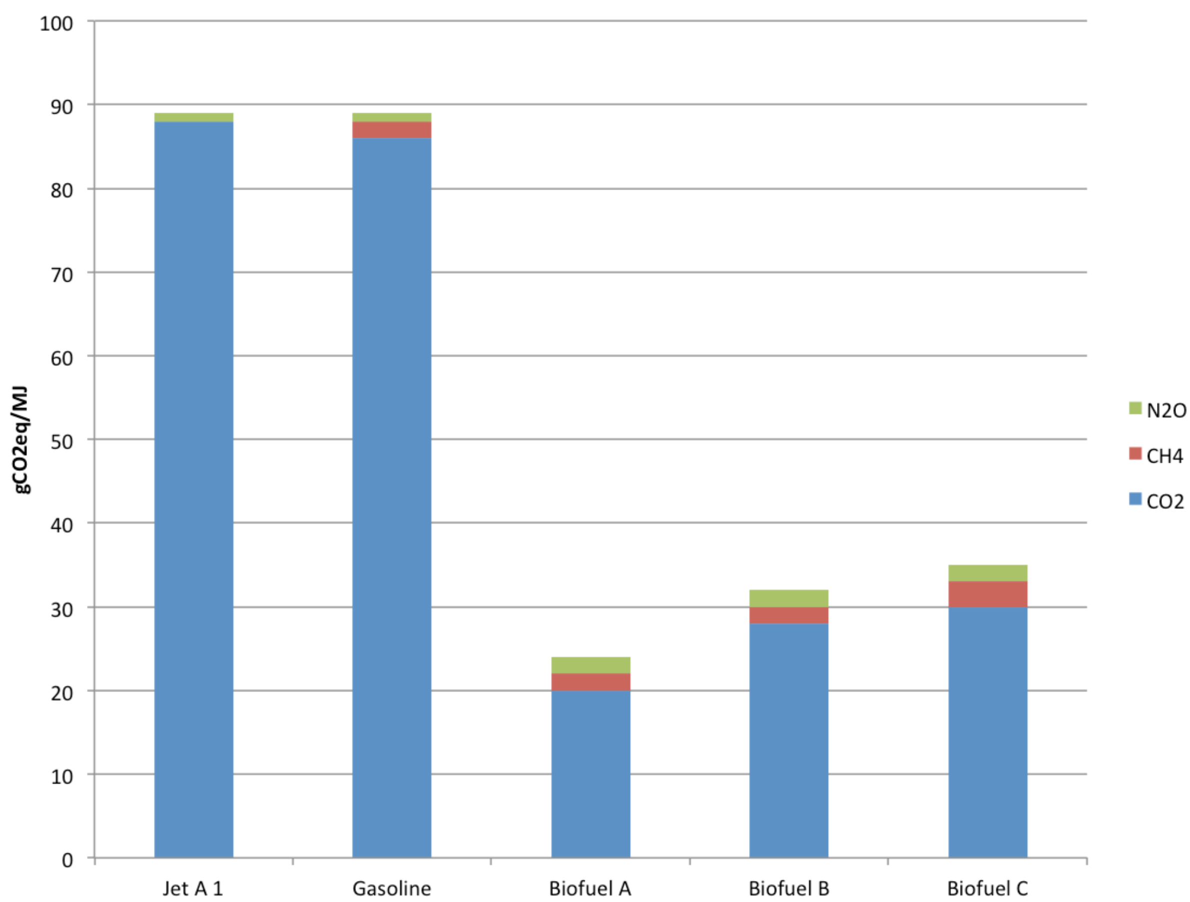


Fig. 14. A hypothetical liquid biofuel GHG assessment of three products by GHG emission type

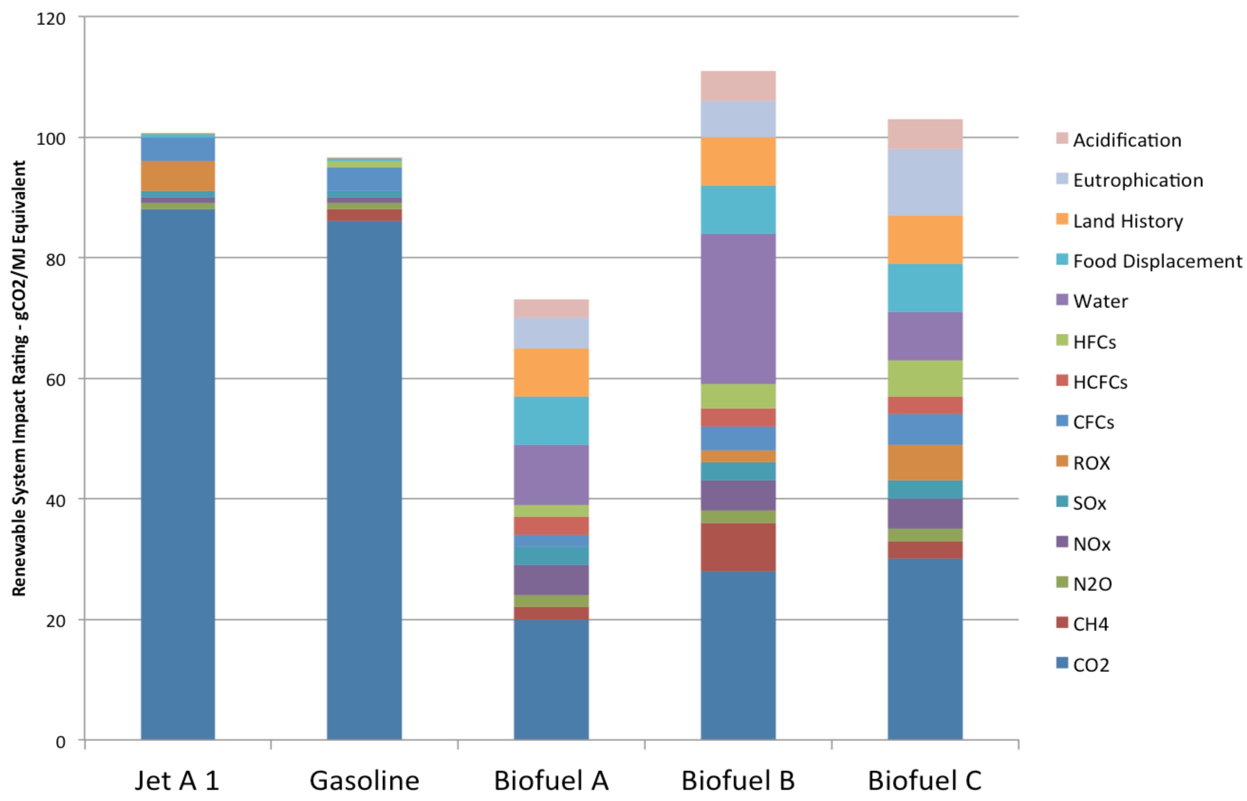


Fig. 15. A hypothetical liquid biofuel impact assessment of three products by 14 impact metrics

boundaries are expanded to include methane impact. With this more comprehensive assessment of the system impact, products B and C become less attractive in comparison to gasoline and diesel, while product A continues to show a relatively favorable impact grading. Expanded impact metrics will also affect fossil fuel LCAs. Crude oil from traditional wells will have lower impact ratings than crude oil derived from oil sands. Extracting natural gas from shale will have a larger impact rating than gas that flows freely from wells. Thus, the fossil fuel system boundaries will have to be modified to stay in line with the RSIR metrics.

The result of this work will be a complex grading system of metrics that allows direct comparison between fuel systems, something that is currently left to estimation and conjecture.

Of course, as the system model boundaries expand to include more impact factors, the complexity of the assessment rises accordingly. Increased complexity inherently introduces more cost. Complexity and cost may lead to incomplete and therefore inaccurate LCAs. This emphasizes the importance of well-funded, neutral providers of LCAs. As the EPA itself directs, the EPA, or neutral entities acting on its behalf, should produce the liquid biofuel LCAs – not the producers [106].

4.6 Case Study Recommendations:

One of the primary goals of the EPA is to avoid shifting environmental problems from one place to another. The principal deficiencies in current biofuel LCA methodology include: inconsistencies in LCA system boundaries; system boundaries that exclude relevant sub-processes, elements and environmental factors; a lack of standardized metrics leading to flawed indices of performance and a reliance on industry average data without regard for relevant impact. These all affect the ability to accurately determine the impact of a biofuel system for comparison or optimization. Taking an approach that uses the entire Dimensions of Systems Thinking to correctly rank and evaluate alternative fuel systems would start with the systemic development of the descriptive scenarios of the respective fuel systems – with emphasis on system boundaries and impact-based indices of performance. Correctly documenting the complexity and impact of biofuel systems through the highest quality lifecycle assessments based on the DST will be a valuable factor in accomplishing that goal for biofuel. It will also provide a valuable tool for optimizing and comparing biofuel production systems.

The proposed EPA policy of assigning metrics to biofuel products regardless of origin or process is flawed and will not accomplish the goals of accurately assessing the environmental impact of a biofuel system, improving quality of life and protecting the environment. Accounting for the system of origin for each product under assessment will be required [106].

Impact metrics for 3 principle greenhouse gasses are included in the most current LCAs. The relative effect of each is unitized as tons of CO_2 equivalent creating linear factors for each impact contributor. This study proposes a standardized metric unit, the Renewable System Impact Rating (RSIR) for all major impact parameters including, but not limited to: CFCs, HCFCs, HFCs, land history, water usage, biomass point of origin, food supply displacement, cultivation, eutrophication harvesting, biomass transport, processing, acidification, GHG, and energy per land area at the pump.

As the complexity of the biofuel system model increases, so too does the complexity of the assessment and the analysis. Advancing technologies and a need to correctly define system boundaries through iteration make lifecycle assessments complicated, expensive endeavors. Liquid biofuel LCAs should be performed by government entities or, on their behalf by properly funded neutral organizations rather than fuel producers in order to provide consistent measurements and avoid bias.

Chapter 5: Case Study: Healthcare and the Dimensions of Systems Thinking

5.1 Chapter Summary and Introduction

This case study was presented at the IEEE Systems Conference in 2013. Much of the information on the mental models of the medical professionals and the underlying factors of Systems-based Practice derive from a series of interviews with medical educators and researches at the University of Virginia Medical School and the Mayo Clinic during February and March of 2013.

This case study considers the U.S. Healthcare system in the context of the Dimensions of Systems Thinking. The scope of this case study will be to consider the U.S healthcare system in broad strokes to highlight areas where the system falls short based on data derived from the literature. The analysis will also focus on the mental models of the key stakeholders – the medical practitioners, and the complex political system and bureaucracy. The mental models of specialist doctors are considered in depth through detailed analysis of the graduate medical education system and an approach known as Systems-based Practice.

The graduate medical education community developed systems-based practice (SBP) as a curriculum to make medical specialists into systems thinkers with the goal of improving the healthcare system. In 1999, the Core Competencies, a curriculum for second-year medical residents was published by The Accreditation Council for Graduate Medical Education (ACGME) in response to safety problems, poor performance and a high rate of expenditure in the U.S. healthcare system. Systems-based Practice – the sixth core competency – was designed specifically to bring systems thinking to the practice of specialized medicine with the stated goal of providing optimal healthcare. Thirteen years after publication, Systems-based Practice has failed to have the desired effect on the healthcare system due to improperly defined objectives & system boundaries, lack of defined metrics & assessment procedures and the systematic nature of the system into which it was introduced.

We make recommendations for improvements to the sixth core competency that would be part of a larger effort to achieve sustainability in the U.S. healthcare system. Recommendations also include changes to the medical education paradigm and an out-of-the box, clear skies alternative to the existing system of health care regulation.

This case study led to the development of the observer effect dimension of systems thinking. The mental model of the analysts – in this case the medical professionals and educators who developed the alternative now known as systems-based practice with the objective of improving the healthcare system. It shows how their mental model has had a pronounced effect on their analysis and on the system.

5.2 The Descriptive Scenario - The Healthcare System in the United States

First, we consider the system of healthcare delivery in the United States writ-large.

5.2.1 Overview

The United States healthcare system is a complex, adaptive system that forms a $2.7 trillion industry representing 17.6% of gross domestic product [2011]. Comparative data on

Organization for Economic Cooperation and Development (OECD) countries show a healthcare system in the U.S. that produces near-bottom-ranked wellness results from the top ranked fiscal investment in healthcare both in terms of per capita investment and as a percentage of Gross Domestic Product (GDP). The U.S. system has evolved to optimize revenue and profit through fees for service rather than to optimize wellness. The system interactions support increasing complexity rather than efficiency. The complexity of the system is amplified through federal health and drug regulations along with local regulations and licensing boards for doctors, nurses, pharmacies and insurance companies in each of the fifty states plus U.S. territories. With 313 million stakeholders, the U.S. healthcare system directly employs 14 million persons. $1.2 Trillion or 43.6% of total healthcare expenditure in 2009 was related to government programs. State and federal healthcare programs include Medicare, Medicaid, The Department of Defense and the Department of Veterans Affairs. Healthcare is ranked as the number-one industry in terms of gross expenditures by federal and local lobbyists, as well as one of the leading industries for advertising expenditure. Data are unavailable for expenditure on political campaigns related to healthcare policy, but it is assumed to be among the primary motivations of political spending in recent years. System boundaries are not limited to the geographic confines of the United States. Eight of the ten largest pharmaceutical corporations doing business in the U.S. are foreign based. [112]–[116], [117].

Historically, the U.S. government has maintained a policy of protecting a competitive market system of healthcare tracing back to 1854 when president Franklin Pierce vetoed the first U.S. national policy intended to affect national healthcare. The Bill for the Benefit of the Indigent Insane took a systems approach to providing for the needs of the mentally ill. Unused federal land would be sold and the proceeds invested to fund institutions built across the country

– much as land grant colleges would be created later in the 19th century. Though the bill passed both houses of Congress, Pierce rejected it proclaiming that the federal government should not commit itself to providing social welfare [118]

In many important aspects, the U.S. does not have just one healthcare system; it has independent healthcare systems in every state, territory and the District of Columbia - each with varying regulations, requirements, goals, metrics and quality. Massachusetts and Vermont offer universal healthcare insurance; 27% of the population of Texas has no healthcare insurance [119].

5.2.2 Metrics

The Centers for Disease Control and Prevention, National Center for Health Statistics of the Department of Health and Human Services publishes annual data on the state and trends of health and healthcare in the United States in their *Health, United States: National Healthcare Disparities and Quality Reports*. The most recent edition reflecting data from 2012, shows an upward trend in several diseases as well as a continued upward trend in emergency room care for those in the U.S. without insurance. Emergency room care is described in the report as being a highly inefficient and costly medium for the delivery of care versus routine preventative care. For comparative data relating the different national healthcare systems, The World Health Organization publishes *World Health Statistics* with data on mortality and burden of disease. Some of these data are reflected in the Organization for Economic Cooperation and Development (OECD) data, which are more relevant because they focus on healthcare systems in countries and economies more similar to the U.S. [114], [115], [117]

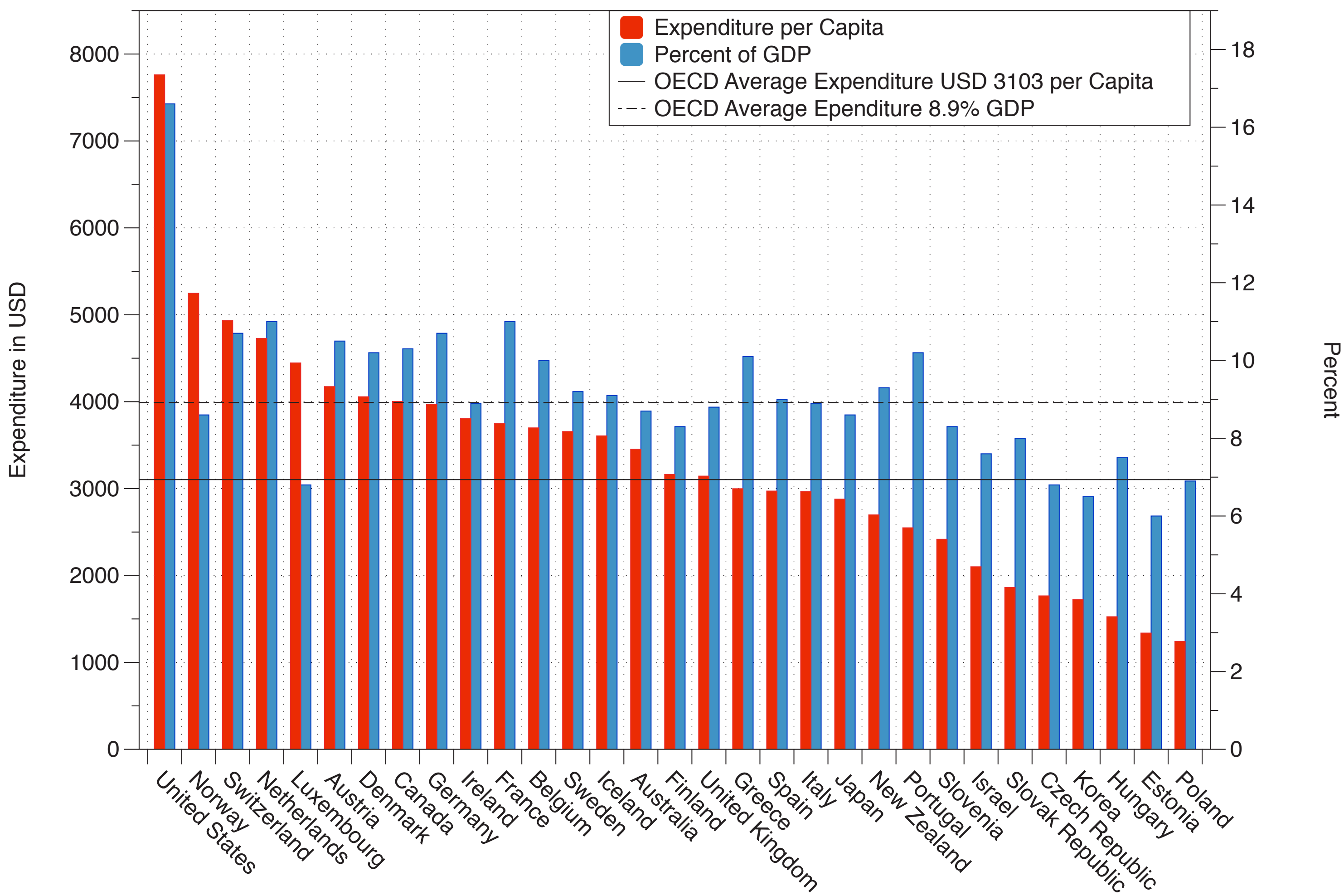


Fig. 16. Healthcare expenditure by country (OECD 2008)

Per the OECD 2008 data shown in Fig. 16, the United States spends two-and-a-half times more per capita than the OECD average of USD 3101 per year per person, and yet ranks thirty-first in the metric of infant mortality and twenty-sixth for life expectancy as shown in Fig. 17 Of the 31 OECD countries shown in the figures, the U.S. is the only one without universal healthcare coverage[10]. The World Health Organization ranks the U.S. 31[st] of 191 countries in healthcare quality.

[10] Figures exclude OECD members Chile, Turkey and Mexico, but they are included in averages. The U.S., Turkey and Mexico are the only OECD countries without universal healthcare coverage.

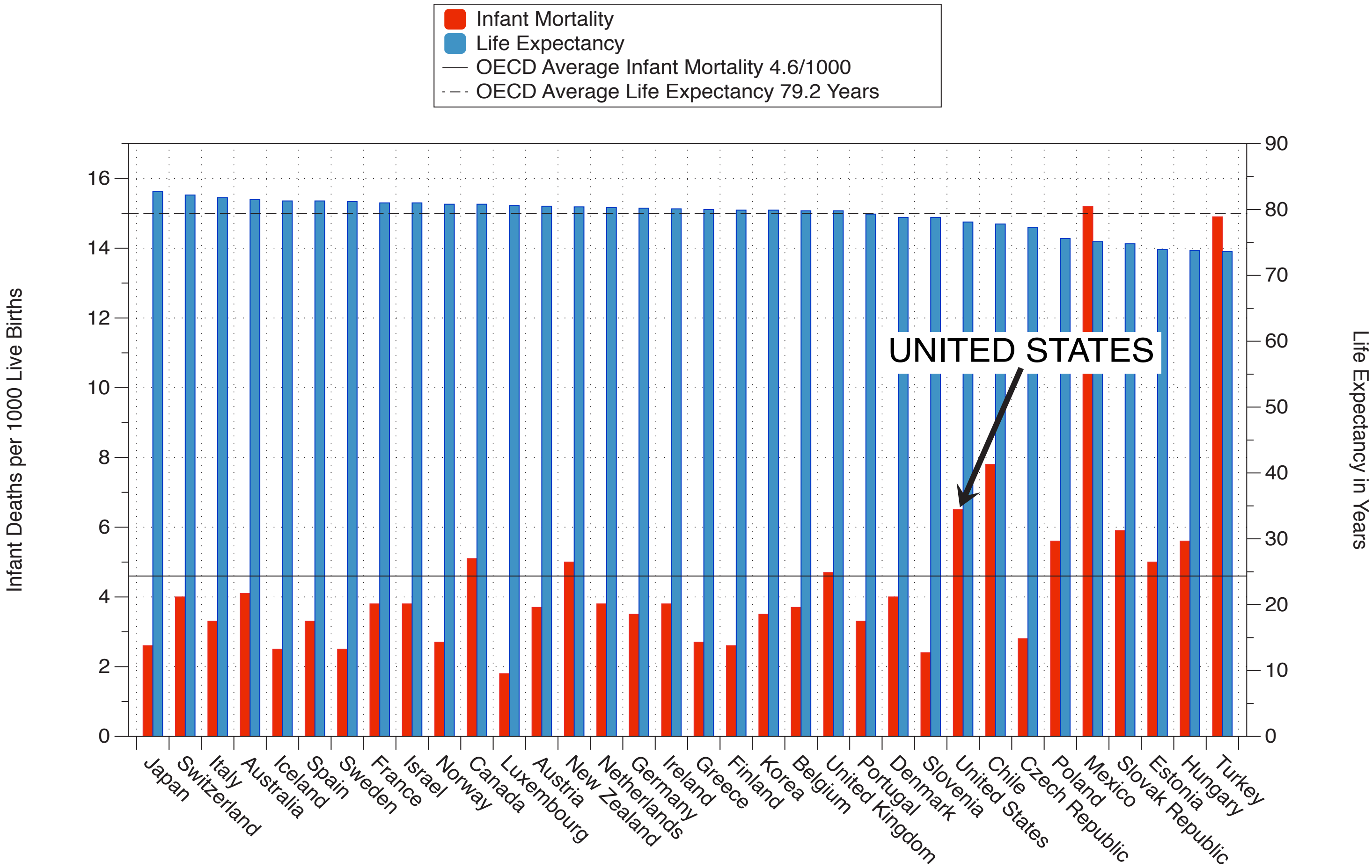


Fig. 17. Infant Mortality and life expectancy at birth by country (OECD 2008)

Harvard University calculated that a lack of healthcare caused 45,000 deaths in the U.S. in 2009. In 2002, the number of healthcare associated infections in the U.S. was 1.7 million [112]–[116], [120].

According to the Center for Responsive Politics, more than five billion dollars were spent on congressional lobbying directly related to healthcare from 1998 to the present – the largest categorically ranked sector at the national level. State level lobbying expenditures are comparable; California reported $35.7 million in 2011, Massachusetts reported $11.6 million spent on healthcare lobbying the same year. Healthcare related advertising included $30.6 billion spent in the U.S. by pharmaceutical manufacturers in 2011, a 3.1% annual decline [121]–[124].

