The Case for Systems Thinking in Undergraduate Engineering Education

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Abstract—Systems Thinking is an approach to solving complex problems that cannot be solved using conventional means. It helps engineers design functional and reliable systems and it helps to understand why the world looks and behaves as it does. However, Systems Thinking is usually not integrated into undergraduate engineering curricula; instead, it is either taught as a stand-alone, independent program or course, or it is not taught at all. We believe that this is sub-optimal. In this position paper we seek to start a discussion by explaining what Systems Thinking is and its benefits, why it is important to teach it to undergraduate engineers, and *how* to teach it, using examples for each of the principal engineering disciplines. We also discuss obstacles and limitations and propose an approach to inculcating systems thinking into engineering curricula.

Keywords—systems thinking, engineering education, engineering curricula

1 Introduction

The world continues to change: it is more complex than ever before. To remain effective, engineering must change along with it. The Internet plus advances in computers and communication technologies have increased the interconnectivity among engineered products and systems, ancillary and support systems, infrastructure, society, and the environment. Conventional engineering solutions typically do not address these complex interactions.

In industry, product engineers are expected to have a holistic understanding of the product, including the ability to answer questions about product reliability, safety, economic viability, and sociological and environmental impacts. These answers are not provided by conventional engineering equations. The current state of the automobile industry, for example, encompasses self-driving, electric powered vehicles capable of communicating with phones, manufacturers' servers, and other vehicles on the road [1]. Similarly, the current state of the art in Smart Homes entails networked appliances and utility services, with the capability for exchange of operational data and remote control by users and manufacturers [2].

Beyond industry, our critical infrastructure (e.g., power systems, transportation systems, communications systems, and potable and wastewater systems) is undergoing a similar engineering paradigm shift. Increasingly the emphasis is on how to improve performance by exploiting the interconnections of the infrastructure with the various interfacing technological systems, society, and the environment. For example, with Smart Highways, cities will be able to both better control traffic (especially in emergencies) and optimize road maintenance schedules. Smart grids will optimize inputs from various energy generation systems based on changing demand.

Societies may be viewed as complex systems with which technology interfaces [3]. In the past, whereas psychology, sociology, culture, politics, and economics were viewed as domains separate from and independent of engineering, it is now recognized that these societal elements are intimately tied to the technologies that serve them, often in complex ways. Considering technology in isolation from them is foolish. Technologies fail where cultures do not embrace them; cultures fail where they do not adopt technologies that their competitors do. Today's engineers must understand the psychological, cultural, economic, political, and environmental implications of their engineering decisions.

Traditional engineering education does not provide the broad systemic perspective outlined above, nor does it facilitate holistic thinking. It does not consider non-technical issues such as culture, politics, and psychology, which are intimately tied to the performance and function of engineered systems and products. It is usually taught from a linear perspective (problem→action→solution) and does not consider feedback. It often does not identify the user system into which engineered products fit. Conventional analytic tools such as differential equations are useful but often do not yield insights into complex problems, and they are sometimes unwieldy or unsolvable in closed form. Basic equations, design paradigms, standard procedures, and rules of thumb have served us well in the past but fall short as the world becomes more interconnected and as solutions become less black-and-white. Systems Thinking, on the other hand, addresses these issues. It is a perspective, a language, and a collection of tools that help to analyze and understand interconnections, complex interactions, feedback, and holism. Unfortunately, it is not widely taught in undergraduate engineering curricula, for several reasons:

- Its benefits are not understood by administrators and instructors.
- Its methodology and tools are not well-understood by instructors.
- It is perceived to be a substitute or replacement for (as opposed to an adjunct to) conventional, tried-and-true engineering approaches.
- Engineering curricula are full and cannot accommodate additional courses.

We aim to address these obstacles in this paper. Engineers of today must be trained to think and problem-solve as Systems Thinkers. They must think holistically and adopt a broad definition of "system," and they must understand the complex interactions (including feedback and emergence) among system components. They must recognize that there is usually more than one solution to any complex problem and that their engineering judgment must be tempered with an appreciation for sociological, cultural, ethical, political, and psychological factors. Addressing socio-technical challenges requires a global perspective since perceptions of engineering solutions acceptable to various cultures can be very different. The organization in charge of accrediting science, computing, technology, and engineering college and university programs (ABET) supports this perspective in stating that all engineering baccalaureate graduates should possess "an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors [4]." Therefore, undergraduate engineering curricula must change to include Systems Thinking. Subsequently, we explain how this can be achieved, how Systems Thinking applies to standard engineering disciplines, how obstacles may be addressed, and how Systems Thinking may be taught to undergraduate engineering students.

Subsequent sections of the paper are organized as follows: In Section 2 we provide a literature review; in Section 3 we offer an overview of Systems Thinking highlighting important concepts and principles applicable to engineering. In Section 4 we apply systems thinking tools to typical engineering problems and provide 8 specific examples covering the major engineering disciplines, demonstrating how these may be integrated into existing curricula. Section 5 presents the results of a preliminary field study. In Section 6 we conclude with proposals for improving the adoption of Systems Thinking in Engineering education.

2 Literature review

There is a significant number of publications on the application of Systems Thinking to engineering education. These entail contributions that inform on topics to teach, methods for evaluating Systems Thinking competencies, and exemplar problems for teaching. However, there is a lack of a discussion that integrates these separate literature strands into a comprehensive case for Systems Thinking in engineering education that addresses why, how, a proposed approach, and obstacles hampering its mainstream adoption.

Several research publications [5–9] have called for the incorporation of Systems Thinking into engineering education. The expected learning outcomes are generally consistent, *viz*. to equip students with competencies required to work collaboratively with others, to draw on multidisciplinary expertise to properly frame problems, and to devise technical solutions that adequately factor in the complexities of the operating environment and human interaction. These competencies are typically associated with the disciplines of Systems Thinking, Systems Engineering, and Systems Design. Literature contributions include the identification of required Knowledge, Skills, and Abilities (KSA's); the description of essential topics and courses that have been implemented; and surveys used to assess the effectiveness of these courses.

Hadgraft et al. [5] note that in Australia teaching Systems Thinking is already mandated by Australian accreditation guidelines and that it must include the contextual framework of social, cultural, ethical, legal, political, economic, environmental, sustainable, and safety considerations, which are very similar to ABET accreditation guidelines in the U. S. Hadgraft also notes that industry ranks Systems Thinking as important for engineering design and management work and touts it as a core engineering competence. They surveyed 307 chemical engineering and civil engineering undergraduates for their opinions and found that Systems Thinking skills are valued by the majority (77%) of students, but that only ~33% of the students felt that Systems Thinking skills were taught or assessed well.

Jain et al. [6] note the need to include societal, business, and environmental considerations in engineering designs, and they argue that Systems Thinking should be part of the core undergraduate engineering curriculum, but their paper is more about Systems Engineering than Systems Thinking. They also argue for starting Systems Thinking training in grades K-12.

Wasson [7] argues that there is an educational void in Systems Engineering instruction for engineers and bemoans the facts that Systems Engineering is taught primarily at the graduate (not undergraduate) level, that its acceptance is limited by curriculum requirements, and that it is not introduced at the K-12 level. He suggests that a Systems Engineering undergraduate course be required for all engineering curricula and that we execute a paradigm shift to a Systems Engineering methodology-based education. Like Jain, Wasson refers primarily to Systems