Simultaneously with the 2013 presentation of this work at IEEE Syscon, Steven Brill' article *Bitter Pill: Why Medical Bills Are Killing Us* was published in Time magazine. It reveals the hidden world of medical charge master directories – the prices charged for medical services at hospitals and medical practices. The article revealed how these directories are not publicly available, so the price for service is completely unknown to the consumer prior to receiving that service; it revealed the margins for products and services provided could be as high as 10,000%; and it showed that individuals with minimal or no insurance are charged the highest fees – often with the objective of maximizing the loss write-off when they cannot pay [125].

From a cursory analysis of the data from the literature in terms of wellness and cost: when compared with healthcare systems in other nations, the US system is providing a lower percentage of wellness at a higher per-capita cost. Some aspects of the system are inefficient to the point of being unsafe as indicated by data on those who die from lack of coverage or healthcare related infections. Conflicting objectives – profits versus wellness – are represented in the data by the hundreds of millions of dollars spent annually by healthcare corporations in ways that do not contribute to actual healthcare such as on advertising and political influence.

5.2.3 Type of System

Healthcare in the United States, as mentioned above, can best be categorized as a complex adaptive system - a type of system that is continuously re-designing itself, changing variables and adding new variables while maintaining the same objectives. System and variables are dynamically affected by politics, economic factors, medical research, healthcare technology and pharmacological development as well as newly discovered or understood genetic variations, viral strains and toxins [126]–[128].

5.2.4 Current Objectives of the U.S. Healthcare System

The current U.S. healthcare delivery system has a fee-for-service structure characterized by zero-sum competition with the primary objective defined as maximizing profit. One health care provider can achieve gains only at the expense of another. Immediate costs are reduced by shifting expenses spatially or temporally, thus increasing short-term profits - though shifted care tends to increase net cost of care. Providers improve profits by reducing the time spent per patient. Consolidation of services reduces costs, again, improving profits. Insurance companies improve returns by restricting payments for services, frequently forcing the covered patient to cover the gap. Likewise, the objective of the pharmacological and medical device industries in the U.S. is to garner sales at the expense of a competitor through research and development, but also with the aid of direct and indirect marketing [129].

5.2.5 State of the System and Life Cycle

The median age of the population in the United States is rising and this trend is expected to continue over the next few decades. From 1950 to 2004 the population under 18 years of age fell from 31 to 25 percent of the total population, while persons 55–64 years increased from 9 to 10 percent of total persons, persons 65–74 years remained at about 6 percent, and persons 75 years and over increased from 3 to 6 percent of the total. With an aging population comes increased need for medical services and the resulting costs and this is reflected in a steady increase in healthcare expenditures over the last 50 years. Some economic analysts say an increasing number of U.S. businesses are less competitive globally because of ballooning healthcare costs [128].

The state of the U.S. health care is therefore dynamic, growing and unreliable. Its life cycle is unknown, but it is dependent upon the U.S. Economy since healthcare is the responsibility of the individual who makes healthcare decisions based upon their economic state. Since healthcare has a significant effect on that same economy, there are causalities from interactions in the system affecting the life cycle.

5.2.6 Normative Scenario

Economists Michael Porter and Elizabeth Teisberg – authors of the best-selling book **REDEFINING HEALTH CARE** - make a valid case that optimal wellness should be the normative scenario. As population wellness improves, total costs will go down. They also write that putting doctors in charge and deregulating the industry will lead to rapid improvement within the existing system[11]. What they fail to see is that, according to the composition of corporate boards of directors surveyed on corporate websites: largely managers who, for the most part, are not doctors already run the U.S. healthcare industry. These corporate boards are responsive to shareholders, not patients. Kaplan and Porter feel the solution to the healthcare crisis will come through better healthcare costing, essentially improving the efficiency of patient care delivery through improved resource capacity utilization and accounting for those care delivery costs through an improved cost measurement process [130].

---

[11] In addition, they call for a universal mandate to purchase insurance while stating that patients cannot be expected to intelligently manage their own healthcare[129]

5.3 System stakeholders and axiological components

Most of the relationships between stakeholders shown in Fig. 18 on page 97 are financially motivated including payment for services and insurance coverage, government entitlements & research funding, marketing, political lobbying, profits and dividends. Other stakeholder relationships shown in Fig. 18 deal with delivery of care, exchange of information, education, licensing and accreditation. Private insurance companies, regulated by the states, decide treatment allowances and limitations for the non-government $1.46 Trillion of U.S. annual healthcare expenditures. Politically appointed officials run the state licensing boards that grant the insurance companies their authority[12].

Porter and Teisberg place doctors as the preeminent decision makers for system change. The U.S. system espouses the right of patient/consumer stakeholders to freely choose their own personal physician, thus placing the median patient above the doctor at the individual decision level. Education, fiscal status, insurance companies and government services play a role in healthcare choices, adding to the complexity of the system. Because one cannot control the state of health, education, or preferences of those who seek health care, one cannot assume that they will be able and willing to manage the complexity of the current system.

The system appears designed to obfuscate the identification of the actual decision making stakeholders. Freedom of the individual to choose a doctor is assumed, but picking a doctor within a prescribed network is encouraged. Political forces advocate for the right to select care

[12] As well as the boards of the territories and District of Colombia

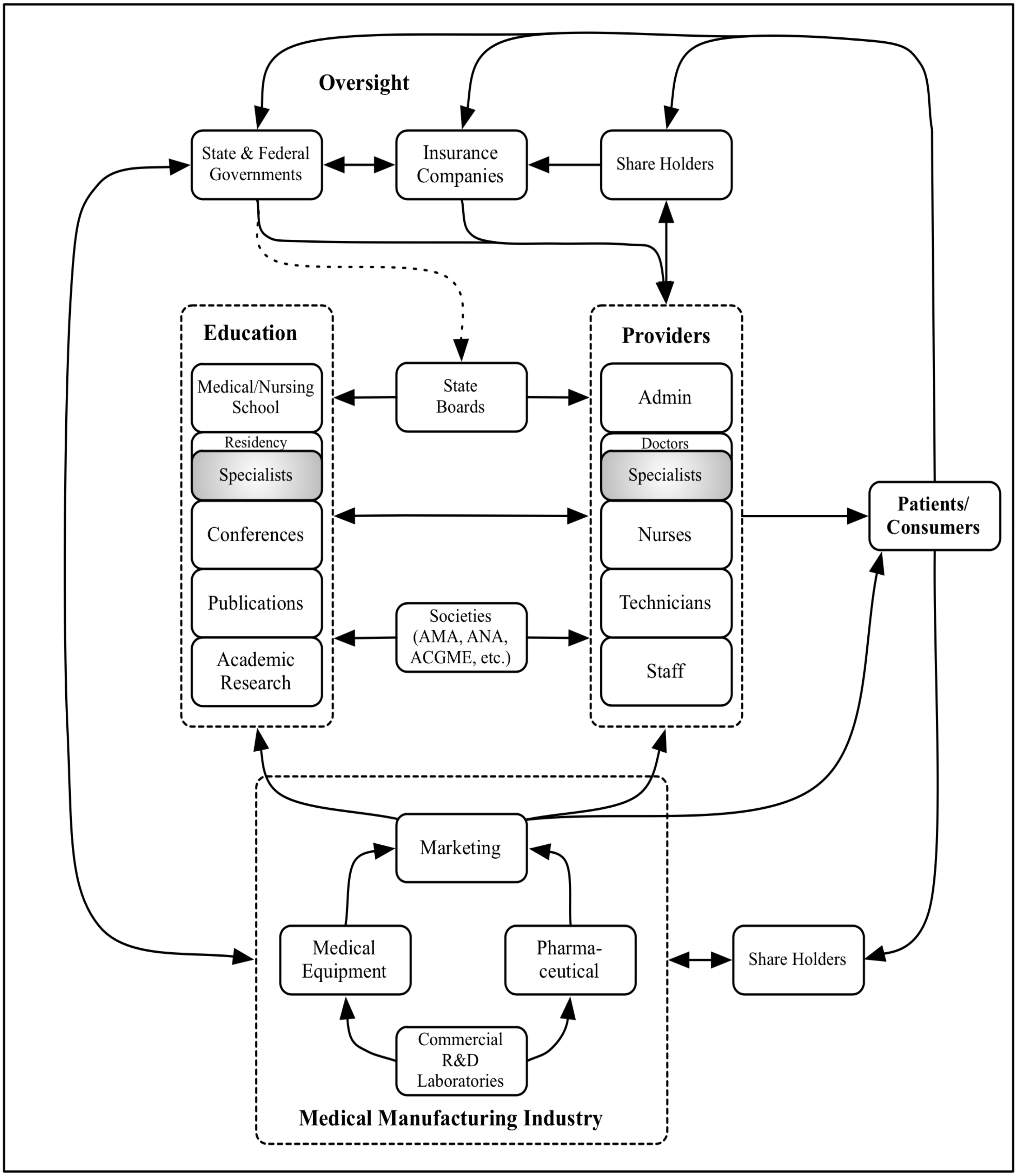


Fig. 18. Overview of the U.S. Healthcare system and its stakeholders

on the open marketplace, thus creating competition and driving down prices – but the prices are concealed from the consumer thus eliminating actual competition. Insurance companies delineate limits on coverage in minute detail and care-delivery systems dictate which insurance they will accept. Care system boards of directors seek to maximize revenue by restricting outlays – even though the majority enjoy tax-exempt non-profit status. The regulation system that oversees the healthcare system is politically managed and thus subject to electoral control. Millions of voters know of no other healthcare service than the last-resort hospital emergency room. The only true right to healthcare choices on the part of the individual stakeholder may, therefore, be at the ballot box [129].

From the rare individual practitioner and the small physicians groups to large healthcare providers, medical doctors are a key decision making stakeholder in terms of the structure of the system. While their median income ranges by specialty from $189k to $407k, they have bills, employees and payment on college loans to consider [131]. They are already taking every step available to better integrate, coordinate and account for all aspects of their practice and to consolidate services – what Kaplan and Porter call improved costing. Private practices find increased efficiencies – and improved revenue – through alliances with or absorption by larger practices, hospitals and hospital systems. Assuming general adherence to medical best practices and the Hippocratic oath, the existing healthcare system accepts as a basic assumption that the primary objectives for healthcare providers are to optimize revenue through means including increased efficiency.

Run down the lists of the largest U.S. health insurance providers and notice that each one has a medical advisory panel, staffed entirely with doctors and endowed with the authority to make all critical decisions regarding allocation of care [132]. These are the doctors in charge –

and subservient in every way to the corporate board of directors. Yet, doctors, according to Porter and Teisberg see that hierarchy reversed with the doctors making critical decisions.

The following healthcare objective quotes from the masthead statement by Michael B. McCallister, Chairman of the Board and Chief Executive Officer of Humana:

> *"At Humana, we stress the importance of conducting ourselves in an ethical, legal and straightforward manner. We emphasize our commitment to integrity by following four basic ethical principles. First, we act fairly and honestly with those whom our actions affect and treat them as we would expect them to treat us if the situation were reversed. Second, we comply with laws -- not only with the letter but also with the spirit of all applicable laws and regulations. Third, we adhere to high ethical standards of conduct in all business activities and act in a manner which enhances Humana's standing as a corporate citizen. And fourth, we promote relationships based on mutual trust and respect and provide an environment in which associates may question a company practice without fear of adverse consequences."[133]*

According to that statement, the corporate objective is to not break the law. There is no mention of care, wellness or health in the statement of the corporation objectives. With 2011 profit of $1.4 billion on revenue of $36.8 billion and assets of $17.7 billion, staying out of jail can apparently be a lucrative endeavor.

This case study will now consider in detail the mental models of the medical professionals who – at varying levels – are among the key decision makers in the U.S. healthcare system. We will consider how these key stakeholders think based on their training and experience.

5.3.1 The Mental Model of Healthcare Providers: Systems-based Practice

Doctors are considered among our societies most well educated members. They are commonly respected as being highly intelligent and considered pillars of the community. Twenty-three medical doctors currently serve in the United States Congress. The mental model of medical doctors takes its root in the rigorous education process they experience. We consider this education process as an axiological component of the healthcare system providing insight to the mental models of doctors and therefore, according to Porter and Teisberg, the mental models of the healthcare system's principle decision makers.

Medical education in the U.S. healthcare system is guided by several, distinct, private associations including The Council of Medical Education of The American Medical Association (AMA), The Association of American Medical Colleges (AAMC), The Council on Graduate Medical Education (COGME) and The Accreditation Council for Graduate Medical Education (ACGME). Regulation of medical education comes from state and territory governance boards appointed politically. The examinations to certify a medical doctor for a license are prescribed by the individual states, but administered, graded and evaluated by the individual medical school/ teaching hospital. [Foreign medical graduates can receive state licenses to practice medicine with the assistance of such organizations as The Educational Commission for Foreign Medical Graduates (ECFMG)][134]

During the early 1990s, the U.S. medical establishment determined that due to endemic safety problems, poor performance and a high rate of expenditure, the U.S. healthcare system was not sustainable. The Council on Graduate Medical Education (COGME), the Pew Health Professions Commission, the Association of American Medical Colleges (AAMC), the Federated Council of Internal Medicine, the Association of Program Directors of Surgery, and the Royal

College of Physicians and Surgeons of Canada all published opinions espousing a need for significant improvement in the knowledge and skills of specialist physicians in order to correct the deficiencies of the U.S. healthcare system and to set it on a track to sustainability. The Accreditation Council for Graduate Medical Education (ACGME) and the organization of state certifying boards, the American Board of Medical Specialties (ABMS), conducted a research and review process starting in January 1998. In February 1999, this effort produced a general competency and outcome assessment initiative called the ACGME Outcome Project. The Outcome Project emphasizes six general competencies: patient care; medical knowledge; practice-based learning and improvement; professionalism; interpersonal skills and communication; and systems-based practice (SBP). Systems-based practice is frequently referenced in the literature as *the sixth core competency* [135], [136].

The origins of the Outcome Project and the sixth core competency are traced in the literature to on-going chronic system failures that degrade patient safety in nearly all facets of the U.S. healthcare system. 1.7 million cases of hospital-acquired nosocomial infections in the U.S. resulted in the deaths of 99,000 patients in 2002. Flaws in the medication delivery system including the misuse and abuse of antibiotics have supported the evolution of drug-resistant strains of many diseases from TB to gonorrhea. ACGME correctly concluded in 1999 that the flawed U.S. healthcare system is unsustainable and requires a systems approach to find solutions. Their approach to a solution established SBP as a way of correcting the healthcare system through residency training [120], [137].

5.3.2 Systems-based Practice

Within the context of the larger Outcome Project, the goal of SBP was to "Examine whether what residents are learning during residency is sufficient to provide care in an environment where some stakeholders advocate evidence-based, cost-effective, patient-centered care as a new standard." It was felt that as the complexity of the health-care delivery system has increased, it is essential for physicians to understand how individual practices relate to the larger system [137], [138].

ACGME published the following official description of Systems-based Practice:

"Residents must demonstrate an awareness of and responsiveness to the larger context and system of health care, as well as the ability to call effectively on other resources in the system to provide optimal health care. Residents are expected to:

- *Work effectively in various health care delivery settings and systems relevant to their clinical specialty.*
- *Coordinate patient care within the health care system relevant to their clinical specialty.*
- *Incorporate considerations of cost awareness and risk-benefit analysis in patient and/or population-based care as appropriate.*
- *Advocate for quality patient care and optimal patient care systems.*
- *Work in inter-professional teams to enhance patient safety and improve patient care quality [138]."*

The ACGME Outcome Project proposed measuring the effectiveness of SBP based on metrics and methods to be determined, including: "ratings tied to specific patient encounters, ratings of patient satisfaction, objective-structured clinical examinations, graduates perceptions of the adequacy of their education and, possibly, practice patterns" [138].

5.3.3 Systems-based Practice in Practice

A survey of the literature since the establishment of the core competency curriculum by ACGME, coupled with interviews of subject matter experts in graduate medical education finds that the common interpretation of SBP by hospital faculty is well summarized by R. A. David and L.M. Reich: "*A greater awareness of one's role within the health care system generates a clear opportunity to contribute to the system's improvement. Physicians, who are frequently aware of barriers to their patients' treatments, as well as the processes especially prone to error, are perfectly positioned to offer and execute ideas that can lead to positive change. And physicians who are aware of these issues are better able to offer optimal care to individual patients in a complex delivery system*."[139]

Research finds several specific criticisms of SBP. They include: no clear, common understanding of SBP leading to a distinct and different approach to SBP in every accredited residency program; a lack of and strong need for standardized assessment criteria and methods for SBP; a lack of understanding of the relationship of SBP to patient outcomes & safety and a lack of integration into daily practice. Several sources addressed the already overloaded schedule of medical students and residents as being a limiting factor of SBP. The variety of instructional methods and resident assessments for SBP found in the literature and through interviews include: morbidity and mortality conferences, quality improvement conferences, outcomes cards, independent study projects, workshops and quality improvement projects. SBP instruction is understood by some to be a function on the part of the individual medical specialist, not the medical establishment where mentoring faculty may lack proficiency or fluency in systems thinking and would therefore be incapable of passing it along. In summary, the definition and guidelines of SBP are considered inadequate in establishing the root objective – incorporating systems thinking in the curriculum of medical specialist training and practice in order to improve health services [137], [140]–[142].

Research shows recognition of SBP deficiencies and also a nascent movement in resident education to reform it, although none approached SBP through systems analysis. Work at The Mayo Clinic combines SBP with practice-based learning and improvement (PBLI) in an approach called transformative learning of quality improvement (QI). Lecture material used at Mayo introduces systems improvement tools such as Lean and Six Sigma to residents, but appears to fall short in promoting fluency in systems thinking.[143], [144]

5.4 Systems-based Practice as the Subject of the Dimensions of Systems Thinking

We now drill-down into the system of systems-based practice by applying the Dimensions of Systems Thinking.

5.4.1 The Descriptive Scenario, System Boundaries, the Normative Scenario and Objectives

Johnson, et. al. stated: " Systems thinking is the cornerstone of SBP… To clarify the definition of SBP and to develop effective strategies for teaching and assessing SBP, it is necessary to provide a broad awareness of systems within a context of systems thinking." [137]

Using the DST technique, this case study starts the systems analysis by translating the descriptive scenario – the current definition of SBP – into the lexicon of DST. Recall the ACGME description of the sixth core competency:

Residents must demonstrate an awareness of and responsiveness to the larger context and system of health care, as well as the ability to call effectively on other resources in the system to provide optimal health care.

In Table II, the description of SBP is shown translated term-by-term into the lexicon of the Dimensions of Systems Thinking. The other tenets of SBP quoted above can be interpreted as guidance for effective practice rather than quantifiable systems objectives.

In defining the system boundaries, recall that the Core Competencies are the product of The Accreditation Council for Graduate Medical Education (ACGME). Their immediate purview is shown in the shaded region of Fig. 18, with primary influence on the education of medical specialists indicated by the shaded block on the left. This case study will consider these two shaded areas to define the boundaries of the system under analysis. This reduction is scope from the entire healthcare system to the education and practice of medical specialists allows the establishment of quantifiable objectives within the system.

Reinterpreting SBP, we arrive at the following statement of the normative scenario: *Medical specialists will be able to demonstrate a capacity for systems thinking in the context of healthcare.* While still broad and subject to some interpretation, this normative scenario is more quantifiable than the ACGME SBP goal of "*Provide optimal healthcare.*" Following the tenets of DST, the normative scenario would be achieved through the following primary objectives:

The medical education system will provide residents with the capacity and capability of being systems analysts and of applying systems thinking in the healthcare systems of which they are a part.

An objectives tree delineating the hierarchy of sub-objectives required to achieve this new primary objective of SBP flows from the DST and Table I:

The medical education system will instruct residents in the ability to:

- *Identify the system boundaries and outscope;*
- *consider the axiological components in the system;*
- *develop alternatives based upon the objectives and within the scope of the analysis;*
- *rank alternatives;*
- *identify leverage points;*
- *and make recommendations*

within the context of improving patient care in the healthcare system.

5.4.2 Axiological Components and the Type of System

The next step in the analysis is to consider the axiological components of SBP in the context of the medical education curriculum in the U.S. To become a medical doctor practicing an established specialty in the U.S., the following course of study is required: 4 years of undergraduate pre-med curriculum including biology, chemistry and mathematics; 4 years of medical school broken into: pre-clinical studies (consisting of didactic courses in the basic sciences); and clinical studies (clerkships consisting of rotations through different wards of a teaching hospital); 1 year of internship considered a transition to residency; 2 to 7 years of residency focused on the chosen medical specialty and frequently followed by a 1 to 2 year fellowship, sometimes considered a transition stage to a permanent position with a hospital or clinic. The first stage, pre-med, is taught at an undergraduate institution that may or may-not be affiliated with a medical school. The medical school stage is distinct and separate from the residency stage – separated by what was described as "*a chasm*" in one interview for this analysis. Residents are full-time employees of the teaching hospital, expected to learn but also beholden to the system that pays them. All three are aligned with different accreditation systems that have distinct and separate objectives.

Table I: Systems-based Practice in Terms of the Dimensions of Systems Thinking

Systems-based Practice	**Dimensions of Systems Thinking**
Awareness of and responsiveness to the larger context and system of health care	Identify the system boundaries and outscope. Consider the axiological components in the system.
Call effectively on other resources in the system	Develop alternatives based upon the objectives and within the scope of the analysis. Identify leverage points.
Provide optimal health care	Rank alternatives. Make recommendations

ACGME prescribed that the core competencies including SBP be incorporated in the second year of residency – the 11^{th} year of formal medical education. Prior to this introduction to the concept of a systems approach to medical care, all medical and applied science instruction will have been based on *case-based reasoning*. Case-based reasoning can most easily be described as a version of decision tree analysis. Acquired by medical students through mnemonics and rote memorization, case-based reasoning follows an if-then logic stream through the analysis of a patient's symptoms and laboratory results concluding with a diagnosis. Derivation of the diagnostic decision tree through statistical analysis is left to researchers, not practicing physicians. Successful doctors are often judged by their memories and ability to quickly conduct diagnoses through case-based reasoning. From pre-med inorganic chemistry through a resident's diagnosis of dermatitis or dengue, the logical process is essentially the same: a systemic step-by-step walk through an established decision tree. A patient presenting symptoms of dermatitis would be subject to the diagnostic tree shown in Fig. 19 [14]. These decision trees have been derived from statistical analyses of medical studies performed since the dawn of modern medicine. In most cases, because of a limit to the number of empirical data points, a diagnosis will have a variance as well as a rate of false positive and false negative

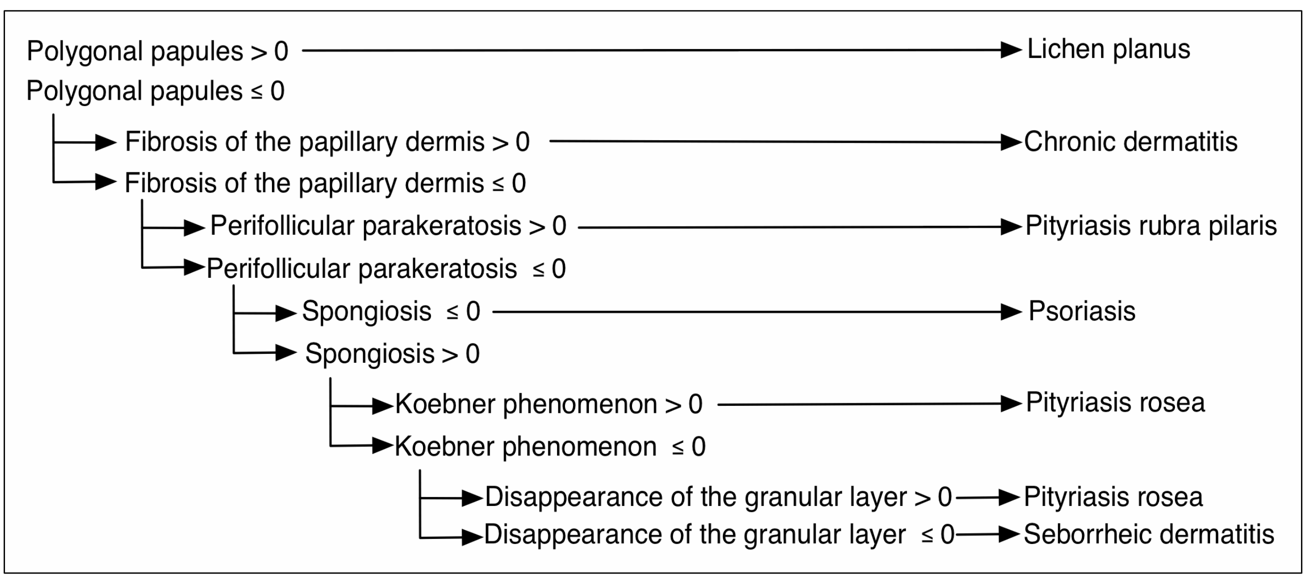


Fig. 19. Dermatitis diagnosis decision tree (Chang, et.al.)

errors. The diagnosis tree in Fig. 20 for dengue fever shows the empirical data for 1200 febrile cases of which 364 were actually positive for dengue. Once the diagnosis is made, another systematic decision tree, generally called a protocol, is employed to prescribe and direct the appropriate course of treatment [145], [146].

An education system designed to replace methodical reasoning with rapid, reflexive decision-tree analysis is appropriate where life and health are at stake. A specialist treating a patient when confronted with symptoms they cannot explain does not resort to basic science or research to derive a diagnosis. Instead, they consult another specialist in the hope that

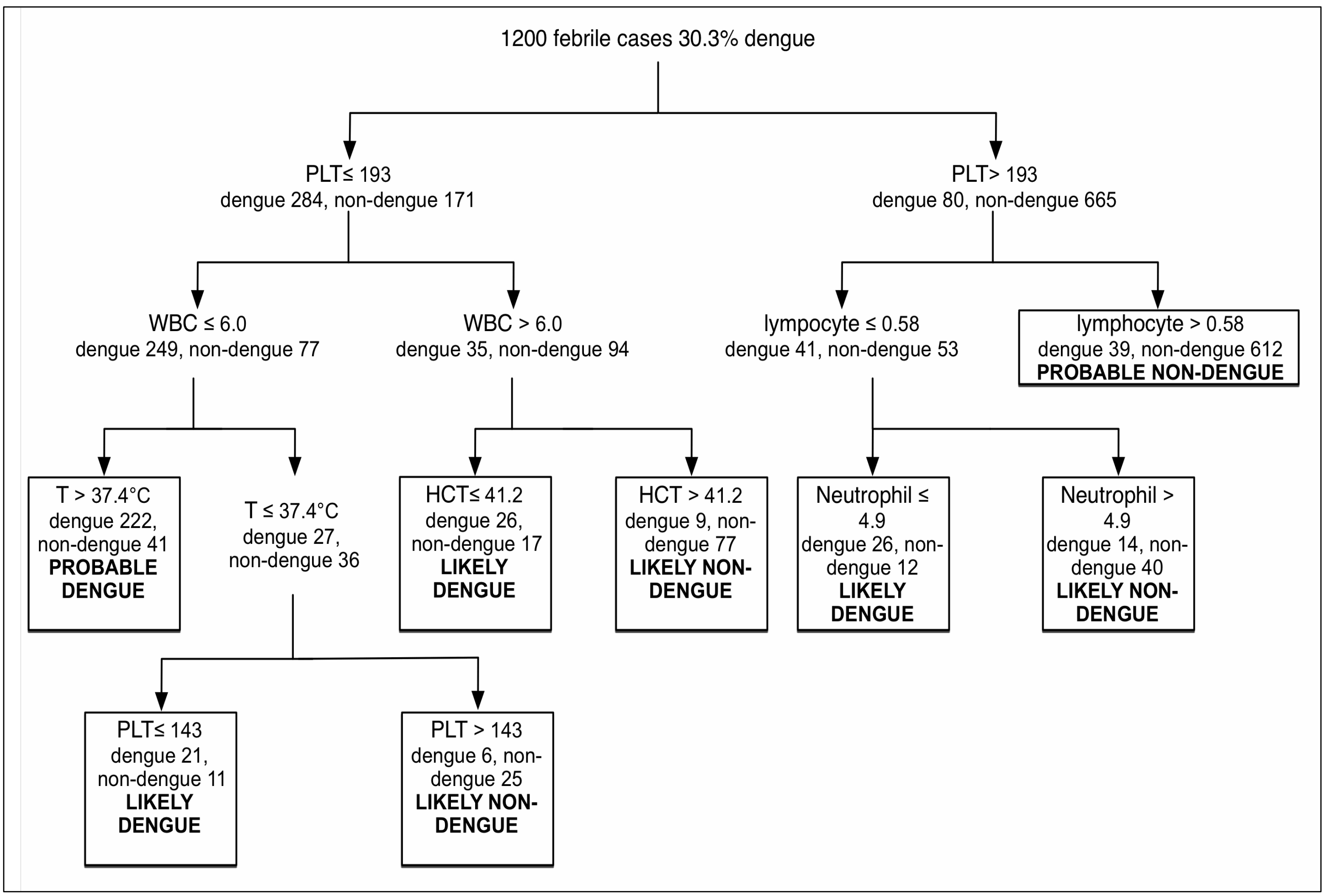


Fig. 20. Dengue diagnosis decision tree (Tanner, et. al.)

knowledge of a different corpus of decision trees will explain the symptoms.

In that light, systems-based practice was conceived and implemented within an institutionalized checklist mental model. The definition and guidelines of the sixth competency are not adequate in establishing the root objective of SBP – incorporating systems thinking in medical training and practice in order to improve health services. I.e.: systems thinking is lacking in both the definition and assessment of SBP [141]. SBP is a systematic approach to coordinating patient care within the healthcare system as it relates to a clinical specialty. It is not a systemic approach to improving healthcare.

5.4.2.1 The Observer Effect

Doctors rely heavily on this checklist methodology throughout their careers. Some have published articles and even best selling books espousing the theory that complex problems of all sorts require, not systems thinking, but better checklists. Systems-based practice was, therefore, conceived and implemented within an institutionalized system of checklists. Thus, a key axiological component of the medical education system is also the type of system: SBP, which espouses systemic thinking, exists within a system of systematic thinking. [147].

In physics, the Observer Effect dictates that the system being observed is unintentionally affected by the act of observation. It is sometimes confused with the Heisenberg Uncertainty Principle. Here, the observer effect is manifested by the analysts – those tasked with developing systems-based practice – affecting the system not with sound systems thinking – as was their intention - but unintentionally affecting the system with their own mental models based on a checklist, systematic approach.

A similar example from Introduction to Systems Engineering at The University of Virginia[13]: The parents of a child with abdomen pain consult their neighbor, a noted heart surgeon. The surgeon diagnoses a heart problem – based upon his mental model of what causes pain in the abdomen. The child is rushed to the hospital for surgery – the logical next step in the care protocol of the surgeon's mental model. However, the child is examined by a pediatrician per hospital procedure - and the pediatrician has a different mental model for abdomen pain in children. Based on the case-based reasoning he was trained on and believes in, the pediatrician diagnoses indigestion, which turns out to be correct. Conclusion: the mental model of the observer has an affect on the observation.

This dimension is different from the mental model considerations of the axiological components in that it specifically considers the affect by the individual or group engaged in the systems approach on that approach. It is of interest here because the origins of systems-based practice lie in the stakeholders of the medical field conducting a systems approach on the system of which they themselves are a part.

A faculty member at a teaching hospital interviewed for this case study described the medical residency system as an apprenticeship system developed over centuries. As such, the residents learn from and are evaluated by mentors in their respective specialties. Given that virtually none of the current medical specialist mentors have been trained in systems thinking, and many of those that have describe themselves as self-trained, the current residency system falls short as a medium for acquiring systems thinking.

---

[13] SYS6001 – Professor William T. Scherer

5.4.3 Metrics and Indices of Performance

Healthcare systems produce many common metrics such as life expectancy, infant mortality, quality of life, cost of health care per capita, health care cost as a percentage of GDP, accidental deaths, rates of nosocomial infections and incidence of drug-resistant infections. However, these metrics do not translate into indices of the performance of Systems-based Practice under the re-defined objectives and system boundaries.

In the DST approach to analysis, metrics must be related to specific objectives. They must be measurable, objective and translate into non-relativistic indices of performance that reflect accurately the effect of SBP in achieving its objectives within the boundaries of the medical specialist education system. Fortunately, there is an established system within academia that already calculates these metrics at several levels in the evaluation of graduate and undergraduate systems engineering students. The systems engineering approach of systems case studies and evaluations (not to be confused with case-based reasoning) would translate well to medical resident training and build upon QI and other efforts at SBP instruction.

Even better would be an analytic methodology for assessing systems thinking. That follows in Chapter 7.

The primary objective of all medical residents is to pass the licensing board examination. In 2013, all specialist-licensing examinations are computerized multiple-choice tests that focus exclusively on medical knowledge. The other five core competencies of the Outcome Project, including SBP, are not subject to any standardized testing. Performance indices of SBP derived from new board examinations would provide the best quantitative evaluation of SBP training.

5.4.4 Outscoping and Leverage Points

Up to this point, the analysis has maintained scope on the residency training of specialists in systems analysis. When outscoped, the system boundary becomes the delivery of optimal patient healthcare in the context of the entire U.S. healthcare system writ large within which specialists work. Thus, the normative scenario as originally proposed by the ACGME can be interpreted as an optimal U.S. healthcare system to be achieved by teaching systemic thinking to second-year residents. The overview of the U.S. healthcare system in Fig. 18 on page 97 shows the context of specialists in education and as providers.

It is difficult to ascertain from the literature exactly how the authors of the ACGME Outcome Project envisioned that modifications to the curriculum at this level would propel the entire system toward delivering optimal care. One subject matter expert interviewed for this paper compared it with trying to understand the mindset of the framers of the Constitution. Taken on face value, systems analysis categorizes the concept of SBP to be a leverage point – where a relatively small action creates a very large result in the system. In summary, the intent of ACGME to change the curriculum in the second year of residency with the projected effect of correcting the deficiencies in safety, performance and expenditure in the U.S. healthcare system and to thus set it on a track to sustainability would define a system leverage point - if it were to have the desired effect.

5.4.5 The Normative Scenario - Adjusting the Mental Model: Systems Thinking and the Medical Education Curricula

While a systematic approach to improving individual patient care is valuable, the impetus leading to the ACGME Outcome Project was a need for systemic improvements. In that light, many improvements could be made to the resident curriculum to promote systems thinking on the part of medical practitioners. In the context of SBP, medical schools and teaching hospitals should first educate their faculty in the skills of systems analysis and then incorporate systems thinking models into their curricula through specifically designed case studies. Students should be taught to understand systems at an abstract level, in order to analyze their own healthcare systems, and participate in quality and patient safety activities. Plan, do, study, act (PDSA) [iterate] is one example of bringing systems thinking into medical care at the patient level [141]. Another example of systems thinking improving care at the patient level can be found in the article on dengue diagosis by Tanner, et al. referenced for Fig. 20. The authors do an excellent job of statistical analysis and error analysis – all in line with a correct design of experiments approach that is a part of systems thinking.

Applying a systemic approach, the limitations of teaching systems thinking at the medical resident level become apparent. After eleven years of decision tree, checklist processing, SBP asks the resident to become fluent in an entirely different language of systems thinking. Not only are the cognitive prerequisites lacking, so is the capacity of a resident within the medical establishment to employ them effectively. Residents, while the future of the medical establishment, lack any immediate power to correct imbalances or make improvements derived through systems analysis. It may be several years before a resident reaches a stage in his career where he can effectively influence decision makers.

As stated before, Porter and Teisberg recommend that change in the healthcare system must start with the doctors – not the insurance companies, government or politicians. They goes on to conclude that wellness, rather than cost, should be the objective of a systems approach to healthcare. A healthy populace will drive down healthcare costs. This conclusion would indicate that to affect the needed change, doctors will require new skills to understand the scope of the system, to analyze the goals and metrics of the system. They must be able to take a systems approach to a U.S. healthcare system that includes 313 million stakeholders [129].

The medical curriculum outlined in the previous section evolved over the decades to engrain a pattern of thought into the minds of doctors. If we consider this thought pattern to be the language of diagnostic thought, let us consider the language of systems thinking: DST. Undergraduate systems engineers are taught a basic fluency in systems during their second year. Practical instruction in out-scoping, goal development, boundary definition, metrics and analysis are coupled with case-based study. At this same level, pre-med students are learning the cookbook procedures of inorganic chemistry and basic biology as they acquire the basic vocabulary of diagnosis. This should also be the level where pre-med students receive their first exposure to the language of systems. Dual-fluency would not be the goal of such an educational system. Instead, undergraduate pre-med students should acquire the basic vocabulary and syntax of systems thinking as they embark on their medical education.

During the four years of medical school, the curriculum should introduce relevant case studies for systems analysis. These cases should vary from individual patient and inter-specialty situations to cases involving entire hospitals and regional medical systems. In other words, the case studies should involve systems of increasing complexity and larger system boundaries. Subsequently, during residency, the concept of systems-based practice can include a more comprehensive systems-thinking approach to the chosen specialty as a part of the much larger health care system. At the resident level, case study based instruction should continue with inter-specialty teams in an effort to weaken the existing silos in the medical education establishment. Many teaching hospitals direct residents to complete master's degrees in relevant fields such as public health and healthcare management. These respective curricula should be modified to include classes in case-based systems analysis and, where available, graduate work in systems engineering should also be encouraged.

The recommended revised Systems-based Practice criteria would be:

Residents must demonstrate an awareness of and responsiveness to the larger context and system of health care, as well as the ability to call effectively on other resources in the system to provide optimal health care. Residents are expected to:

Take a systemic approach in all health care delivery settings and systems, including their clinical specialty.

Ensure that patient care is coordinated and integrated within their specialty and the health care system.

In patient and/or population-based care as appropriate: establish goals of patient wellness, risk reduction and cost effectiveness as well as clearly defined metrics and analytical methods to evaluate performance.

Advocate for quality patient care and optimal patient care systems.

Work in inter-professional teams to enhance patient safety and improve patient care quality through systems analysis methodology.

Participate in identifying system errors and implementing potential systems solutions through correct application of systems thinking and statistical analysis.

A recurring point in the literature is the lack of a set of effective evaluation criteria for SBP as part of resident training [148]. Through the curriculum described above, case studies are presented before peers and mentors, subject to questions and comments. The ability of the presenting individual or team to effectively present and discuss the case study is subjectively graded. Critical points within the case such as key take-aways can be quantitatively graded and progress tracked as the cases become more complex. Finally, local board examinations should include case analysis as part of the licensing procedure.

This is admittedly an expansion of the already intensive medical curricula, but note that it is an expansion originally proposed and implemented by the ACGME and the ABMS in 1999. In light of the nature and severity of the healthcare problem in the United States outlined in the first section, these changes cannot be implemented too soon.

5.5 Iterate, Outscope

The next step is to out-scope the system boundaries from medical schools to the medical community at large. Continuing with the theme established by Porter that the doctors (and other medical professionals such as nurses) must be the decision makers that compel change in the system; combined with the original concept of systems-based practice: doctors must first become proficient in systems thinking. State licensing boards require continuing competency credits – ungraded proof that courses and seminars were attended to maintain licensing as medical doctor or nurse practitioner[14]. The mechanism exists, therefore, to provide systems thinking instruction

[14] Licensing requirements and boards vary widely by state. In Virginia, up to 30 of the 60 CCC hours required of a doctor each year may be "self-study, attending professionally related meetings, research and writing for a journal, learning a new procedure, sitting with the hospital ethics panel, etc." [149]. The Virginia medical licensing board is appointed by the governor and currently presided over by a chiropractor (Valerie Lowe Hoffman, DC) [150].

to each practicing medical professional each year through conference tutorials, conference papers and articles published by the faculties at teaching hospitals. Medical practitioners must develop at least moderate fluency in systems thinking. They must become proficient in analyzing and improving the complex adaptive systems in which they work.

5.5.1 Indices of Performance – Trade Study of Healthcare Data by State

In Section 5.2, we looked at healthcare system metrics internationally. Now, in the interest of systemically identifying best practices, we consider healthcare metrics intra-nationally. We now consider the multiplicity of healthcare systems within the United States to identify those areas where best practices have led to optimal wellness results. The Agency for Healthcare Research and Quality (AHRQ) of the Department of Health and Human Services analyzed empirical data that included more than 250 healthcare quality variables from 45 databases [151],[152],[153]. The United Health Foundation independently compiled the NHQDR data along with CDC, Census Bureau and other data to rank by state based on the metrics of: community & environment, behaviors, clinical care, public & health policy and health outcomes. The resulting rank ordering of the 50 states is as follows [154]:

Table II: Rank Order of States by Healthcare (United Health Foundation)

Rank	State	Rank	State	Rank	State
1	Vermont	18	New York	35	Alaska
2	New Hampshire	19	Idaho	36	Ohio
3	Connecticut	20	Virginia	37	Georgia
4	Hawaii	21	Wyoming	38	Indiana
5	Massachusetts	22	Maryland	39	Tennessee
6	Minnesota	23	South Dakota	40	Missouri
7	Utah	24	California	41	West Virginia
8	Maine	25	Montana	42	Nevada
9	Colorado	26	Kansas	43	Kentucky
10	Rhode Island	26	Pennsylvania	44	Texas
11	New Jersey	28	Illinois	45	South Carolina
12	North Dakota	29	Arizona	46	Alabama
13	Wisconsin	30	Delaware	47	Arkansas
14	Oregon	30	Michigan	48	Oklahoma
15	Washington	32	North Carolina	49	Louisiana
16	Nebraska	33	Florida	50	Mississippi
17	Iowa	34	New Mexico		

Table III: Comparison of the Highest and Lowest Ranked States (UHF)

Metric	Miss.	Vt.	Best
Behaviors			
Smoking (Percent of adult population)	22.9	15.4	9.1
Binge Drinking (Percent of adult population)	10	17.1	6.7
Obesity (Percent of adult population)	34.5	23.9	21.4
High School Graduation (Percent of incoming ninth graders)	63.9	89.3	89.6
Community & Environment			
Violent Crime (Offenses per 100,000 population)	270	130	122
Occupational Fatalities (Deaths per 100,000 workers)	7.2	4.3	2.5
Infectious Disease (Cases per 100,000 population)	10.5	3.1	2.3
Children in Poverty (Percent of persons under age 18)	33.7	13.5	6.2
Air Pollution (Micrograms of fine particles per cubic meter)	10.3	7.1	5.2
Public & Health Policies			
Lack of Health Insurance (Percent without health insurance)	19.2	9.5	5
Public Health Funding (Dollars per person)	$73	$154	$244
Immunization Coverage (Percent of children ages 19 to 35	92.7	91.2	96
Clinical Care			
Early Prenatal Care (Percent with visit during first trimester)	82.30	82.6	82.6
Primary Care Physicians (Number per 100,000 population)	82.2	170.3	191.9
Preventable Hospitalizations (per 1,000 Medicare enrollees)	95	54.7	25.6
Outcomes			
Diabetes (Percent of adult population)	12.4	6.8	5.3
Poor Mental Health Days (Days in previous 30 days)	3.9	3.3	2.3
Poor Physical Health Days (Days in previous 30 days)	4.3	3.2	2.6
Geographic Disparity (Relative standard deviation)	13.5	4.8	4.8
Infant Mortality (Deaths per 1,000 live births)	10	4.8	4.7
Cardiovascular Deaths (Deaths per 100,000 population)	366.4	235.1	197.2
Cancer Deaths (Deaths per 100,000 population)	218.3	190.6	137.4
Premature Death (Years lost per 100,000 population)	10,976	5,862	5481

[See Table IV in the Appendix for a description of the metrics above.]

Within the boundaries of the United States the study finds two healthcare systems with strikingly different levels of wellness. The lowest ranking state has double the infant mortality rate and 187% the premature death rate of the highest-ranking state. It would be overly simplistic to recommend that we simply take the best practices of Vermont and apply them to Mississippi. While the cultural differences are easy to discern, the political differences that come from the cultural differences are even starker. Note that in Vermont the per-capita public health funding is three times greater than Mississippi and the percentage without insurance in Mississippi is nearly four times that of Vermont. Behaviors, environment and public policies all show a stark difference in attitudes towards health culminating in a rate of preventable hospitalizations in Mississippi nearly four times that of Vermont.

5.6 Case Study Recommendations

Based on an application of the Dimensions of Systems Thinking, Systems-based Practice includes some aspects of sound systems thinking and should be revisited and revised as part of a larger effort to guide the U.S. healthcare system toward sustainability. SBP lacks concisely defined objectives within the system boundaries of specialist resident training and also lacks indices of performance based upon realistic assessments. Recommendations include new system objectives, sub-objectives and the derivation of performance indices from case study exercises and assessments used in systems engineering education. Assessments would be a part of the training and culminate in a specific section of the medical board licensing examinations. The study finds and recommends enhancements to the medical specialist licensing board examination system that would include machine learning and multi-media capability as a medium to assess systems thinking capability. The axiological aspect of creating a curriculum of systemic thinking within a system of systematic thinking will be difficult and should not be underestimated. The three distinct systems within which medical education exists and the apprenticeship nature of residency training will have to be addressed through common objectives, new curricula and training the trainers in systems analysis.

An editorial published in 2011 by medical students at Penn State indicates an interest systems thinking: "*Whether systems thinking is a possible strategy to integrate content into traditional curricula or simply a strategy to better understand a complex system, its use is an intriguing prospect.*" However, a summary review of the published curricula (2012) from seven leading medical schools and the Mayo Clinic found no clear reference to courses or requirements in systems thinking at six of them, thirteen years after the publication of the ACGME core competencies. [UCSF clearly addressed SBP in their curriculum and Mayo published their SBP curriculum in 2006 and has a department of Healthcare Systems Engineering] [155]–[162].

If the system objective is to make doctors adept at both systematic diagnosis and systemic thinking, we recommend coursework in systems analysis that would become part of the medical curriculum beginning at the undergraduate, pre-med level, then revisited over the course of medical school and residency requiring common objectives at all three levels of medical education. Fluency in the systemic approach requires regular practice. Systems thinking exercises and case studies would be integrated throughout the curriculum with the participation of medical and non-medical systems analysis experts. This would necessarily require the expansion of faculty capability to include specialists in systems analysis. A few residency programs require a supplemental Masters degree program in an adjunct field such as Public

Health Management. The MPH curriculum should be modified to include full courses in systems analysis with the goal of bringing systems thinking to aspects of the healthcare system beyond specialist medicine.

The SBP approach on the part of ACGME to make medical specialists into systems thinkers marks a milestone in the progress of applying systems thinking to the U.S. Healthcare system. Since SBP exists within the boundaries of the resident training system, this study has presented objectives that are achievable within those boundaries but it recommends that the boundaries of systems thinking education in the healthcare system be expanded. With systemic problems in U.S. healthcare related to safety, cost and delivery of quality care, much more systems analysis needs to be done with emphasis on policy and oversight. On-going systems analysis will need to include the critical axiological factors of politics and financial interests in this $2.7 trillion industry of which we are all stakeholders.

5.6.1 Education

Medical professionals at all levels must become proficient in systemic thinking. The ACGME guidelines for achieving this in medical school are deficient and should be replaced with a set of curricula at the undergraduate, graduate and resident level that truly teaches the language of systems analysis through case studies and reviews. Practicing medical professionals must receive systems analysis training through their continuing competency credits or face loss of licensing.

The general population must be educated in the tenets of wellness and the effects of their choices. UHF data show stark differences in wellness across the nation and an apparent correlation with behavioral factors including smoking and obesity. Environmental and policy considerations can also be linked to education in wellness.

Advertising for prescription healthcare products and devices should be banned from all media. Tens of billions of dollars are spent annually to influence the zero-sum game with no practical benefit to the wellness of the population. Laymen are not equipped with the professional knowledge to properly process such advertisements so they can only drive product misuse. This poses no more of an infringement of First Amendment rights than did the ban on television cigarette advertisements in the 1960s. Some of the tens of billions of dollars not spent on advertising should be used to sponsor conferences and educational forums where, in addition to product promotion, systems thinking courses can be presented.

5.6.2 Best practices

With such a disparity of outcomes within the United States, states with poor wellness metrics should transition to the practices of the states with superior results. Efforts over the last 50 years to reduce the effects of income disparity on wellness should continue and include more health education for those in poverty at the earliest possible levels. This may seem a naïve recommendation given the political climate and animosity on the part of many towards centralized health care reform of any sort. Yet, the inefficiency and expense of 50+ healthcare systems within our national borders will be hard to overcome without eliminating the multiplicity and replacing it with independent, centralized direction.

5.6.3 Outside the Box – A Systemic Sea Change in U.S. Healthcare

This study has considered the descriptive scenario where the true identity of the key decision makers has become an elusive quarry thanks to the obfuscation designed into the system. We now consider an alternative to improve the system where the identity of the key decision makers is not only clarified; the key decision makers are removed from influence in a way that has historically proven effective.

When Franklin Pierce was president and vetoed the Bill for the Benefit of the Indigent Insane, the United States had no centralized monetary policy. This was known as the Free Bank Era where any bank, town or state might find it in their best interest to issue their own currency. Many had seen the centralized banking system as suspect; so when the charter of the Second National Bank expired in 1836, Andrew Jackson did not renew it. The resulting financial system led to most banks securing their currencies through state government bonds. When weaker states devalued their bonds the resulting instability ruined the private banks. When the Union needed currency backed by US securities to pursue the Civil War, the National Banking Act created a uniform currency, but not a central bank. Many financial crises, panics and attempts at reform later, two Virginians, Carter Glass and H. Parker Willis labored through the year of 1912 and presented fellow Virginian President Wilson with what would become the Federal Reserve Act in December of 1913. The Banking Acts of 1933 and 1935 finalized what we now know as the Federal Reserve System, an independent public/private entity whose monetary policy does not require the approval of the executive or legislative branches of government. The Fed's mission can be summarized by the following mandate for monetary policy from the Federal Reserve Act:

- Maximum employment
- Stable prices
- Moderate long-term interest rates[163]

The systemic sea change to U.S. healthcare is the following recommendation: the creation of a Federal Reserve System for healthcare – a Federal Healthcare System. Directed by an appointed board of governors and the directors of twelve regional centers, U.S. healthcare would be de-politicized and centralized much the same way monetary control was centralized by the Federal Reserve Act. 50+ healthcare systems would be replaced with twelve or fewer regional Health Fed bureaus. Regional sensibilities and approaches to healthcare would thus be preserved, but redundancy reduced and best practices reinforced. State and territorial boards would be eliminated and replaced by licensing and accreditation through the bureaus – standardizing the process and reducing costs. All pharmaceutical and medical device advertising and lobbying would be eliminated. The Health Fed would work alongside HHS to control the 20% of our GDP that healthcare represents, just as the Fed and the Treasury Department work together for fiscal stability. The seven-member Health Fed board of Governors would be appointed by the President and confirmed by the Senate, serving 14-year terms with the chair and vice-chair selected from the board and serving four-year terms. Bureau presidents would be appointed by the board and serve five year terms. Elected officials as well as current and past members of the administration would be exempt from serving on the Health Fed board. Without the income from government securities enjoyed by the Fed, Health Fed would be financed through fees for licensing and accreditation. Constitutionality of the Health Fed has judicial precedence in the many Supreme Court challenges to the Federal Reserve since its inception.

This recommendation finds its foundation in the many similarities between the history of the U.S. healthcare system and that of the U.S. monetary system. Each has a record of patches, fixes and upgrades to control and improve a patchwork of 50+ independent systems. Both pit advocates of a liberal, free-market system without regulation against those who support centralized control – and all opinions in-between. This recommendation does not prescribe a single-payer system any more than the Federal Reserve Act nationalized banking. This recommendation builds upon the insurance mandate and other aspects of the Affordable Care Act.

The Health Fed would create a decision mechanism to apply systems thinking to the healthcare systems without political or industry influence. It would remove crucial healthcare policy decisions from the political system and place them in the realm of subject-matter experts and systems thinkers, adapting the duties of the Federal Reserve System into the Federal Healthcare System as follows:

- Maximum wellness
- Sustainable care and coverage
- Moderate health insurance rates

The Health Fed would be in a position to negotiate economies of scale from manufacturers without the influence of lobbyists, thus reducing costs. The Health Fed would, along with HHS, represent the U.S. healthcare system at the WHO as well as international forums designed to improve wellness and reduce costs on an international level. It would function along side HHS just as the Federal Reserve and the Treasury Department cooperate in the implementation of policy. The Health Fed would be able to take long-term views without interference from re-election campaigns, lobbyists or PACs. This isolation from politics would allow for a sustainable approach to healthcare optimization, just as the Fed looks at interest rates long-term.

It took 150 years of difficult political growth in monetary policy to arrive at the Federal Reserve System. There can be no illusions that the birth of a Health Fed will be any less difficult. This is not a politically naïve scenario, but a systemically derived normative scenario in which the healthcare system in the United States would be optimized for sustainable population wellness and lower net costs.

5.7 Case Study Appendix

Table IV: Description of Metrics used in State Healthcare Rankings

BEHAVIORS	
Smoking	Percentage of population over age 18 that smokes on a regular basis.
Binge Drinking	Percentage of population over age 18 that drank excessively in the last 30 days.
Obesity	Percentage of the population estimated to be obese, with a body mass index (BMI) of 30.0 or higher.
High School Graduation	Percentage of incoming ninth graders who graduate in four years from a high school with a regular degree.
COMMUNITY AND ENVIRONMENT	
Violent Crime	The number of murders, rapes, robberies and aggravated assaults per 100,000 population.
Occupational Fatalities	Number of fatalities from occupational injuries per 100,000 workers.
Infectious Disease	Number of reported measles, pertussis, syphilis and hepatitis A cases per 100,000 population.
Children in Poverty	The percentage of persons under age 18 who live in households at or below the poverty threshold.
Air Pollution	The average exposure of the general public to particulate matter of 2.5 microns or less in size (PM2.5).
PUBLIC AND HEALTH POLICIES	
Lack of Health Insurance	Percentage of the population that does not have health insurance privately ,through their employer or the
Public Health Funding	State funding dedicated to public health as well as federal funding directed to states by the CDC and the
Immunization Coverage	The average percentage of children ages 19 to 35 months who have received these individual vaccinations:
CLINICAL CARE	
Early Prenatal Care	Percentage of pregnant women receiving prenatal care during the first trimester.
Primary Care Physicians	Number of primary care physicians (including general practice, family practice, OB-GYN, pediatrics and internal medicine) per 100,000 population.
Preventable Hospitalizations	Discharge rate among the Medicare population for diagnoses that are amenable to non-hospital based care.
OUTCOMES	
Diabetes	Percentage of adults who have been told by a health professional that they had diabetes (does not include pre-diabetes or diabetes during pregnancy).
Poor Mental Health Days	Number of days in the previous 30 days when a person indicates their activities are limited due to mental health difficulties.
Poor Physical Health Days	Number of days in the previous 30 days when a person indicates their activities are limited due to physical health difficulties.
Geographic Disparity	The variation in overall mortality rates among the counties within a state.
Infant Mortality	Number of infant deaths (before age 1) per 1,000 live births.
Cardiovascular Deaths	Number of deaths due to all cardiovascular diseases, including heart disease and strokes, per 100,000 population.
Cancer Deaths	Number of deaths due to all causes of cancer per 100,000 population.
Premature Death	Number of years of potential life lost prior to age 75 per 100,000 population.

Chapter 6: Case Study: Science Policy and the Dimensions of Systems Thinking

6.1 Chapter Summary and Introduction

During the author's tenure as an AAAS Science and technology Policy Fellow, an opportunity arose to try-out the Dimensions of Systems Thinking at a very high level of policy decision-making. At a meeting of the President's Council of Advisors on Science and Technology (PCAAST), a senior staff member of the Office of Science and Technology Policy (OSTP) approached the author. He explained to me that within OSTP was an office dedicated to security and technology. That office was looking for ways to optimize the use of several hundred billion dollars in national laboratory S&T facilities and infrastructure and could systems thinking help.

Knowing the time constraints of decision makers at that level, the resulting approach was kept very brief and concise. The case study that follows is an expansion of that presentation.

OSTP saw the benefits in the systems approach that came from the DST and adopted it, along with inviting the author to participate in relevant working groups as a consultant.

6.2 Science Policy in the Age of Shrinking Budgets

In advance of meeting with the OSTP staff, Several internal documents were received explaining the work that they were doing. Looking at the documentation with systems eyes, it was evident that the issues were all problem driven. For example, communications are bad followed by ways to fix communications; recruitment is bad, infrastructure is bad, etc. It seemed that the work was motivated by complaints. The foundations of the Dimensions of Systems

Thinking direct an objective-based approach, so that was at the top of the recommendations. The actual objectives of the national laboratories are largely classified. So, a fictitious case study was developed to present showing the applicability of the DST approach to policy generation at the White House level. It had to do with the then very tense situation in Syria early in that country's civil war. It would present the objectives-driven approach of the DST quickly and in an easy to absorb context.

6.3 The House of Policy

The study started with a normative scenario that broke-down into a back-of-the-envelope list of policy objectives:

Regional stability
Israel secure
Turkey secure
Lebanon stable
WMD/chemical weapons secure
Influence of Al Qaeda (minimize)
Displaced Refugees Secure
Ex Patriate Refugee Right of Return
End of Assad Rule of Syria
Peaceful transition of Syrian gov't
Influence of Iran (minimize)
Human rights in Syria
Women's rights in Syria
Minority religious rights in Syria
New Syrian gov't allied w/ US
New Syrian gov't secular

These objectives would be ranked from 0 low to 5 high in terms of importance to the U.S. The system boundaries are the system boundaries of U.S. foreign policy. The scope of the analysis is everything unclassified available in a short period for the purpose of a case study. The type of the system is dynamic and stochastic in a context where other countries in the region had been experiencing states of flux known as the Arab Spring. The current state of the system is largely contained to Syria and surrounding countries with the potential to expand. The life cycle of the system in historic terms of other countries in the region indicates that Syria may be due for an internally motivated regime change. Metrics include displaced persons, casualties, quantities of chemical weapons and other armaments and numbers of fighters in the various factions and armies.

By now, the Dimensions of Systems Thinking mental model had led to a process of adapting the Japanese manufacturing design technique from the 1960s known in the West as the House of Quality. HoP was very useful in putting engineering and design objectives in the context of capability, the consumer, the marketplace and the competition – all in an easy-to-read graphic. That ease of use and facility for recognizing system leverage points and system interactions made the HoP very suitable as a Dimensions of Systems Thinking approach at this level of decision making. Thus was born the House of Policy.

The next step was to develop a list of policy options –alternatives - again, these are fictitious, but common sense driven to relay the concept to the decision makers.

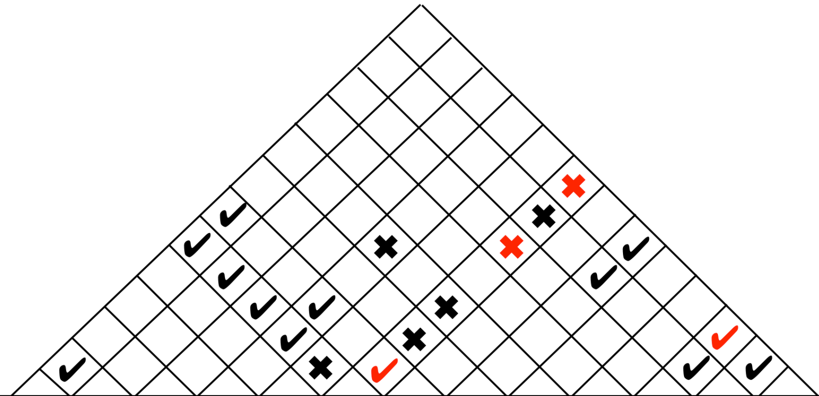
Economic Sanctions	Travel restrictions	Whidrawal of assets	Humanitarian Assistance	Support shadow gov't	Negotiation w/ Assad	Asylum for Assad regime	Drone strikes	Weapons to rebels	Intelligence on Assad Regime	U.S. or Allied Air strikes	Special operations	Invasion

Then, a simple 5 level key for describing the ranking of each option in terms of each objective – from the DST: develop alternatives, evaluate and rank the alternatives. Bring these elements together and populate the matrix. Add some numerical scoring where strong positive is 1, strong negative is -1, blank is neutral and equal zero, but a question mark adds some uncertainty with a range of +/- 0.5

✔	Strong Positive
✔	Positive
	Neutral
✖	Negative
✖	Strong Negative
?	Unknown

Policy Objectives / Policy Options	Importance to U.S. (1-5)	Economic Sanctions	Travel restrictions	Whidrawal of assets	Humanitarian Assistance	Support shadow gov't	Negotiation w/ Assad	Asylum for Assad regime	Drone strikes	Weapons to rebels	Intelligence on Assad Regime	U.S. or Allied Air strikes	Special operations	Invasion
	BC	0.5	1	1	3.5	7	2	2.5	1	-1.5	0.5	1	1	-2
	WC	0.5	1	1	3.5	7	2	2.5	1	-5.5	0.5	1	1	-6
Regional stability	5				✔		✔	✔		✖				✖
Israel secure	5									✖				✖
Turkey secure	4				✔					✖				✖
Lebanon stable	4									✖				✖
WMD/chemical weapons secure	5					✔				✖	✔			✔
Influence of Al Qaeda (minimize)	5					✔			✔	?		✔	✔	✖
Displaced Refugees Secure	4				✔	✔	✖			✖				
Ex Patriate Refugee Right of Return	4				✔	✔	✔							
End of Assad Rule of Syria	4	✔	✔	✔	✔		✔	✔						✔
Peaceful transition of Syrian gov't	4	✔	✔	✔	✔	✔	✔	✔		✖				✖
Influence of Iran (minimize)	3					✔			✔			✔	✔	✖
Human rights in Syria	3					✔				?				✖
Women's rights in Syria	3					✔				?				?
Minority religious rights in Syria	2	✖				✔				?				?
New Syrian gov't allied w/ US	2					✔								?
New Syrian gov't secular	2					✔	✔							?

Next, we consider the DST dimension of interactions. For example, invasion is probably going to have a negative effect on negotiation but economic sanctions may have a positive effect on negotiations – all hypothetical to demonstrate the approach to the stakeholders. This populates a diagonal lattice of interactions that looks like the roof of a house, ergo the name.



	BC	0.5	1	1	3.5	7	2	2.5	1	-1.5	0.5	1	1	-2
	WC	0.5	1	1	3.5	7	2	2.5	1	-5.5	0.5	1	1	-6
Policy Options / **Policy Objectives**	Importance to U.S. (1-5)	Economic Sanctions	Travel restrictions	Whidrawal of assets	Humanitarian Assistance	Support shadow gov't	Negotiation w/ Assad	Asylum for Assad regime	Drone strikes	Weapons to rebels	Intelligence on Assad Regime	U.S. or Allied Air strikes	Special operations	Invasion
Regional stability	5				✔		✔	✔		✖				✖
Israel secure	5									✖				✖
Turkey secure	4				✔					✖				✖
Lebanon stable	4									✖				✖
WMD/chemical weapons secure	5					✔				✖	✔			✔
Influence of Al Qaeda (minimize)	5					✔			✔	?		✔	✔	✖
Displaced Refugees Secure	4				✔	✔	✖			✖				
Ex Patriate Refugee Right of Return	4				✔	✔	✔							
End of Assad Rule of Syria	4	✔	✔	✔	✔		✔	✔						✔
Peaceful transition of Syrian gov't	4	✔	✔	✔	✔	✔	✔	✔		✖				✖
Influence of Iran (minimize)	3					✔			✔			✔	✔	✖
Human rights in Syria	3					✔				?				✖
Women's rights in Syria	3					✔				?				?
Minority religious rights in Syria	2	✖				✔				?				?
New Syrian gov't allied w/ US	2					✔								?
New Syrian gov't secular	2					✔	✔							?

Next, consider the principle stakeholders. They have interests and objectives in the system, but they also have varying capabilities to affect the objectives. This adds matrices of interests and capabilities resembling the garage and basement of the house.

United States
Saudi Arabia
Israel
NATO
EU
Syria (Assad)
Russia
China
Iran
Al Qaeda

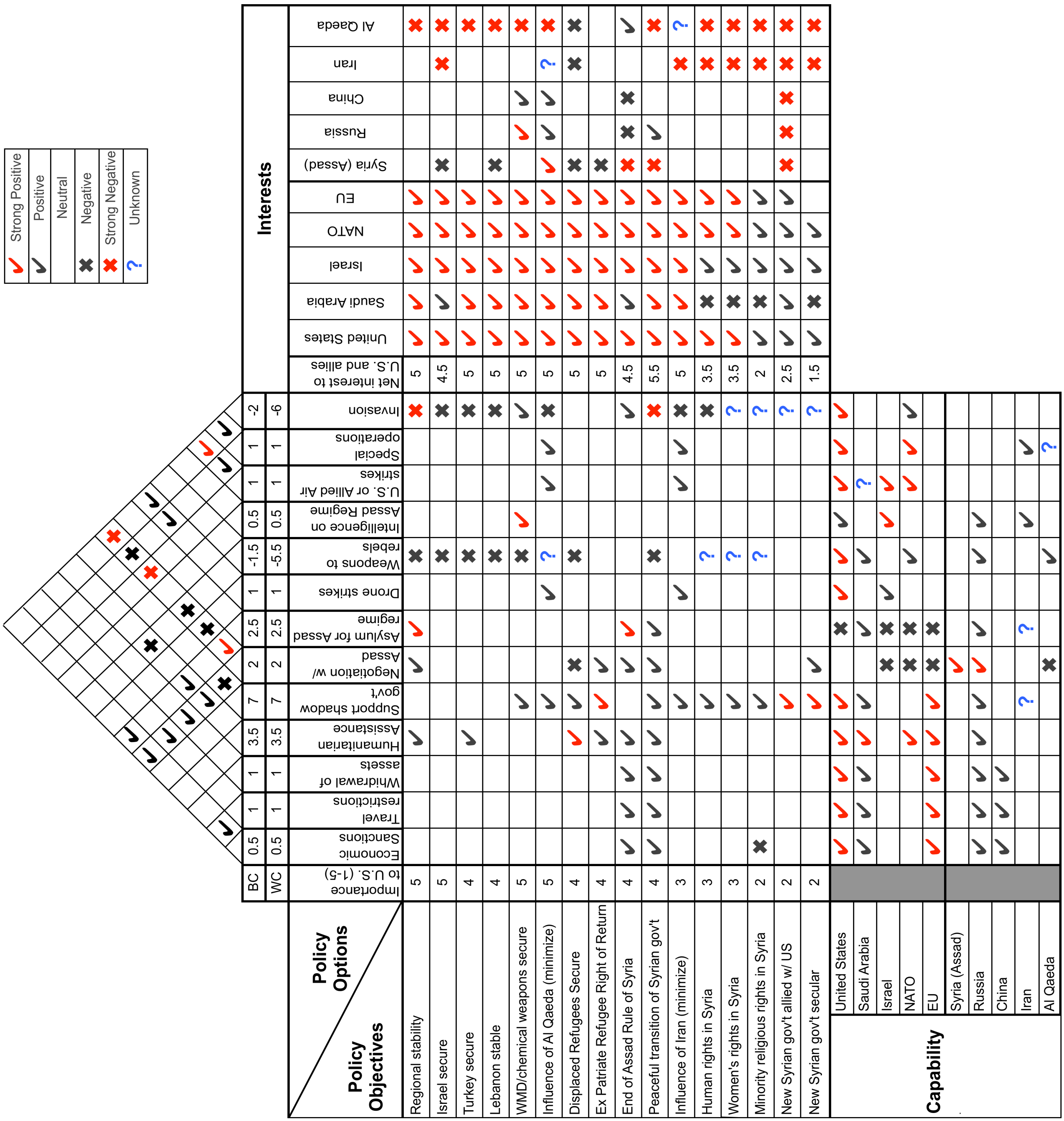


Fig. 21. The House of Policy

Thus was born the House of Policy. There are certain factors of note in this back-of –the-envelope (BOE) exercise. Consider the objective of WMD/Chemical weapons Secure – which became a key part of US policy. Notice that the BOE hypothesis was that Israel had key intelligence on WMD, but Russia had a strong positive interest in that objective. Russia also had a strong positive capability for negotiation with the Assad regime.

The purpose of the HoP as a manifestation of the Dimensions of Systems Thinking is to help stakeholders visualize the system as well as their own mental models on policy. It facilitates iterations of the analysis and helps to visualize interactions leverage points as the one described with Russia and Israel in the WMD objective. At the time of this dissertation, the HoP might make an interesting tool for use regarding U.S. policy regarding Crimea.

6.4 Outcomes

Of course realistically, a part of the mental model of the real stakeholders in foreign policy is that they spend good money on this kind of decision support. They are not pre-disposed to accept free advice from a science policy fellow. After the first meeting at the White House, there came an invitation to give the same presentation at two offices in the State Department that deal with threat analysis. While these presentations went well, there are no false pretenses that this will become a part of any foreign policy initiative.

OSTP, however, has virtually no budget of their own, so they were happy to adopt the Dimensions of Systems Thinking approach in science policy. The author became a member of a working group under Pat Falcone, associate director of OSTP for National Security and International Affairs. Thus far, the group has produced a series of recommendations on optimizing use of national laboratory facilities. The author is not at liberty to publish any of the details beyond the snapshot of an HoP matrix below.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Mission Clarity and Research Strategy			**Agency Oversight**				**Regulatory Standards**				**Funding Mechanisms**		**Collaboration**	
	Policy Options:	Maintain or increase research independence (Section 219 for DOD and LDRD for DOE).	Set interagency mission strategy for all Federal laboratories through interagency action	Lengthen the tenure of laboratory directors to allow them time to implement strategic vision	Increase use of existing mechanisms or create new mechanisms for staff to rotate between laboratory and headquarters	Modify staffing practices or policy to retain long-term personnel at headquarters	Utilize advisory committees of internal and external personnel to provide institutional memory	Facilitate additional technical training for headquarters staff or increase rotations	Implement oversight standards that are in line with other laboratory systems, such as industry standards	Develop an adaptive oversight mechanism, implement increased oversight on site-by-site basis as needed relax oversight on historically high performing laboratories	Establish policy review before implementing new oversight policies to understand whether system level or site-specific policy is required	Develop policy for laboratories to provide regular feedback to site offices and headquarters level to make those offices accountable as well	Formalize a research portfolio approach with a strategic WFO plan to sustain core capabilities and reduce barriers for competitive WFO	Revise budgeting process to reduce categories of funding allocated, without decreasing overall funding levels	Increase partnerships with universities and industry rotations in Federal laboratories and the reverse	Increase the use of cooperative R&D agreements, material transfer agreements, facility use agreements, and WFO agreements
Objectives: Top Level	**Governance**															
Lead and manage organizations to effectively and efficiently address needs and requirements for current and future technical capabilities for U.S. national security purposes that achieve:	Mission Effectiveness	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Efficiency	0	1	1	0	1	1	0	1	1	1	1	1	1	0	1
	Quality/Innovation	2	0	0	1	0	1	1	1	1	0	0	1	1	2	2
	Communication	0	1	1	2	1	1	1	0	0	1	2	0	-1	1	1
	Adaptability/agility	1	-1	0	1	0	1	1	1	1	1	1	1	2	2	1
	Security	0	1	0	0	1	0	0	0	0	0	0	1	0	-1	-1
Feasibility	Agency Funders	0	1	0	1	0	1	0	-1	-1	0	0	0	-1	0	1
	FFRDC labs	2	0	1	1	1	1	1	1	1	1	1	1	1	2	1
	UARC labs	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
	GOGO labs	2	1	1	1	1	1	1	0	0	1	1	1	1	1	1
	Private Performers	1	0	0	1	1	1	1	1	0	0	0	1	0	1	1

2	Strong Positive
1	Positive
0	Neutral
-1	Negative
-2	Strong Negative

Fig. 22. OSTP House of Policy

6.5 Case Study Conclusions

Systems thinking is often perceived as the prevue of consultants that are brought in to help resolve issues. In this case, the Dimensions of Systems Thinking were proven very useful in outscoping the available tools to create something new for exactly that scenario. Consideration of the mental models and axiological components in the system proved very useful, as did the careful development of recommendations to suit the stakeholders.

The House of Policy provides the key decision making stakeholders with an at-a-glance application of the scope of the analysis where the system boundaries of, in this case foreign policy may expand into such areas as politics. Where, as in this case, the type of system is complex, adaptive and dynamic, the state of the system can be succinctly represented and continuously updated in the rows and columns of the HoP. Metrics can be represented in the HoP such as the expected cost of a policy option, the time an option could require to be exercised and the expected time an option may require to have an effect. Axiological components are a key part of the formation of the HoP. Good systems thinking will include as many as possible in the matrix, though the mental models of the stakeholders may prevent that. Observer effects can be mollified by getting input for the HoP from as many subject matter experts as possible.

Normative scenarios on the part of the key stakeholders for a systems thinking approach with the HoP may be blue-sky perspectives such as world peace, economic prosperity and re-election. Objectives must, however, be obtainable, and measurable – though sometimes subjectively so. In the HoP example, different countries may have different definitions of "secure".

Indices of performance for the HoP derive from the expert advice of the subject matter experts that provide the input to populate the matrix. Capabilities and interest, for example, require intelligent perspectives and frank assessments.

HoP visually develops a comparison of alternatives in real time. Patterns, interactions and leverage points in complex, multi-objective, multi-alternative systems can be represented. In the version developed for the OSTP policy options, color coded cells turned out to facilitate the detection of trends and leverage points in the objectives and alternatives. Moving forward, this may be a better approach in many applications. Flexibility of the tool allows easy changes to accommodate outscoping, iterations and feedback from recommendations.

This fast-paced real-world study proved the application of all twenty dimensions and the usefulness of the concept of having a framework on which to develop systems thinking.

Chapter 7: An Analytic Approach to the Dimensions of Systems Thinking

7.1 Chapter Summary and Introduction

Systems thinking has been around for a very long time, yet the field lacks cohesive foundation in language and assessment. If language is the manifestation of thought per Chomsky, then systems thinking has a specific underlying language. In Chapter 3, this early foundation in language was developed based upon the relationship between critical thought and systems in the definition of systems thinking. Failure to have and employ fluently a unified framework of linguistic concepts may lead to the omission of critical aspects of a systems analysis. Fluency in a foundational language of systems concepts means the ability to consider all of the terms available and apply them correctly.

The objective of this chapter is to study the concept of analytically identifying the level of systems thinking in a corpus of documents. In doing so, this work considers the semantic characteristics of term frequency and inverse document frequency – tf-idf – cosine similarity and Naïve Bayes classifiers such as Rocchio classifiers and quadratic discriminant classification. If the capability to analytically determine the level of systems thinking in unread text through the language used can be demonstrated, it reinforces the hypothesis of the prior chapters and establishes a foundation for the assessment of all systems applications.

The results of this work show that capability. The approach establishes correlation and allows us to analytically assess the systems thinking quality of a corpus of unread research studies on life cycle assessment. Furthermore, it shows that analytic relations between the specific Dimensions of Systems Thinking and a document can be established, which would be useful for improving the quality of systems approaches.

Recall the DST taxonomy that elucidates the twenty Dimensions of Systems Thinking from the prior chapters. Any systems approach can be expressed in terms of these twenty dimensions and a good approach will consider all of the dimensions.

1. Descriptive scenario
    a. System boundaries
    b. System stakeholders
    c. Scope of the analysis
    d. Type of system
        i. State of system
        ii. Life cycle of system
    e. Metrics
    f. Axiological components
    g. Observer effects
2. Normative scenario
    a. Objectives
3. Indices of performance
4. Develop alternatives
    a. Outscope
    b. Evaluate & rank alternatives
        i. Iterate analysis
        ii. Interactions
    c. Leverage points
5. Recommendations

7.2 Motivation: The Need for an Analytic Assessment of a Systems Approach

While the premise of DST is that fluency in the foundational dimensions listed above will result in *good* systems thinking, the subjective nature of such an evaluation is the motivation of this chapter. There are ways of analytically determining the quality of an engineering design or of a block of computer code, but not of a systems analysis. How is the quality of a systems approach objectively and quantitatively measured? What are the indices of performance?

Taking the foundation of DST as a starting point, this chapter attempts a preliminary first-look at whether systems thinking can be analytically identified. It intends to establish a proof of concept methodology for quantitative assessment based upon language – a semantic classifier of systems thinking. This work will consider semantics in the most general way as reflecting the meaning in natural language of a text and, from that perspective, how that language reflects a systems thinking approach. From previous chapters, we call this approach metathinking – thinking about thinking in systems.

The Internet and the Internet economy have made analytical assessments of language commonplace. While computers can still actually comprehend very little in terms of the meaning of human language, every time we use a search engine, shop online, or send an email a computer is working to understand our thoughts via the words we type. According to Wikipedia, the first recorded instance of receiving an unwanted mass-distributed electronic message was in May of 1864 when a select group of British politicians all received identical telegrams advertising a dentist. (As if we needed another reason to not like dentists.) We have been looking for ways to tame unwanted messages ever since. Thus evolved methods to quickly classify incoming electronic text into two classes: spam and not spam. These naïve Bayes classifiers also have applications in discerning the intent of those communicating (planning a vacation or planning terrorism?). Turney and Pantel called the theme that underlies all of these approaches the *statistical semantics hypothesis*: statistical patterns of human word usage can be used to figure out what people mean. This chapter will show that information classifying techniques can be adapted to determine whether authors are engaged in good systems thinking or less good systems thinking. Note: the chapter appendix goes into some detail on the probabilistic nature of naïve Bayes classifiers [164], [165].

7.3 Approach

This work intends to show that given any document describing a systems approach, statistical semantics can (or cannot) assess the level of systems thinking used by the authors. The process flowchart in Fig. 23 shows the step-by step approach to test this hypothesis. It begins with a corpus of unread documents, all having some propensity for systems analysis and/or a systems approach based on the subjects and sources. We will then process the corpus with the goal of classifying a test set as being good systems thinking or less good systems thinking. First, we describe some background on the approach starting with the concept of vector space models of documents.

7.3.1 The Term-Document Matrix

Vector space models (VSM) -- developed by Gerald Salton and others for the SMART information retrieval system at Harvard -- pioneered the concepts still used in modern search engines, information retrieval and text classifiers. VSMs exhibit a close relationship to the distributional hypothesis of semantics, to wit: words that occur in similar contexts tend to have similar meanings. Applying this hypothesis to concrete algorithms for measuring the similarity of meaning leads to vectors, matrices and the linear algebraic approaches we will use. What made VSM unique from other approaches to artificial intelligence and information retrieval was the use of term frequencies in a corpus of text as a clue for discovering semantic information. As a part of this research, advanced applications of VSM such as Apache Lucene, Mahout and Solr were studied as approaches for systems thinking assessments, but for this initial proof-of-concept research, a more fundamental approach as well as more direct access to the data and the processing were desired [164], [166], [167].

In a standard term–document matrix, rows correspond to terms and columns correspond to documents. A document column vector represents the corresponding document as a bag of words. A bag is easily understood to be a random collection – the order of the set is irrelevant, but mathematically we consider it as a set with duplicates allowed. The bag of words hypothesis of VSM allows us to estimate the relevance of documents to a query by representing each as respective bags of words. Salton, et al. proved that despite the loss of the context or sentence structure, just the frequencies of words in a document tend to provide a good indicator of the relevance of a document to a categorization or query. Tracing this hypothesis back to language being the expression of thought, an intuitive justification for the term-document matrix is, according to Turney, et al., that the topic of a document will probabilistically influence the author's choice of words when writing the document. Therefore, if the author thinks in systems, this will probabilistically influence the language expressed in the text [164], [166].

Before generating a term-document matrix, we apply some text processing to derive raw data from the corpuses. We will translate the documents from PDF format to Unicode text.

Then, we will tokenize the raw text; that is, decide what constitutes a term and we extract the terms from raw text. A token is a single instance of a symbol, whereas a type is a general class of tokens. *Process* may be a type, whereas *process*, *processes*, *processing*, *processor* and *processed* are all tokens. Typical word sense disambiguation algorithms deal with word tokens (instances of words in specific contexts) rather than word types. Deriving tokens from text for this analysis will require case-folding – converting all words to lower case – and special consideration for multi-word terms as single tokens. The result of this initial processing would be a large matrix with all the terms in the corpus defined by the rows, the individual documents under consideration defined by the columns and the values populating the matrix would be the term frequencies. However, does term frequency translate easily to statistical semantics?

7.3.2 Term Frequency and Inverse Document Frequency

The literature shows that simple term frequency lacks the ability to show the semantic relationships that we are looking for. Normalizing term frequency based on document word count helps to alleviate the bias of longer documents vs. shorter ones, but weighting is needed to down-play similarities and emphasize distinctions. One hypothesis prevalent in information retrieval is that surprising events, if shared by two document vectors, are more discriminative of the similarity between the vectors than less surprising events. In information theory, a surprising event has higher information content than an expected event. A common way to formalize this idea for term–document matrices is the tf-idf (term frequency/inverse document frequency) approach. Tf-idf serves to attenuate terms that occur frequently in a corpus and thus have less meaning –- for example the token *car* in a corpus on the automotive industry. It also serves to add weight and thus emphasize terms that occur less frequently in the corpus and thus add distinction and meaning to that document. In the above example, the token *turbo* might add occur less frequently in an automotive corpus and thus deserve added weight. An element of the matrix gets a high weight when the corresponding token is frequent in the corresponding document (i.e., tf is high), but the token is rare in other documents in the corpus (i.e., df is low, and thus idf is high). Salton and Buckley demonstrated that tf-idf weighting can yield significant improvements over simple token frequency in determining semantics [164], [166], [168], [169].

Equation (1) shows the formula used for determining the term frequency, normalized for the number of words in the respective document. The term frequency $tf(t,d)$ equals the frequency of the term t in the document d, divided by n the number of words in d.

$$tf(t,d) = \frac{f(t,d)}{n} \qquad (1)$$

The idf is calculated as shown in Equation (2)

$$idf(t,D) = \log \frac{N}{|\{d \in D : t \in d\}|} \qquad (2)$$

where N is the number of documents in the corpus and $|\{d \in D : t \in d\}|$ is the number of documents in the corpus that contain the term, i.e. $tf(t,d) \neq 0$

The tf-idf is:

$$tf \cdot idf(t,d,D) = tf(t,d) \times idf(t,D) \qquad (3)$$

Thus, if all documents in the corpus contain a term, log 1 is zero for that term, as is tf-idf. The vectors in a term-document matrix are necessarily sparse – containing many zero values. Matrix smoothing attempts to improve efficiency by removing many rows considered as contributing little to the objectives of the classifier. In Fig. 23 we show our process proceeds directly from the Unicode text to the tf-idf term-document matrix. Next, our process will significantly smooth the matrix by eliminating tokens that occur in all the documents and manually reduce the list to terms that relate to the Dimensions of Systems Thinking. This is a part of the supervised learning aspect of naïve Bayes classifiers, described in detail in the appendix -- but to summarize: prior probabilities as prescribed by supervised learning can contribute to optimizing text classification.

7.3.3 Supervised Learning

Our process involves supervised learning in two steps, first the matrix smoothing process described in the previous section and second the manual classification of documents in the learning/training corpus.

Returning to the documents in their original form, we will divide the set of documents in the corpus into a learning/training (L/T) set and a test set – also dividing the term-document matrix into two matrices for L/T and test per Fig. 23. The test set will be set aside unread while the L/T set of original documents will be read and manually scored based on their Dimensions of Systems Thinking content. These scores will then be used to annotate the corresponding columns of the L/T term-document matrix. These supervised learning scores will form the basis for the vector space classification steps in the next section.

7.3.4 Document Classification in Vector Space

We now have a set of scored learning/training vectors in our term-document matrix and we want to classify them per naïve Bayes classification. The simplicity, transparency and efficacy of a Rocchio approach leads us to select that method for this proof of concept [164], [169].

7.3.4.1 Rocchio Classification

Rocchio classification describes a common, simple and efficient method of determining linear document classification boundaries using centroid vectors. The centroid vector $\vec{q}(c)$ (also reference or classification vector) of a class c is computed as the vector average or center of mass of its members:

$$\vec{q}(c) = \frac{1}{|D_c|} \sum_{d \in D_c} \vec{v}(d) \qquad (4)$$

where D_c is the set of documents in D whose class is $c : D_c = \{d : \langle d, c \rangle \in \mathbb{D}\}$. The process for cosine similarity described in section 7.3.4.3 also normalizes the vectors, negating the need for the $1/D_c$ component of equation (4).

$$\vec{q}(c) = \sum_{d \in D_c} \vec{v}(d) \qquad (5)$$

In vector space classification (VSC) all documents are represented by length normalized vectors that point to the surface of a hypersphere. The classification boundary between two classes using the Rocchio classification approach is the set of points on the hyperplane that is equidistant from the two centroid classification vectors.

Fig. 23 shows that the next step after the supervised learning scoring the L/T set of documents will be to sort them by score. Then, the document vectors of the documents scored at the top and those scored at the bottom will be summed to create two centers of mass for Rocchio classification: Top and Bottom. These two centers of mass for classification will represent the class of good systems thinking and the class of less good systems thinking. To classify a document vector, we determine the distance to the two centroids and select the one that is closest as the correct class.

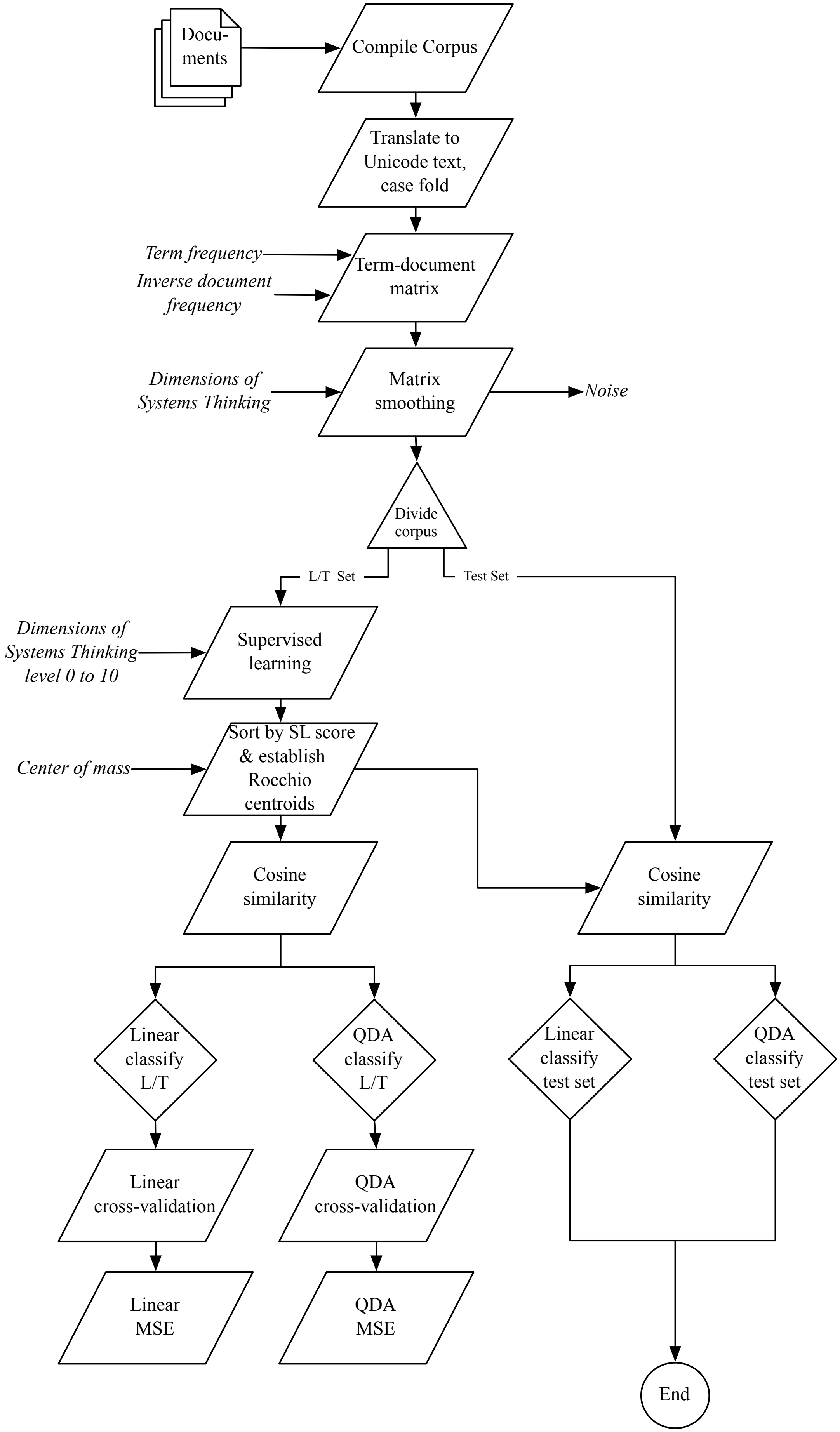


Fig. 23. Process flowchart of a proposed method to classify the level of systems thinking in a corpus of documents.

7.3.4.2 Euclidian Distance

To test the similarity of documents in hyperspace, Euclidian distance was considered but discounted because it allows too much weight for term frequency at the expense of meaning unless the vectors are normalized -- and if the vectors are normalized, Euclidian distance is merely an expression of the sine of the angle between the vectors. Consider in Fig. 24 the VSC of a two-dimensional example term-document matrix where the terms to be considered are *long*

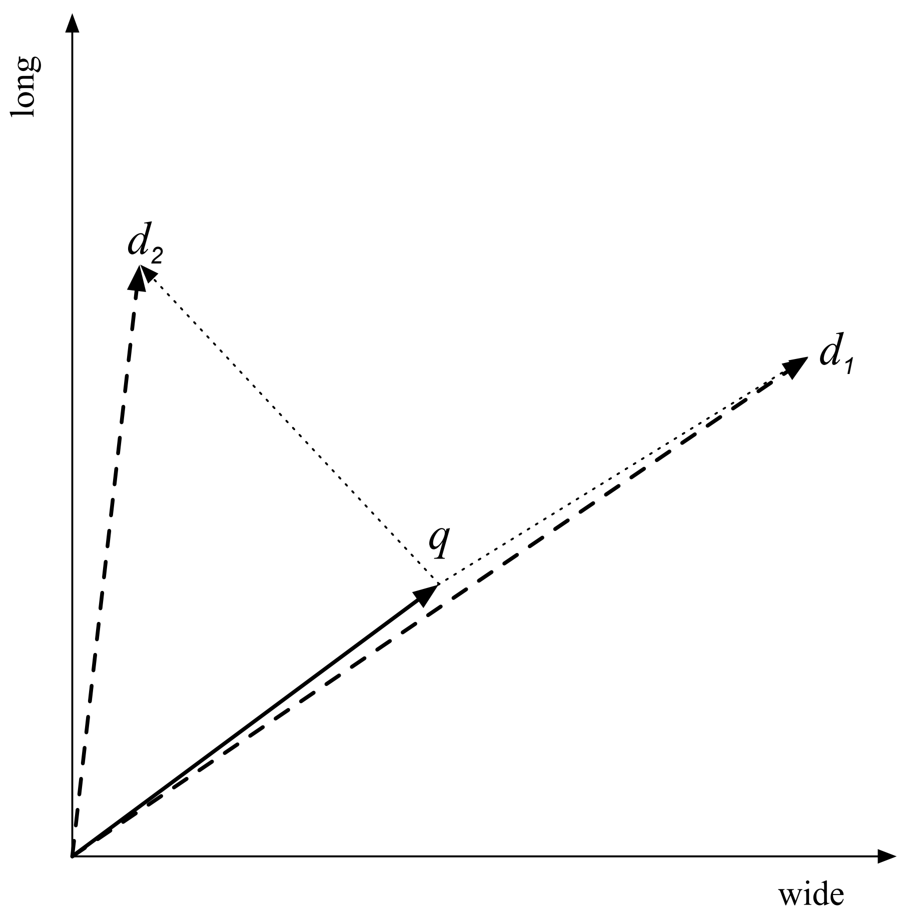


Fig. 24. Example of Euclidian distance to a reference vector q in a two-dimensional term vector space comparing long with wide. Vector d_2 would indicate a different meaning from the reference vector q – more long than wide - but it has the same Euclidian distance as another vector d_1 that indicates a similar meaning.

and *wide*. We want to compare document vectors d_1 and d_2 to a reference vector q in terms of these two terms. Our reference vector q has slightly more emphasis on *wide* than *long*. Notice in Fig. 24 that the two documents score the same in Euclidian distance (dotted lines) from the reference vector even though vector d_1 has a more similar proportion of *long* and *wide* to q than does d_2. Test runs showed this to be an issue with the learning corpus data, so we looked for another linear approach to classification and selected cosine similarity.

7.3.4.3 Cosine Similarity

Cosine similarity (CS) considers the angle between two normalized vectors in hyperspace to be an accurate measure of the distance between them. Simplifying, the cosine of that angle represents a measure of correlation between the two vectors. If the cosine of two document vectors in a term-document matrix equals 1.0, the vectors are collinear and thus express the same information. A cosine of negative one indicates the two vectors are 180 degrees out of phase and express opposite meanings while a cosine of zero indicates the two vectors are orthogonal and thus independent. Since there are no negative values in tf-idf weighting, cosine similarity values will range from 1 to 0. This is a different classification approach from vector space kNN as shown in Fig. 25. Notice that vector d_3 is close to vector d_2, the latter already classified as similar to vector q_2. Vector d_3 is, however classified as similar to q_1 through Rocchio classification and cosine similarity.

Mathematically, if the dot product of two vectors a and b is expressed:

$$a \cdot b = \|a\| \, \|b\| \cos\theta \qquad (6)$$

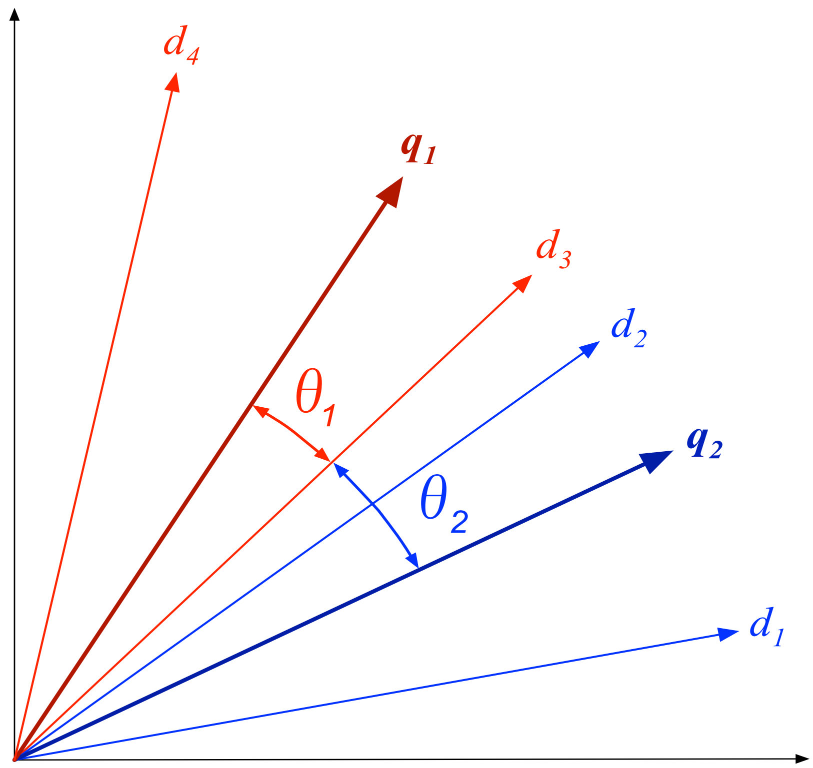


Fig. 25. Classification with two reference vectors showing the difference between CS and kNN approaches to classification of vector d_3. The nearest neighbor is classified as similar to reference vector q_2, but d_3 is classified as similar to q_1.

then, the cosine similarity between two document vectors A & B is:

$$similarity = \cos\theta = \frac{A \cdot B}{\|A\| \, \|B\|}$$

$$similarity = \frac{\sum_{i=1}^{n} A_i \times B_i}{\sqrt{\sum_{i=1}^{n} (A_i)^2} \times \sqrt{\sum_{i=1}^{n} (B_i)^2}} \tag{7}$$

7.3.4.4 Linear classification

We will use the cosine similarity values to establish the distance to the two Rocchio centroids for a linear classification of the documents in the L/T corpus. If the result is satisfactory, we will extend the linear classification to the test corpus. This is depicted in Fig. 23 as the Cosine similarity processes followed by the Linear classify L/T and Linear classify test set decision processes.

7.3.4.5 Quadratic Discriminant Analysis

Linear approaches to classification are known to have a high bias because they can only model a linear hyperplane. Nonlinear classifiers such as Quadratic discriminant analysis (QDA) can reduce the bias – if the data are nonlinear. It would be safe to assume that the document data we will be considering will be nonlinear in nature. QDA is a naïve Bayes approach that permits non-linear, quadratic classification boundaries thus reducing bias at the possible expense of variance.

Where the covariance matrices of the classes are not assumed to be equal -- as is the case with document data -- QDA is a preferred method of classification. It permits determining the parameters of Gaussian distributions through supervised learning data as we plan to use in the supervised learning step of the process.

In order to compare the efficacy of the linear classification approach described above to a non-linear classification approach, we will calculate quadratic discriminants based on the supervised learning scores and the cosine similarity values of our L/T corpus. We will then use them to classify our test corpus based on the test corpus cosine similarity values through a QDA classification process as shown in Fig. 23, and compare the mean-squared error of the two processes.

QDA also easily allows the incorporation of prior probabilities into the naïve Bayes classification. We will analyze this feature and how it may be useful in actual assessments of the Dimensions of Systems Thinking.

7.3.4.6 Cross-validation and Mean Squared Error

We have established two approaches to classifying the systems thinking content of a corpus of documents. In order to quantitatively evaluate and compare them, we will perform cross-validation using both approaches and calculate the respective mean squared errors.

Mean squared Error (MSE), the sum of the bias squared and the variance is the benchmark for evaluating the quality of any learning method of statistical classification. An optimal classifier is one that minimizes MSE [169].

We will define MSE in the manner described by Manning, et al. starting with the assumption that all the learning/training documents and test documents have the same underlying distribution. When calculating the tf-idf values for the term-document matrix – and the resulting centroid vectors - the combined T/L and test corpuses were used but the test corpus was not graded. Therefore, the actual distribution of the test corpus is assumed to be similar to the T/L corpus, but the only way to verify that is to violate the blind test and grade the test corpus.

Next, we define a learning method Γ as a function that takes a labeled training corpus set $\mathbb{D}$ of known distribution as input and returns a text classifier.

$$Bias(\Gamma, d) = \left[P(c|d) - E_{\mathbb{D}}[\Gamma_{\mathbb{D}}(d)]\right]^2 \qquad (8)$$

$$Variance(\Gamma, d) = E_{\mathbb{D}}\left[\Gamma_{\mathbb{D}}(d) - E_{\mathbb{D}}[\Gamma_{\mathbb{D}}(d)]\right]^2 \qquad (9)$$

$$MSE = \mathrm{Var}(\Gamma, d) + \left(Bias(\Gamma, d)\right)^2 \qquad (10)$$

Note that $P(c|d)$ is the true conditional probability of a document d being in classification c and $E_{\mathbb{D}}[\Gamma_{\mathbb{D}}(d)]$ is the prediction of the classifier averaged over training sets [169].

This concludes the description of the approach we propose for analytically determining the level of systems thinking in a document. Now, we proceed to a proof-of-concept assessment of that approach.

7.4 Proof of Concept: A Case Study

The author devised the following case study to establish a proof of concept: A corpus of approximately three hundred documents would be classified using the approach described above. Sixty-two of these documents would be randomly selected from academic journals based only on their subject matter being related to life cycle assessment, which was considered in an earlier analysis by the authors presented at the IEEE Green Technology Conference in 2010. These sixty-two would form the test set corpus and thus be evaluated only by the analytic classification tools [3].

The balance of the corpus, the learning/training corpus, would be randomly selected from the IEEE Systems Journal – spanning all subjects. There was considered to be a high likelihood of finding articles there that would span the Dimensions of Systems Thinking and thus establish a valid distribution for creating the center-of-mass centroid vectors in the Rocchio classification. We show the entire proof-of-concept case study as a product flow in Fig. 28 (page 162) that correlates to the process flow diagram in Fig. 23.

.

7.4.1 Data

As mentioned above, two corpuses of natural language text as PDF documents form the input of the proof of concept. Randomly selected articles from the IEEE Systems Journal (2007 to 2013) totaling 233 documents are combined with 62 published articles on the topic of life cycle assessment to form the 295 Journal articles at the top of Fig. 28. These 62 documents were selected randomly from the following journals: Journal of Environmental Management, Journal of Hazardous Materials, Applied Energy, Building and Environment, Forest Ecology and Management, Energy and Buildings, Solar Energy Materials & Solar Cells, Journal of Cleaner Production, Bioresource Technology, Biomass and Bioenergy, Agricultural Systems, Fisheries Research, Chemical Engineering Journal, Polymer Degradation and Stability, Environment International, Agriculture, Ecosystems and Environment and Energy Policy, EcoInvent, AIChE Journal, Journal of Industrial Ecology, International Journal of LCA, Clean Technology, Environmental Policy, Journal of Nanoparticle Research, Energy & Fuels, Environmental Science & Technology, and Sustainability.

These 295 documents are then translated into 295 Unicode text files, the next step (second row) in Fig. 28. As mentioned in Section 7.3, deriving tokens from text for the DST analysis requires case-folding – converting all words to lower case – and special consideration for multi-word terms as single tokens. We list these multi-word terms in Table XI of the appendix. Stemming of terms – reducing all terms down to their root form – can cause some meaning to be lost and we have selected to not stem the terms in our data. Stemming and case folding are referred to as *normalizing* in the field of information retrieval [169].

TF-idf values were determined using the combined 295 total document learning/training corpus and test corpus. [The test corpus was not read or graded.] The combined corpuses described above resulted in 2.44 million total tokens with 72,424 distinct tokens in 295 documents. In the idf calculations, stop words such as the, and, if (listed in Table XII of the appendix) are omitted to improve efficiency and provide noise reduction. The 72,424 distinct tokens were manually reduced through matrix smoothing to 1020 distinct tokens as described in Section 7.3. Each token of the 1020 is associated with one or more of the Dimensions of Systems Thinking and considered to be discipline and application agnostic. These 1020 distinct tokens became the vertical basis of the term-document matrices as shown starting with the fourth row of Fig. 28 and shown in Fig. 27.

7.4.2 Supervised Learning

The process has thus translated the systems thinking information in the corpuses into term-document vectors of weighted tf-idf factors. We now set aside the 62-document test corpus matrix. In order to determine if the 233 documents represented by the learning/training matrix are of good systems thinking or less good systems thinking, we employ a naïve Bayes approach of supervised learning. Each document is read and manually graded on a scale of 0 being no systems thinking and 10 being very good systems thinking in terms of the DST. Fig. 26 shows the distribution of these grades over the 233-document L/T corpus. In the distribution: 84 documents score 7 or better (top) and 84 documents score 4 or lower (bottom). This distribution establishes the basis for a two-class vector space classification (VSC) based on the top graded documents and the bottom graded documents.

Per the Rocchio center-of-mass centroid classification approach, we sum the 84 top vectors to calculate a 1020 component centroid vector representing the top classification which

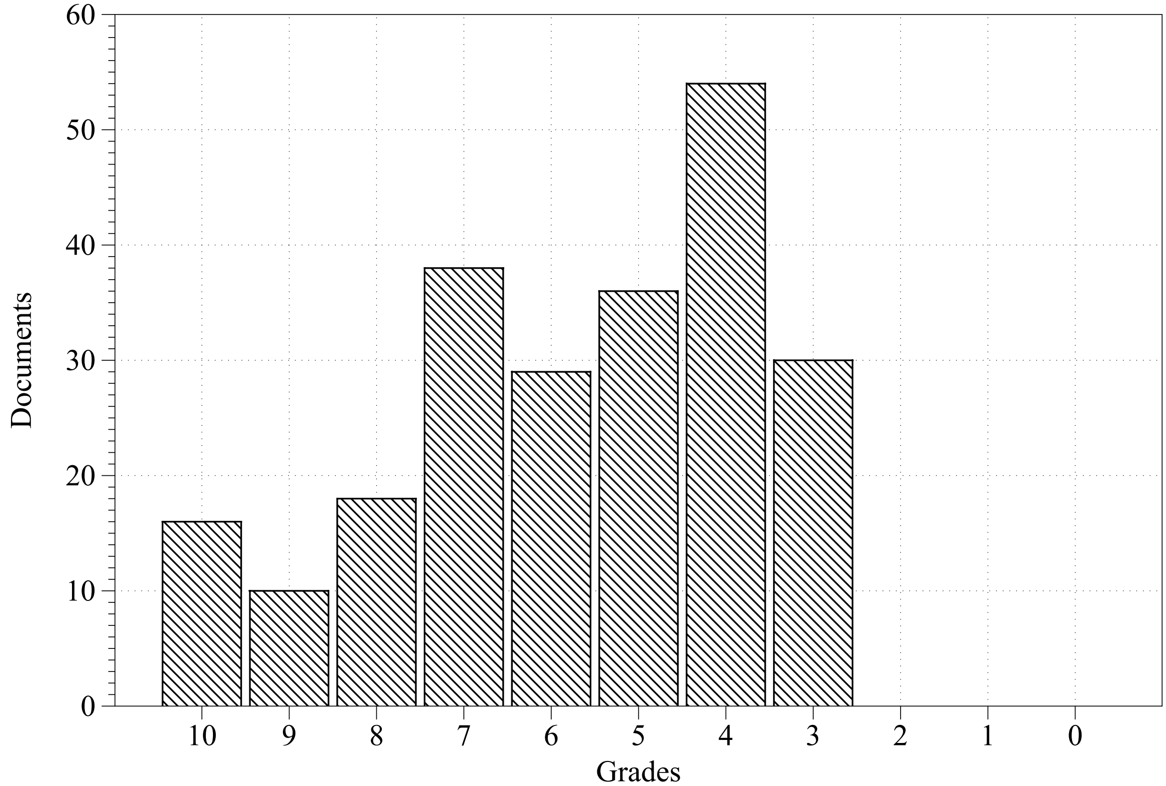


Fig. 26. Distribution of supervised learning grade scores over the learning and testing corpus of documents. Notice 84 documents were scored 7 and above and 84 documents were scored 4 and below.

will be the reference vector , Q for good systems thinking. Likewise, we sum the 84 lowest scoring vectors to create the bottom centroid vector representing less good systems thinking $\bar{Q}$. This step is depicted in the sixth row of Fig. 28

7.4.3 Document Classification

In line 7 of Fig. 28, we show that the vector space classification began with calculations of the cosine similarities between the 233-learning/training document tf-idf vectors, the 62 test tf-idf vectors and the Rocchio centroid classification vectors. The cosine similarity distances to the two Rocchio centroid classification vectors, Q and $\bar{Q}$ were compared and the distance to the closest reference vector used to determine the classification.

$$classification_{Q,\bar{Q}}(D) = \begin{cases} \{Q : \cos\theta_{Q,D} > \cos\theta_{\bar{Q},D} \\ \{\bar{Q} : \cos\theta_{\bar{Q},D} > \cos\theta_{Q,D} \end{cases} \tag{11}$$

Fig. 27 shows the proof-of-concept term-document matrix. Column A row 19 begins the first twelve of 1020 tokens, manually smoothed from 72,424. Column C shows the first twelve

	A	B	C	D	E	F	G	H
1					1	2	3	4
2					42939970.tx	42940010.tx	42980760.tx	42980800.tx
3				S/L Score	10	7	7	10
4				CS Classification	TOP	BOTTOM	TOP	TOP
5				Error		2		
6					**CS Top**	**CS Top**	**CS Top**	**CS Top**
7					**0.59007**	**0.384618**	**0.251203**	**0.534741**
8					0.00549510	0.00226633	0.00404750	0.01036710
9					0.47549789	0.47549789	0.47549789	0.47549789
10					0.01958499	0.01239207	0.03388552	0.04077231
11					**CS Bottom**	**CS Bottom**	**CS Bottom**	**CS Bottom**
12					**0.140474**	**0.401531**	**0.161651**	**0.081348**
13					0.00174407	0.00315434	0.00347247	0.00210260
14					0.6339358	0.6339358	0.6339358	0.6339358
15					0.01958499	0.01239207	0.03388552	0.04077231
16					0.4495963	0.01691297	0.08955151	0.45339301
17			Top Vector	Bottom Vector				
18	Token	2444460	662210	639454	5659	9300	11088	8188
19	absence	0.01675359	0.00307452	0.005940423	0	0	0.0001619	0.00021924
20	abstraction	0.02171597	0.00841419	0.008352003	0	0	0	0.00028759
21	access	0.08659672	0.02262204	0.038913351	0.00012309	0	0	0
22	according	0.04044577	0.01038301	0.012731309	0	0.0003089	0.00012955	4.39E-05
23	accordingly	0.02292847	0.00684842	0.009973763	0	0.00058903	0.00074106	0
24	accuracy	0.04373939	0.01318923	0.014693306	0	0.00012765	0	0
25	accurately	0.01507147	0.00367152	0.004675824	0	0	0	0
26	acquisition	0.04592476	0.01225026	0.01811847	0.0004568	0	0	0.0025257
27	active	0.04947387	0.01427839	0.01980272	0.00053763	0	0	0
28	actual	0.03741368	0.01048156	0.010861073	0	0.00023359	0	0
29	adapted	0.01999421	0.00398671	0.005477108	0	0.00016772	0	0
30	addresses	0.02151986	0.00692885	0.00750286	0	0	0	0.00015937

Fig. 27. Corner of the Excel term-document matrix showing the first 12 of 1020 term rows and the first four of 295 document columns. Row 3 is the supervised learning score; row 4 is the cosine similarity classification; rows 7 and 12 are the cosine similarity values to the top centroid and the bottom centroid, respectively; columns C and D are the centroid vectors for the top and the bottom, respectively.

elements of the centroid center-of-mass representing the top class, and column D shows the same for the bottom class. Row 2 shows the document identifier codes. Row 3 shows the supervised learning scores for the respective documents and row 4 shows the respective classification result of the linear cosine similarity calculation in Equation (11). Row 5 shows the error indication if the linear classifier did not agree with the supervised learning score: 1 if a low scoring document was classified as top, 2 if a high scoring document was classified as bottom. Rows 7 and 12 show the cosine similarity distance to the top and bottom centroids, respectively. Finally, E:19 to H:30 show a sample of the tf-idf values for the corresponding tokens and documents.

Cross-validation was conducted by withholding three different random sets of 1/3 of the document vectors from the rest of the data for learning; deriving centroid classification vectors from the remaining 163 document vectors based on the grades as described in the previous section and using them to classify the remaining 1/3 of the document vectors. The results are shown in confusion matrix form in Table V and Table VI on page 163 [169].

A quadratic discriminant analysis of the cosine similarity data and the supervised learning scores (using Minitab) determined quadratic classification parameters that were used to classify the test corpus. Classification of the L/T corpus along with the 233-fold cross-validation results are in Table VII on page 164 [170].

Analysts consider linear vector space models to have a high bias and low relative variance since they do not over-fit the learning and training sets. Nearly all Non-linear classifiers such as QDA tend to have a lower bias and higher variance – but QDA is known for balancing variance and bias [170].

Using the data from the respective cross-validations, we calculate the MSE for the two classification approaches and present the results in Table VIII on page 165.

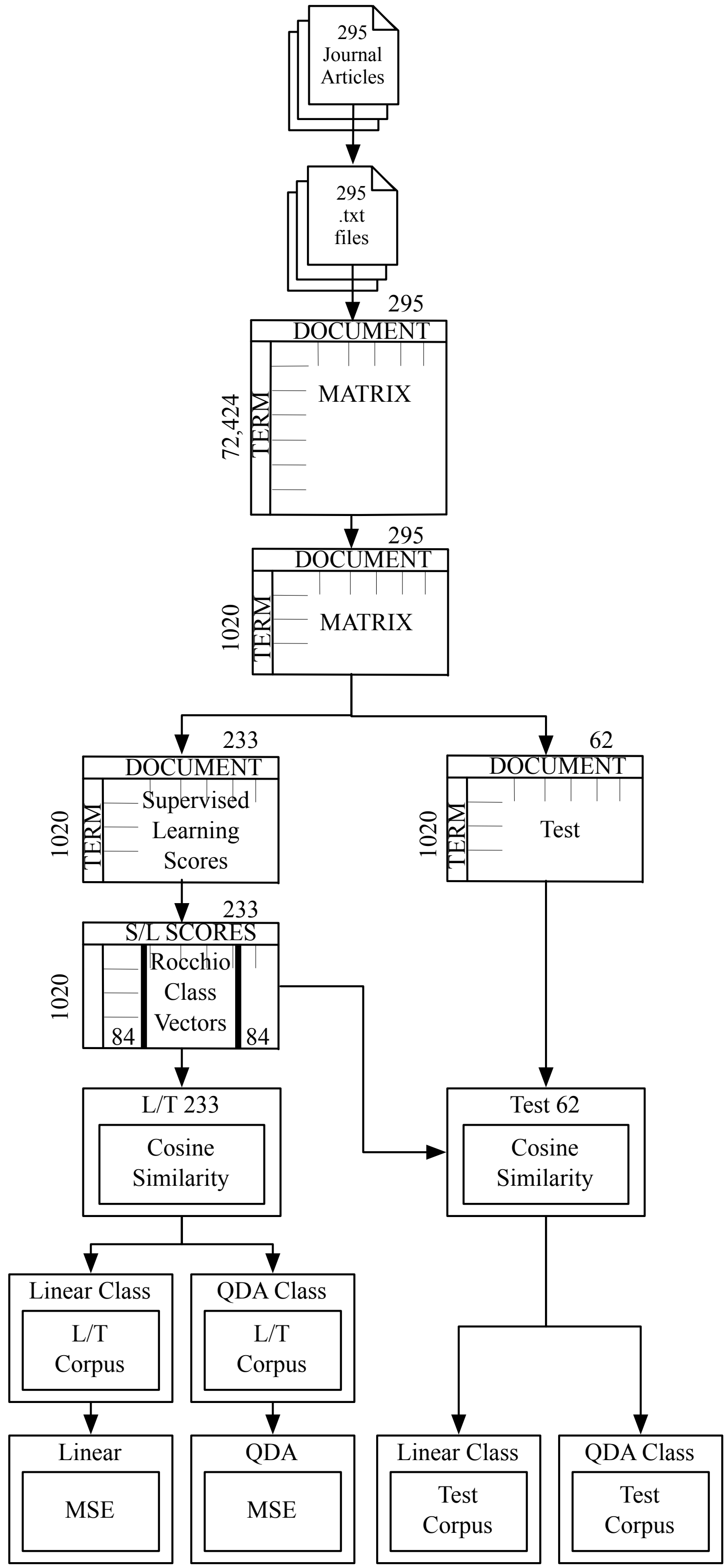


Fig. 28. Product flow diagram of the proof-of-concept case study showing the analytical products at each step of the process described in Fig. 23.

Table V: Confusion Matrix: VSC Entire L/T Corpus

	True Group	
Put Into Group	Bottom	Top
Bottom	95	35
Top	25	78
Total N	120	113
N Correct	95	78
Proportion	0.792	0.690
N	N Correct	% Correct
233	173	74.25%

Table VI: Confusion Matrix: VSC 3-fold Cross Validation

	True Group	
Put Into Group	Bottom	Top
Bottom	84	54
Top	36	59
Total N	120	113
N Correct	84	59
Proportion	0.700	0.522
N	N Correct	% Correct
233	143	61.37%

Table VII: Confusion Matrix: QDA, ENTIRE L/T CORPUS

	True Group	
Put Into Group	Bottom	Top
Bottom	106	56
Top	14	57
Total N	120	113
N Correct	106	57
Proportion	0.883	0.504
N	N Correct	% Correct
233	163	70%

With Cross Validation	True Group	
Put Into Group	Bottom	Top
Bottom	105	59
Top	15	54
Total N	120	113
N Correct	105	54
Proportion	0.875	0.478
N	N Correct	% Correct
233	159	68.2%

Table VIII: Mean Square Error Results

	VSC	QDA
Bias	0.0060835	0.0011804
Variance	0.0172208	0.0114852
MSE	0.0172578	0.0114866

Analysis of the data in Table VIII above shows that the MSE values are comparable for the two approaches, but that the quadratic classifier is slightly superior to the L/T data.

7.4.4 Classification of the Evaluation Corpus

As mentioned before and shown in the bottom right side of Fig. 28, The 62 documents of the evaluation corpus set were classified by linear vector space classification and by quadratic discriminant analysis classification and the results presented below in Table IX. 40 documents, 64.5%, were classified the same by both methods. Of those, 38 showed quantitative indications of good systems thinking in common with the top ranked documents in the learning/training corpus set. The two other documents showed quantitative indications of less good systems thinking in common with the bottom ranked documents in the learning/training corpus set. The remaining 22 documents split between the top and bottom classification.

Table IX: Analytic Classification of the Test Corpus

Index	QDA	VSC	Index	QDA	VSC
1	Bottom	Top	32	Top	Top
2	Bottom	Top	33	Top	Top
3	Bottom	Top	34	Bottom	Top
4	Top	Top	35	Bottom	Top
5	Top	Top	36	Top	Top
6	Top	Top	37	Top	Top
7	Top	Top	38	Top	Top
8	Top	Top	39	Top	Top
9	Top	Top	40	Top	Top
10	Top	Top	41	Top	Top
11	Bottom	Top	42	Bottom	Top
12	Top	Top	43	Bottom	Top
13	Bottom	Top	44	Top	Top
14	Top	Top	45	Top	Top
15	Top	Top	46	Top	Top
16	Bottom	Top	47	Top	Top
17	Bottom	Top	48	Top	Top
18	Bottom	Botton	49	Top	Top
19	Bottom	Botton	50	Top	Top
20	Top	Top	51	Top	Top
21	Top	Top	52	Bottom	Bottom
22	Bottom	Botton	53	Bottom	Top
23	Bottom	Top	54	Top	Top
24	Top	Top	55	Top	Top
25	Top	Top	56	Bottom	Top
26	Bottom	Top	57	Bottom	Top
27	Bottom	Top	58	Bottom	Top
28	Top	Top	59	Bottom	Top
29	Top	Top	60	Bottom	Top
30	Bottom	Top	61	Top	Top
31	Top	Top	62	Bottom	Top

7.4.5 Relating the Classification to the Dimensions of Systems Thinking

The 1020 tokens in the term dimension of the term-document matrix were individually correlated to one or more of the five top-level dimensions of the DST taxonomy. Five binary classification vectors were established, one for each of the dimensions, based on this correlation. The dot product of these DST correlation vectors, the document tf-idf vector and the centroid vector for good systems thinking were calculated providing five individual scores for each document relevant to the respective dimensions. These values were summed to provide a total score for each document. The DST total score values were calculated to have a positive correlation of 0.29 with the supervised learning grades, thus proving some correlation between this analytic approach and the Dimensions of Systems Thinking.

7.4.6 Adjusting the naïve Bayes prior probability

One of the features of the naïve Bayes classifiers is the acceptance of prior probabilities into the classification. We know from inspection (Fig. 26) that the prior probability of a document in the L/T corpus set being in the Top class is 0.485. Adding this prior probability to the QDA classifier results in the confusion matrix in Table X

Compared to the data in Table VII, this simple adjustment, albeit slight, improved the probability of correctly classifying good systems thinking by nearly 3% without altering the probability of correctly classifying less good systems thinking. If the goal is, for example, to ensure that good ST is recognized by the classifier, improvements such as this can contribute to that goal. Note also in Table X, in the cross-validation confusion matrix, a document analytically classified as Top has a 79.5% chance of actually being in class Top - with acknowledgement of the cost of classification (58 out of 113).

Table X: Confusion Matrix: QDA, L/T Corpus with Prior Probabilities

P(Top|doc) = 0.485, P(Bottom|doc) = 0.515

	True Group	
Put Into Group	Bottom	Top
Bottom	105	53
Top	15	60
Total N	120	113
N Correct	105	60
Proportion	0.875	0.531
N	N Correct	% Correct
233	165	70.8%

With Cross Validation	True Group	
Put Into Group	Bottom	Top
Bottom	105	55
Top	15	58
Total N	120	113
N Correct	105	58
Proportion	0.875	0.513
N	N Correct	% Correct
233	163	70%

7.5 Chapter Conclusions

Some say: *A good systems analysis is like pornography – I know it when I see it*. That may very well be true, but would you consider a bridge or a plane safe because they looked good to the engineers? Engineers, analysts, researchers and all systems practitioners should agree that an analytic assessment of the systems approach would be useful. We have shown as a preliminary proof-of-concept that it is possible to evaluate the quality of a systems approach analytically with accuracy on the order of 70%. We showed that a corpus of unread documents could be classified as containing good systems thinking or not using two analytic approaches and we compare the results showing that both the linear hyperspace vector classifier and the nonlinear quadratic discriminant classifier do well. We started with our own ground truth, but that is the nature of any supervised learning classification system. The long-term goal of systems assessment is the establishment of effective benchmarks similar to those for other aspects of applied science.

Follow-on work for this research would include improving the ground truth basis and developing multiple classifications to more closely correlate to the 20 Dimensions of Systems Thinking. The latter would allow the practitioner to determine exactly where the systems approach being assessed needs improvement. It would also include assessment of other methods of text classification such as support vector machines, k Nearest Neighbor and techniques that allow improvement through relevance feedback.

7.6 Chapter Appendix

Table XI: Multiword Tokens

axiological components	outside the box
mental model	step back
value model	bottom line
value theory	scope of the analysis
descriptive scenario	state of system
develop alternatives	system boundaries
evaluate alternatives	system stakeholders
indices of performance	type of system
iterate analysis	man-made
leverage points	non-reactive
life cycle	mental model
normative scenario	system type
observer effects	

Table XII: Stop words

0	a	for	on
1	an	from	or
2	and	has	that
3	are	ieee	the
4	as	in	this
5	at	is	to
6	be	it	we
7	by	no	with
8	can	not	
9	fig	of	

7.6.1 Naïve Bayes Classifiers

Naïve Bayes classifiers assume the presence or absence of a specific qualifier is independent of any other qualifier. For example, a document may contain the terms *stereo*, *tires*, *fog lamps* or *turbo-charged*, but a naïve Bayes classifier regards the terms *stereo*, *tires*, *fog*, *lamp*, *turbo* and *charged* as contributing independently to the probability that the document containing those terms would be classified in a corpus set defined as documents related to cars. If we consider documents as containing words that are randomly distributed - as in the bag of words concept - and we have a class of documents related to cars, class C, and the probability that the *i*th word of an unclassified document *D* occurs in the class of documents with probability $p(w_i|C)$, then the probability that an unclassified document *D* contains all the words w_i given the class *C* is:

$$p(D|C) = \prod_i p(w_i|C) \qquad (12)$$

In order to determine if an unclassified document D belongs to class C, we use Bayes' theorem to determine $p(C|D)$. By definition:

$$p(D|C) = \frac{p(D \cap C)}{p(C)}$$

and (13)

$$p(C|D) = \frac{p(D \cap C)}{p(D)}$$

Combining to solve for $p(C|D)$ in terms of a statistical model (likelihood):

$$p(C|D) = \frac{p(C)}{p(D)} p(D|C) \qquad (14)$$

Now, rather than the single classification cars, consider two classifications: systems thinking Q and not systems thinking $\bar{Q}$:

$$p(D|Q) = \prod_i p(w_i|Q)$$

and (15)

$$p(D|\bar{Q}) = \prod_i p(w_i|\bar{Q})$$

Using the results in equation (14):

$$p(Q|D) = \frac{p(Q)}{p(D)} \prod_i p(w_i|Q)$$

and (16)

$$p(\bar{Q}|D) = \frac{p(Q)}{p(D)} \prod_i p(w_i|\bar{Q})$$

Dividing the two equations and re-factoring gives:

$$\frac{p(Q|D)}{p(\bar{Q}|D)} = \frac{p(Q)\ \prod_i p(w_i|Q)}{p(\bar{Q})\ \prod_i p(w_i|\bar{Q})}$$
$$= \frac{p(Q)}{p(\bar{Q})} \prod_i \frac{p(w_i|Q)}{p(w_i|\bar{Q})} \quad (17)$$

Using log-likelihoods, taking the logarithm of both sides:

$$\ln \frac{p(Q|D)}{p(\bar{Q}|D)} = \ln \frac{p(Q)}{p(\bar{Q})} \sum_i \ln \frac{p(w_i|Q)}{p(w_i|\bar{Q})} \quad (18)$$

Note that the actual probability $p(Q|D)$ can be calculated from $\ln p(Q|D)/p(\bar{Q}|D)$ based on the observation that:

$$p(Q|D) + p(\bar{Q}|D) = 1$$

Finally, the unclassified document *D* belongs to the class *Q* – systems thinking - if:

$$p(Q|D) > p(\bar{Q}|D) \qquad (19)$$

that is:

$$\ln \frac{p(Q|D)}{p(\bar{Q}|D)} > 0 \qquad (20)$$

Naïve Bayes classifiers have been shown to train very efficiently in supervised learning applications such as the one we will be employing [171], [172].

Chapter 8: Summary, Review of Contributions and Future Work

8.1 Summary

On September 23, 1999, the Mars Climate Orbiter disintegrated in the Martian atmosphere. Analysis showed that the systems team developing the ground-based computer code were working in units of pound-seconds and the systems team that developed the spacecraft were working in units of newton-seconds. The two teams working on the same system were speaking different languages and the system that cost $650 Million to develop and launch, suffered a catastrophic failure as a result.

The objective of this thesis is to develop a common, foundational language to express any systems approach. It starts with several motivational examples, a history of systems thinking, and a literature survey of prominent authors who have shown the need for such a language of systems thinking. We then consider the definition of systems and the definition of critical thinking to derive a definition of systems thinking. Next, we map this definition to the twenty lexical components of a foundation of systems thinking: the Dimensions of Systems Thinking.

These twenty dimensions underlie the concept of a fluency in systems thinking both for transparent communication and for ensuring completeness. Considering all of the DST concepts in a systems approach helps to avoid the types of errors that we described in the motivation for this work.

We presented three case studies that were instrumental in the development of this thesis. In the first, a study is made of liquid biofuel and the metrics used to assess liquid fuels. This study shows a need for better indices of performance due to the complexity of the environmental impacts of the respective fuel systems and makes recommendations to achieve that goal. The next case study considers the healthcare system in the United States and the medical education system that affects the mental model of many of the principle decision makers. This study shows a need for improvements to the medical education system and a need for improvements to the healthcare regulation system, and the study makes recommendations to achieve those goals. Lastly, a real-world case study applies the DST at the invitation of the Office of Science and Technology Policy. This study considers science policy decisions in the context of the 20 dimensions. It shows the utility of a DST foundation in a time-critical environment where decisions need to be objectives driven.

A wise man once said that good systems thinking is like pornography, he knows it when he sees it. For everyone else, there is a need for a method to analytically assess the quality of systems thinking. Chapter 7 explores statistical semantic classification approaches to DST assessment and concludes through a proof-of-concept that the concept is sound.

8.2 Review of Contributions

This thesis proposes the Dimensions of Systems Thinking as the beginning of a new epistemology on the part of the systems community -- a baseline for a common language -- with the goal that such a common language, fluently employed, will improve transparent communication between disciplines and the overall quality of systems approaches. This thesis also contributes the analytic nature of DST assessment, showing the possibility of objectively assessing work in terms of its systems thinking content.

Other contributions of this dissertation include the concept of an improved assessment index of performance for liquid biofuel, curricula changes to bring systems thinking to medical specialists, a way to politically reform the U.S. healthcare system and a new tool for evaluating and ranking multiple policy options with multiple policy objectives.

An analytic assessment tool such as the concept proven in this thesis could be useful across domains. Assessments of fuel, energy and manufacturing could be analytically evaluated for systems thinking, helping to avoid the problems of LCA. The teaching of and implementation of systems-based practice in healthcare would benefit from the analytic assessment of the quality of systems thinking – and the respective dimensions of the DST. The academic grading of case-study submissions by engineering and management students would be facilitating by such an objective analytic tool. Certainly, policy would benefit from an analytic approach to systems thinking assessment. While politics will always prevail over systems thinking, transparent analytics can only be a good thing.

This thesis will significantly enhance the field of systems engineering

8.3 Future Work

8.3.1 Foundation of Systems Thinking

Further development and acceptance of a foundational common language of systems thinking will require a forum of the systems community. Through societies, publications, conferences, NSF and the National Academies, I hope to help motivate action toward that goal as I continue this work.

One of the factors that made this dissertation possible was the AAAS S&T Policy Fellowship that placed me in the Engineering Directorate at NSF. The fellowship has facilitated access to Government decision makers at NSF, OSTP, DoD, DoE and DARPA. I plan to use this access over the next four months to promote the discussion of a common foundation for Systems Thinking. For example, one of the topics of note within the Engineering Directorate at NSF has been systems engineering education. A workshop with invited subject matter experts is planned for the near future and that would be an excellent forum in which to reach those experts and promote discussion on the DST. I will work with the NSF program manager to be included in the schedule.

Within the academic and professional society realm, our work continues to publish papers on the Dimensions of Systems Thinking. The definition paper is currently in the second round of reviews for the IEEE Systems Journal and – among the reviewers, editors and the authors – the dialogue about the foundations is well under way. Once the definition paper is approved for publication, the analytics paper will be submitted immediately as follow-on. I will also then submit conference papers to INCOSE, INFORMS and IEEE in the interest of engaging conversation about the DST in real-time at annual meetings. It would be ideal to develop specific sessions on the topic of systems thinking at these meetings and entertain other approaches to the foundation.

The Engineering Directorate of NSF holds internal lectures where a single member of the directorate addresses the entire directorate on a topic of interest. I will submit a request to deliver such a lecture as an opportunity to engage a trans-disciplinary forum on the DST.

The concept of analytical assessment of systems thinking is just getting started. There are many information retrieval and classification techniques that could be brought to bear in future work – as well as other approaches worth exploring. Supervised learning on a grand scale could allow the scored classification of documents in terms of systems thinking and the resolution of the specific dimensions with corresponding scores to facilitate improvement. Codifying the supervised learning ground truth of systems thinking will involve expanding the corpus within the learning set as well as multiple graders to reduce the bias of the individual graders.

8.3.2 Analytical Assessment of Systems Thinking

The analytical approach that was done here as a proof of concept will benefit from more advanced statistical semantic classification approaches including, but not limited to: support vector machines, k nearest neighbor and semantic distance approaches including WordNet and term multiples that discern more contextual meaning from the text than tf-idf.

An important next step in this research path will be to study the outcomes produced by different levels of systems thinking with the goal of verifying the benefits of a good systems thinking foundation. This verification will require historical data that includes both the original systems approach as well as the outcomes of the systems in terms of the objectives. This will also require the establishment of an outcome index of performance that transcends fields and disciplines. The historical data may come from such sources as the World Bank database of water projects or the NSF database of proposals (which currently lacks standardized results information, but those data will be forthcoming). The system outcomes correlated with the analytically assessed level of systems thinking in the design document will help determine the actual outcome benefits of the Dimensions of Systems Thinking as a structure and process.

Chapter 9: Epilogue

If humility is the beginning of wisdom then we must concede that outcomes are uncertain. The system under consideration may result in the desired objectives – but with unintended consequences that may change the paradigm. For example, if we cure disease, we will have more population to feed or to let starve. In another example, the deliberate introduction of an alien species into an ecosystem may have one desirable result and many unforeseen and undesirable results. We may solve the wicked problem only to realize that the constraints imposed by the original problem prevented other wicked problems.

Every time we apply systems thinking to a problem, we exercise only a partial view of the world. We can do our collective best, but we can never be certain that in the end we did not overlook something critical, something unforeseeable. That is not to say that we should not act. We must always take action in the face of big problems. We must always acknowledge at the same time that outcomes are uncertain.

Systems thinking is not a panacea. It is a tool, an approach, a philosophy. Collectively defining its foundations will improve the practice and analytical assessment will improve the foundation.

References

[1] C. W. Churchman, R. L. Ackoff, and E. L. Arnoff, “Introduction to operations research.,” 1957.

[2] R. L. Ackoff, “Towards a system of systems concepts,” *Manag. Sci.*, vol. 17, no. 11, pp. 661–671, 1971.

[3] N. Whitehead, W. Scherer, G. Louis, and M. Smith, “Improving lifecycle assessments of biofuel systems,” *IEEE Green Technol. Conf.*, May 2010.

[4] N. P. Whitehead and W. T. Scherer, “Moving from systematic treatment to a systemic approach A path for sustainable US healthcare,” in *Systems Conference (SysCon), 2013 IEEE International*, 2013, pp. 317–324.

[5] M. A. Johnson, S. Writer, and N. B. C. News, “Watchdog report deals another blow to F-35 Joint Strike Fighter,” *NBC News*, 01-Oct-2013. [Online]. Available: http://usnews.nbcnews.com/_news/2013/10/01/20777728-watchdog-report-deals-another-blow-to-f-35-joint-strike-fighter. [Accessed: 27-Oct-2013].

[6] “Kendall Cites Flawed Army Future Combat Systems as Costly Lesson - Bloomberg.” [Online]. Available: http://www.bloomberg.com/news/2011-11-29/kendall-cites-flawed-army-future-combat-systems-as-costly-lesson.html. [Accessed: 29-Sep-2013].

[7] T. A. Press, “Affordable Care Act website builders saw problems with deadlines and complexity of system,” *The Oregonian - OregonLive.com*. [Online]. Available: http://www.oregonlive.com/today/index.ssf/2013/10/health_care_website_builders_s.html. [Accessed: 27-Oct-2013].

[8] G. E. P. Box and N. R. Draper, *Empirical model-building and response surfaces.* John Wiley & Sons, 1987.

[9] B. Richmond, “Systems thinking/system dynamics: Let’s just get on with it,” *Syst. Dyn. Rev.*, vol. 10, no. 2–3, pp. 135–157, 1994.

[10] B. Richmond and High Performance Systems, Inc., *An introduction to systems thinking : stella software*. Lebanon NH: High Performance Systems, 2003.

[11] A. Hyman, *Charles Babbage, pioneer of the computer*. Princeton, N.J.: Princeton University Press, 1985.

[12] A. Smith, *An Inquiry into the Nature and Causes of the Wealth of Nations*. A. and C. Black, 1863.

[13] F. W. Taylor, *The principles of scientific management*. Harper, 1914.

[14] “History and Mission | RAND.” [Online]. Available: http://www.rand.org/about/history.html. [Accessed: 26-May-2013].

[15] M. S. Viteles and A. Brief, *Industrial psychology*. WW Norton New York, 1932.

[16] J. Tiffin and E. J. McCormick, *Industrial psychology*, vol. 7. Prentice-Hall Englewood Cliffs, NJ, 1965.

[17] T. J. Van De Water, “Psychology’s entrepreneurs and the marketing of industrial psychology.,” *J. Appl. Psychol.*, vol. 82, no. 4, p. 486, 1997.

[18] Rand and R. Corporation, *Preliminary Design of an Experimental World-Circling Spaceship*. Rand Corporation, 1946.

[19] J. W. Forrester, *Principles of systems: text and workbook chapters 1 through 10*. Wright-Allen Press, 1968.

[20] J. W. Forrester, *World dynamics*. Cambridge, Mass.: Wright-Allen Press, 1973.

[21] J. W. Forrester, “System dynamics, systems thinking, and soft OR,” *Syst. Dyn. Rev.*, vol. 10, no. 2–3, pp. 245–256, 1994.

[22] J. W. Forrester, “Counterintuitive behavior of social systems,” *Theory Decis.*, vol. 2, no. 2, pp. 109–140, Dec. 1971.

[23] D. C. Lane, “Should system dynamics be described as a‘hard’ or‘deterministic’ systems approach?,” *Syst. Res. Behav. Sci.*, vol. 17, no. 1, pp. 3–22, 2000.

[24] P. N. Johnson-Laird, *Mental models: Towards a cognitive science of language, inference, and consciousness*, vol. 6. Harvard University Press, 1983.

[25] D. Meadows, *Thinking in systems : a primer*. White River Junction Vt.: Chelsea Green Pub., 2008.

[26] D. Meadows, “Leverage Points: Places to Intervene in a System,” *Solutions*, vol. 1, no. 1, pp. 41–49, 2009.

[27] D. Luenberger, *Introduction to dynamic systems : theory, models, and applications*. New York: Wiley, 1979.

[28] C. W. Churchman, *The Systems Approach*. Delacorte Press, 1968.

[29] T. Jere Lazanski and D. M. Dubois, “Systems Thinking : Ancient Maya’s Evolution of Consciousness and Contemporary Systems Thinking,” 2010, pp. 289–296.

[30] C. W. Churchman, *The systems approach and its enemies*. New York: Basic Books, 1979.

[31] R. L. Flood, *Dealing with complexity: an introduction to the theory and application of systems science*. Springer, 1993.

[32] P. Checkland, “Systems thinking, systems practice: includes a 30-year retrospective,” 1999.

[33] P. M. Senge, *The fifth discipline: The art & practice of the learning organization*. Crown Business, 2006.

[34] K. J. Schlager, “Systems engineering-key to modern development,” *IRE Trans. Eng. Manag.*, vol. EM-3, no. 3, pp. 64–66, Jul. 1956.

[35] A. Sage, *Systems Methodology for Large-Scale Systems*. McGraw Hill, New York, 1977.

[36] D. M. Buede, *The engineering design of systems: Models and methods*, vol. 55. Wiley, 2011.

[37] E. Rechtin and M. W. Maier, *The art of systems architecting*. CRC Press, 2000.

[38] J. Gibson, W. T. Scherer, and W. F. Gibson, *How to do systems analysis*. Hoboken N.J.: Wiley-Interscience, 2007.

[39] N. Chomsky, *Knowledge of language: Its nature, origins, and use*. Greenwood Publishing Group, 1986.

[40] D. Cabrera, L. Colosi, and C. Lobdell, “Systems thinking,” *Eval. Program Plann.*, vol. 31, no. 3, pp. 299–310, 2008.

[41] C. W. Churchman, “Towards a theory of application in systems science,” *Proc. IEEE*, vol. 63, no. 3, pp. 351–354, 1975.

[42] N. Chomsky, “LANGUAGE AND THE MIND.,” 1968.

[43] M. D. Hauser, “The Faculty of Language: What Is It, Who Has It, and How Did It Evolve?,” *Science*, vol. 298, no. 5598, pp. 1569–1579, Nov. 2002.

[44] D. Isac and C. Reiss, *I-language: An introduction to linguistics as cognitive science*. Oxford University Press, 2013.

[45] D. G. Myers, *Exploring psychology*. Macmillan, 2004.

[46] J. H. Holland, “Complex adaptive systems,” *Daedalus*, pp. 17–30, 1992.

[47] C. Magee and O. De Weck, “Complex system classification,” 2004.

[48] G. of C. T. C. Programs, “The Social Implications of Sustainable and Active Transportation,” 07-Feb-2007. [Online]. Available: http://www.tc.gc.ca/eng/programs/environment-utsp-socialimplications-1013.htm. [Accessed: 18-May-2013].
[49] “Some NGOs CAN adjust to Failure: The PlayPumps Story.” [Online]. Available: http://aidwatchers.com/2010/02/some-ngos-can-adjust-to-failure-the-playpumps-story/. [Accessed: 18-May-2013].
[50] “Soil: securing the future - Address causes, not symptoms.” [Online]. Available: http://www.new-ag.info/01-6/focuson/focuson5.html. [Accessed: 18-May-2013].
[51] “Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy.” [Online]. Available: http://www.nap.edu/openbook.php?record_id=13105&page=383. [Accessed: 18-May-2013].
[52] “Telework Adoption and Energy Use in Building and Transport Sectors in the United States and Japan: Journal of Infrastructure Systems: (ASCE).” [Online]. Available: http://ascelibrary.org/doi/abs/10.1061/%28ASCE%291076-0342%282005%2911:1%2821%29. [Accessed: 18-May-2013].
[53] “Failure to consider available alternatives to hysterectomy and loss of kidney function as a result - Penningtons.” [Online]. Available: http://www.penningtons.co.uk/Global/Case%20studies/Failure-to-consider-available-alternatives-to-hysterectomy-and-loss-of-kidney-function-as-a-result.aspx?th=PIPink&pa=62A597C2-976E-43C3-8599-D830AFE16BA6. [Accessed: 18-May-2013].
[54] “Defense Base Closure and Realignment Commission (BRAC).” [Online]. Available: http://www.brac.gov/. [Accessed: 18-May-2013].
[55] “Bitburg Air Base.” [Online]. Available: http://www.globalsecurity.org/military/facility/bitburg.htm. [Accessed: 18-May-2013].
[56] “Decision Trees for Differential Diagnosis.” [Online]. Available: http://202.30.0.11/~lmk/title.htm. [Accessed: 18-May-2013].
[57] “BMC Cancer | Full text | Support Vector Machine Model for Diagnosis of Lymph Node Metastasis in Gastric Cancer with Multidetector Computed Tomography: A Preliminary Study.” [Online]. Available: http://www.biomedcentral.com/1471-2407/11/10. [Accessed: 18-May-2013].
[58] “The integration of energy and agricultural markets - Tyner - 2010 - Agricultural Economics - Wiley Online Library.” [Online]. Available: http://onlinelibrary.wiley.com/doi/10.1111/j.1574-0862.2010.00500.x/full. [Accessed: 18-May-2013].
[59] “Spy Agencies Say Iraq War Worsens Terrorism Threat - New York Times.” [Online]. Available: http://www.nytimes.com/2006/09/24/world/middleeast/24terror.html?pagewanted=all&_r=0. [Accessed: 18-May-2013].
[60] “Energy Citations Database (ECD) - - Document #145216.” [Online]. Available: http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=145216. [Accessed: 18-May-2013].

[61] "Three Moves Ahead: What Chess Can Teach You about Business | Free eBooks Download - EBOOKEE!" [Online]. Available: http://ebookee.org/Three-Moves-Ahead-What-Chess-Can-Teach-You-about-Business_609425.html. [Accessed: 18-May-2013].
[62] P. Schwartz, *The art of the long view : paths to strategic insight for yourself and your company*, 1st Currency pbk. ed. New York: Currency Doubleday ;, 1996.
[63] R. Lilienfeld, "Review of Life Cycle Data Relating To Disposable, Compostable Biodegradable, and Reusable grocery Bags," *ULS Rep. June*, vol. 1, 2007.
[64] I. Wallerstein, *The Modern World-System I: Capitalist Agriculture and the Origins of the European World-Economy in the Sixteenth Century, With a New Prologue*, vol. 1. Univ of California Press, 2011.
[65] "OECD Real-Time Data and Revisions Database." [Online]. Available: http://stats.oecd.org/mei/default.asp?rev=1. [Accessed: 18-May-2013].
[66] "Is There a Strong Link between Extreme Weather Events and Climate Change?: Scientific American." [Online]. Available: http://www.scientificamerican.com/article.cfm?id=climate-change-and-extreme-weather. [Accessed: 18-May-2013].
[67] B. Sørensen, *Low energy consumption scenarios*. IPCC Expert Meet. Mitig. Stab. Scenar., Copenhagen, 1999.
[68] "Pentagon Chief Rips Heart Out of Army's 'Future' | Danger Room | Wired.com."[Online]. Available: http://www.wired.com/dangerroom/2009/04/gates-rips-hear/. [Accessed: 18-May-2013].
[69] "JSTOR: Daedalus, Vol. 97, No. 4 (Fall, 1968), pp. 1141-1164." [Online]. Available: http://www.jstor.org/discover/10.2307/20013416?uid=3739936&uid=2&uid=4&uid=3739256&sid=21102299862517. [Accessed: 18-May-2013].
[70] "Future Combat Systems Solicitation." [Online]. Available: http://www.fas.org/man/dod-101/sys/land/docs/fcs-solicit.htm. [Accessed: 18-May-2013].
[71] "CRS: The Army's Future Combat System (FCS): Background and Issues for Congress, November 28, 2008 - WikiLeaks." [Online]. Available: http://wikileaks.org/wiki/CRS-RL32888. [Accessed: 18-May-2013].
[72] "New Pentagon policy urges more telework | Federal Times | federaltimes.com." [Online]. Available: http://www.federaltimes.com/article/20120420/PERSONNEL03/204200303/New-Pentagon-policy-urges-more-telework. [Accessed: 18-May-2013].
[73] "The Apple Way: How The Second-Gen Nest Thermostat Evolves To Help Users | Co.Design: business + innovation + design." [Online]. Available: http://www.fastcodesign.com/1669515/the-apple-way-how-the-second-gen-nest-thermostat-evolves-to-help-users. [Accessed: 18-May-2013].
[74] "Talking Transit: Atlanta votes no on solving traffic congestion, What's next? — Metropolitan Planning Council." [Online]. Available: https://www.metroplanning.org/news-events/article/6490. [Accessed: 18-May-2013].
[75] "Investor pitch powerpoint example." [Online]. Available: http://www.slideshare.net/ExecutivePlan/investor-pitch-powerpoint-example. [Accessed: 18-May-2013].
[76] "Integrated Life Cycle Chart." [Online]. Available: https://ilc.dau.mil/. [Accessed: 18-May-2013].

[77] K. Fischer, F. Besnard, and L. Bertling, “A Limited-Scope Reliability-Centred Maintenance Analysis of Wind Turbines,” in *Scientific Proceedings of the European Wind Energy Conference & Exhibition EWEA 2011, 14-17 March 2011, Brussels, Belgium*, 2011, pp. 89–93.
[78] “Living Earth Simulator project to create a real-time global model of human activity -- GCN.” [Online]. Available: http://gcn.com/articles/2011/01/11/scientists-plan-a-real-time-virtual-earth-simulation.aspx. [Accessed: 18-May-2013].
[79] I. Abel, “From technology imitation to market dominance: the case of iPod,” *Compet. Rev. Int. Bus. J. Inc. J. Glob. Compet.*, vol. 18, no. 3, pp. 257–274, 2008.
[80] “$35B Missile Defense Misses Bullet With Bullet - Bloomberg.” [Online]. Available: http://www.bloomberg.com/news/2011-08-03/missile-defense-costing-35-billion-misses-bullets-with-bullets.html. [Accessed: 18-May-2013].
[81] M. Birch, W. Moomaw, B. Gramig, and O. Doering, “Why Metrics Matter: Evaluating Policy Choices for Reactive Nitrogen in the Chesapeake Bay Watershed† - Environmental Science & Technology (ACS Publications).” [Online]. Available: http://pubs.acs.org/doi/abs/10.1021/es101472z. [Accessed: 20-Mar-2011].
[82] “Truck and SUV Sales Plunge as Gas Prices Rise.” [Online]. Available: http://www.washingtonpost.com/wp-dyn/content/article/2005/10/03/AR2005100301657.html. [Accessed: 18-May-2013].
[83] “FALLBROOK: Judge rejects Indians’ bid to halt construction over burial site Page 1 of 2 | UTSanDiego.com.” [Online]. Available: http://www.utsandiego.com/news/2012/feb/29/fallbrook-judge-rejects-indians-bid-to-halt/. [Accessed: 18-May-2013].
[84] “US corn ethanol fuels food crisis in developing countries - Opinion - Al Jazeera English.” [Online]. Available: http://www.aljazeera.com/indepth/opinion/2012/10/201210993632838545.html. [Accessed: 18-May-2013].
[85] “DSpace@MIT : Complex System Classification.” [Online]. Available: http://dspace.mit.edu/handle/1721.1/6753. [Accessed: 18-May-2013].
[86] “[Abstract] Dynamic Multi-Criteria Decision Analysis of Electricity Generation Mix Choices for Future Sustainability.” [Online]. Available: http://www.actapress.com/PaperInfo.aspx?PaperID=454306&reason=500. [Accessed: 18-May-2013].
[87] W. A. Magat, “Pollution control and technological advance: A dynamic model of the firm,” *J. Environ. Econ. Manag.*, vol. 5, no. 1, pp. 1–25, Mar. 1978.
[88] S. B. McLaughlin, *Biomass Use in Future Energy Production: Demonstration and Commercial Application for Agricultural Bioproducts and Cellulosic Biomass Use*. Oak Ridge National Laboratory, 2004, pp. 1–8.
[89] “EISA.” [Online]. Available: http://www.google.com/url?sa=t&source=web&cd=1&ved=0CBgQFjAA&url=http%3A%2F%2Ffrwebgate.access.gpo.gov%2Fcgi-bin%2Fgetdoc.cgi%3Fdbname%3D110_cong_bills%26docid%3Df%3Ah6enr.txt.pdf&rct=j&q=EISA&ei=EG3pTMmWGsGBlAfb_ajUCQ&usg=AFQjCNGQ1pANj3D9ctR41eXJCm3jD_b2bg&sig2=EEH2NRZK65MoEWNNO17mpQ. [Accessed: 21-Nov-2010].

[90] U.S. Congress, "ENERGY INDEPENDENCE AND SECURITY ACT OF 2007 Public Law 110-140." [Online]. Available: http://www.gpo.gov/fdsys/pkg/PLAW-110publ140/html/PLAW-110publ140.htm. [Accessed: 28-Mar-2014].
[91] F. Sissine, "Energy Independence and Security Act of 2007: a summary of major provisions," 2007.
[92] S. A. I. C. (SAIC) and M. A. Curran, *Life-cycle Assessment: Principles and Practice*. National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency, 2006.
[93] European Commission [E.C.], "Proposal for a Directive Of The European Parliament And Of The Council, on the promotion of the use of energy from renewable sources." Brussels, 2008.
[94] U. N. E. P. B. W. Group and U. N. E. P. I. P. for S. R. Management, *Towards sustainable production and use of resources: assessing biofuels*. UNEP/Earthprint, 2009.
[95] E. D. Larson, "A review of life-cycle analysis studies on liquid biofuel systems for the transport sector," *Energy Sustain. Dev.*, vol. 10, no. 2, pp. 109–126, 2006.
[96] E. Menichetti and M. Otto, "Energy Balance & Greenhouse Gas Emissions of Biofuels from a Life Cycle Perspective," *Proc. Sci. Comm. Probl. Environ. SCOPE Int. Biofuels Proj. Rapid Assess. RW Howarth Bringezu Eds*, p. Pages 81–109, Sep. 2008.
[97] F. W. Rusco and W. D. Walls, *Biofuels, Petroleum Refining, and the Shipping of Motor Fuels*. Institute for Advanced Policy Research, University of Calgary, 2008.
[98] T. W. Patzek, "Thermodynamics of the corn-ethanol biofuel cycle," *Crit. Rev. Plant Sci.*, vol. 23, no. 6, pp. 519–567, 2004.
[99] A. Elobeid, S. Tokgoz, D. J. Hayes, B. A. Babcock, and C. E. Hart, "The long-run impact of corn-based ethanol on the grain, oilseed, and livestock sectors with implications for biotech crops," 2007.
[100] R. Trostle, *Global Agricultural Supply and Demand: Factors Contributing to the Recent Increase in Food Commodity Prices (rev*. DIANE Publishing, 2010.
[101] R. Howarth, S. Bringezu, L. Martinelli, R. Santoro, D. Messem, and O. Sala, "Introduction: Biofuels and the Environment in the 21st Century," *Biofuels Environ. Consequences Interact. Chang. Land Use Proc. Sci. Comm. Probl. Environ. SCOPE Int. Biofuels Proj. Rapid Assess.*, pp. 22–25, 2008.
[102] D. Daggett, O. Hadaller, R. Hendricks, and R. Walther, "Alternative fuels and their potential impact on aviation," in *The 25th Congress of the International Council of the Aeronautical Sciences (ICAS) hosted by the German Society for Aeronautics and Astronautics Hamburg, Germany*, 2006.
[103] "Ensyn I RTP Renewable Liquid Fuels from Residual Biomass." [Online]. Available: http://www.ensyn.com/. [Accessed: 28-Mar-2014].
[104] M. A. Gabriel, *Visions for a sustainable energy future*. The Fairmont Press, Inc., 2008.
[105] M. Z. Jacobson, "Effects of ethanol (E85) versus gasoline vehicles on cancer and mortality in the United States," *Environ. Sci. Technol.*, vol. 41, no. 11, pp. 4150–4157, 2007.
[106] EPA, Environmental Protection Agency, "40 CFR Part 80 Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Proposed Rule." Federal Register pp. 24904-25143, 2009.
[107] S. Suh and G. Huppes, "Methods for Life Cycle Inventory of a product," *J. Clean. Prod.*, vol. 13, no. 7, pp. 687–697, Jun. 2005.

[108] E. Gallagher, "The Gallagher Review of the indirect effects of biofuels production." UK Secretary of State for Transport and the UNIDO, 2008.
[109] "RFA: Renewable Fuels Association." [Online]. Available: http://www.ethanolrfa.org/. [Accessed: 28-Mar-2014].
[110] C. L. Pereira and E. Ortega, "Sustainability assessment of large-scale ethanol production from sugarcane," *J. Clean. Prod.*, vol. 18, no. 1, pp. 77–82, 2010.
[111] T. Kalnes, G. Hopkins, M. Reno, and D. Shonnard, "Envergent Biofuel Technology and Life Cycle Assessment," in *2009 International Conference TC Biomass Conversion Science*, 2009, pp. 16–18.
[112] "Health Expenditures - The 2012 Statistical Abstract - U.S. Census Bureau." [Online]. Available: http://www.census.gov/compendia/statab/cats/health_nutrition/health_expenditures.html. [Accessed: 11-Jul-2012].
[113] "Healthcare Costs and U.S. Competitiveness - Council on Foreign Relations." [Online]. Available: http://www.cfr.org/health-science-and-technology/healthcare-costs-us-competitiveness/p13325. [Accessed: 10-Jul-2012].
[114] "OECD Health Data 2012 - Frequently Requested Data." [Online]. Available: http://www.oecd.org/document/60/0,3746,en_2649_33929_2085200_1_1_1_1,00.html. [Accessed: 11-Jul-2012].
[115] "WHO | World Health Organization Assesses the World's Health Systems." [Online]. Available: http://www.who.int/whr/2000/media_centre/press_release/en/index.html. [Accessed: 11-Jul-2012].
[116] "New study finds 45,000 deaths annually linked to lack of health coverage | Harvard Gazette." [Online]. Available: http://news.harvard.edu/gazette/story/2009/09/new-study-finds-45000-deaths-annually-linked-to-lack-of-health-coverage/. [Accessed: 12-Jul-2012].
[117] "NationalHealthAccountsProjected," 14-Jun-2012. [Online]. Available: https://www.cms.gov/Research-Statistics-Data-and-Systems/Statistics-Trends-and-Reports/NationalHealthExpendData/NationalHealthAccountsProjected.html. [Accessed: 15-Jul-2012].
[118] S. W. Manning, "The Tragedy of the Ten-Million-Acre Bill," *Soc. Serv. Rev.*, vol. 36, no. 1, pp. 44–50, Mar. 1962.
[119] "Uninsured: Highest Percentage in Texas, Lowest in Mass." [Online]. Available: http://www.gallup.com/poll/122387/uninsured-highest-percentage-texas-lowest-mass.aspx. [Accessed: 14-Jul-2012].
[120] R. M. Klevens, J. R. Edwards, C. L. Richards, T. C. Horan, R. P. Gaynes, D. A. Pollock, and D. M. Cardo, "Estimating health care-associated infections and deaths in US hospitals, 2002," *Public Health Rep.*, vol. 122, no. 2, p. 160, 2007.
[121] "Pfizer, Crestor tops for global promotional spend in 2011 - Medical Marketing and Media." [Online]. Available: http://www.mmm-online.com/pfizer-crestor-tops-for-global-promotional-spend-in-2011/article/238922/. [Accessed: 15-Jul-2012].
[122] "Lobbying Spending Database | OpenSecrets." [Online]. Available: http://www.opensecrets.org/lobby/top.php?indexType=c. [Accessed: 15-Jul-2012].
[123] "AP: Mass. Health Care Lobbying Topped $51M Over Past 5 Years « CBS Boston." [Online]. Available: http://boston.cbslocal.com/2012/03/25/ap-mass-health-care-lobbying-topped-51m-over-past-5-years/. [Accessed: 15-Jul-2012].

[124] "Health Care Largest Lobbying Industry in CA in 2011; HMO Kaiser... -- SANTA MONICA, Calif., March 12, 2012 /PRNewswire-USNewswire/ --." [Online]. Available: http://www.prnewswire.com/news-releases/health-care-largest-lobbying-industry-in-ca-in-2011-hmo-kaiser-tops-list-142355375.html. [Accessed: 15-Jul-2012].
[125] S. Brill, "Bitter Pill: Why Medical Bills Are Killing Us | TIME," *TIME.com*. .
[126] W. B. Rouse, "Health care as a complex adaptive system: Implications for design and management," *BRIDGE-Wash.-Natl. Acad. Eng.-*, vol. 38, no. 1, p. 17, 2008.
[127] N. C. for H. S. (US and others, "Health, United States, 2012," 2013.
[128] N. C. for H. S. (US), *Health, United States, 2006 with chartbook on trends in the health of Americans*. Government Printing Office, 2007.
[129] M. E. Porter and E. O. Teisberg, "How physicians can change the future of health care," *JAMA J. Am. Med. Assoc.*, vol. 297, no. 10, pp. 1103–1111, 2007.
[130] R. S. Kaplan and M. E. Porter, "THE BIG IDEA-How to Solve the Cost Crisis In Health Care," *Harv. Bus. Rev.*, p. 46, 2012.
[131] "Physicians and Surgeons : Occupational Outlook Handbook : U.S. Bureau of Labor Statistics." [Online]. Available: http://www.bls.gov/ooh/Healthcare/Physicians-and-surgeons.htm#tab-5. [Accessed: 14-Jul-2012].
[132] "Top 25 US Health Insurance Companies - US News Health Plans." [Online]. Available: http://health.usnews.com/health-plans/national-insurance-companies. [Accessed: 14-Jul-2012].
[133] "Humana - Corporate Governance." [Online]. Available: http://phx.corporate-ir.net/phoenix.zhtml?c=92913&p=irol-governance. [Accessed: 14-Jul-2012].
[134] "ECFMG® | Educational Commission for Foreign Medical Graduates." [Online]. Available: http://www.ecfmg.org/. [Accessed: 02-Mar-2013].
[135] P. Batalden, D. Leach, S. Swing, H. Dreyfus, and S. Dreyfus, "General Competencies And Accreditation In Graduate Medical Education," *Health Aff. (Millwood)*, vol. 21, no. 5, pp. 103–111, Sep. 2002.
[136] R. C. Ziegelstein and N. H. Fiebach, "' The Mirror' and' The Village': A New Method for Teaching Practice-Based Learning and Improvement and Systems-Based Practice," *Acad. Med.*, vol. 79, no. 1, p. 83, 2004.
[137] J. K. Johnson, S. H. Miller, and S. D. Horowitz, "Systems-based practice: improving the safety and quality of patient care by recognizing and improving the systems in which we work," *Adv. Patient Saf. New Dir. Altern. Approaches*, vol. 2, pp. 321–330, 2010.
[138] S. Swing, "ACGME Launches Outcomes Assessment Project," *JAMA J. Am. Med. Assoc.*, vol. 279, no. 18, pp. 1492–1492, May 1998.
[139] R. A. David, L. M. Reich, and others, "The creation and evaluation of a systems-based practice/managed care curriculum in a primary care internal medicine residency program," *Mt. SINAI J. Med.*, vol. 72, no. 5, p. 296, 2005.
[140] R. S. Gonnering, "Complexity Theory and the 'Puzzling' Competencies: Systems-Based Practice and Practice-Based Learning Explored," *J. Surg. Educ.*, vol. 67, no. 2, pp. 122–124, Mar. 2010.
[141] C. Y. Colbert, P. E. Ogden, A. R. Ownby, and C. Bowe, "Systems-Based Practice in Graduate Medical Education: Systems Thinking as the Missing Foundational Construct," *Teach. Learn. Med.*, vol. 23, no. 2, pp. 179–185, 2011.
[142] A. Didwania, W. C. McGaghie, E. Cohen, and D. B. Wayne, "Internal Medicine Residency Graduates' Perceptions of the Systems-Based Practice and Practice-Based

Learning and Improvement Competencies," *Teach. Learn. Med.*, vol. 22, no. 1, pp. 33–36, 2010.
[143] D. Reed, C. Wittich, M. Drefahl, and F. McDonald, *A quality improvement curriculum for internal medicine residents*. MedEdPORTAL, 2009.
[144] C. M. Wittich, D. A. Reed, F. S. McDonald, P. Varkey, and T. J. Beckman, "Perspective: transformative learning: a framework using critical reflection to link the improvement competencies in graduate medical education," *Acad. Med.*, vol. 85, no. 11, p. 1790, 2010.
[145] C.-L. Chang and C.-H. Chen, "Applying decision tree and neural network to increase quality of dermatologic diagnosis," *Expert Syst. Appl.*, vol. 36, no. 2, pp. 4035–4041, Mar. 2009.
[146] L. Tanner, M. Schreiber, J. G. H. Low, A. Ong, T. Tolfvenstam, Y. L. Lai, L. C. Ng, Y. S. Leo, S. G. Vasudevan, C. P. Simmons, and others, "Decision tree algorithms predict the diagnosis and outcome of dengue fever in the early phase of illness," *PLoS Negl. Trop. Dis.*, vol. 2, no. 3, p. e196, 2008.
[147] A. Gawande, *The checklist manifesto: How to get things right*. Profile Books, 2010.
[148] P. L. Dyne, "Systems-Based Practice: The Sixth Core Competency," *Acad. Emerg. Med.*, vol. 9, no. 11, pp. 1270–1277, Nov. 2002.
[149] "Virginia Board of Medicine - Frequently Asked Questions." [Online]. Available: http://www.dhp.virginia.gov/medicine/medicine_faq.htm. [Accessed: 09-Jul-2012].
[150] "Virginia Board of Medicine - Board Members." [Online]. Available: http://www.dhp.virginia.gov/medicine/medicine_board.htm. [Accessed: 09-Jul-2012].
[151] "Agency for Healthcare Research and Quality Guidelines for Ensuring the Quality of Information Disseminated to the Public." [Online]. Available: http://aspe.hhs.gov/infoquality/Guidelines/AHRQinfo.shtml. [Accessed: 15-Jul-2012].
[152] "NHQR State Snapshots." [Online]. Available: http://statesnapshots.ahrq.gov/snaps11/. [Accessed: 12-Jul-2012].
[153] "2011 National Healthcare Quality and Disparities Reports: Data Sources." [Online]. Available: http://www.ahrq.gov/qual/qrdr11/datasources/index.html. [Accessed: 15-Jul-2012].
[154] "The Rankings - United Health Foundation." [Online]. Available: http://www.americashealthrankings.org/rankings. [Accessed: 15-Jul-2012].
[155] "Graduate Medical Education - Stanford University School of Medicine." [Online]. Available: http://gme.stanford.edu/. [Accessed: 04-Mar-2013].
[156] "Academic Information." [Online]. Available: http://www.hopkinsmedicine.org/som/students/academics/. [Accessed: 07-Dec-2012].
[157] "Medical Education Program of the David Geffen School of Medicine at UCLA." [Online]. Available: http://dgsom.healthsciences.ucla.edu/dgsom/education/pages/mep. [Accessed: 07-Dec-2012].
[158] "Medical School Curriculum — School of Medicine at the University of Virginia." [Online]. Available: http://www.medicine.virginia.edu/education/medical-students/admissions/ume-curriculum/ume-curriculum.html. [Accessed: 07-Dec-2012].
[159] "HMS Course Catalog." [Online]. Available: http://www.medcatalog.harvard.edu/. [Accessed: 07-Dec-2012].
[160] "UPENN || School of Medicine || Admissions Office || Curriculum." [Online]. Available: http://www.med.upenn.edu/admiss/curriculum.html?1. [Accessed: 04-Mar-2013].

[161] "MD Competencies | UCSF Medical Education." [Online]. Available: http://meded.ucsf.edu/ume/md-competencies. [Accessed: 04-Mar-2013].

[162] "Center for the Science of Health Care Delivery at Mayo Clinic - Health Care Systems Engineering Program." [Online]. Available: http://mayoresearch.mayo.edu/mayo/research/science-of-health-care-delivery/health-care-systems-engineering-program.cfm. [Accessed: 04-Mar-2013].

[163] "FRB: Mission." [Online]. Available: http://www.federalreserve.gov/aboutthefed/mission.htm. [Accessed: 15-Jul-2012].

[164] P. D. Turney, P. Pantel, and others, "From frequency to meaning: Vector space models of semantics," *J. Artif. Intell. Res.*, vol. 37, no. 1, pp. 141–188, 2010.

[165] "Spamming - Wikipedia, the free encyclopedia." [Online]. Available: http://en.wikipedia.org/wiki/Spamming. [Accessed: 19-Mar-2014].

[166] G. Salton, A. Wong, and C.-S. Yang, "A vector space model for automatic indexing," *Commun. ACM*, vol. 18, no. 11, pp. 613–620, 1975.

[167] G. S. Ingersoll, T. S. Morton, and A. L. Farris, *Taming text: how to find, organize, and manipulate It*. Manning Publications Co., 2013.

[168] K. S. Jones, "A statistical interpretation of term specificity and its application in retrieval," *J. Doc.*, vol. 28, no. 1, pp. 11–21, 1972.

[169] C. D. Manning, P. Raghavan, and H. Schütze, *Introduction to information retrieval*, vol. 1. Cambridge university press Cambridge, 2008.

[170] T. Hastie, R. Tibshirani, J. Friedman, T. Hastie, J. Friedman, and R. Tibshirani, *The elements of statistical learning*, vol. 2. Springer, 2009.

[171] H. Zhang, "The optimality of naive Bayes," *A*, vol. 1, no. 2, p. 3, 2004.

[172] R. Caruana and A. Niculescu-Mizil, "An empirical comparison of supervised learning algorithms," in *Proceedings of the 23rd international conference on Machine learning*, 2006, pp. 161–168.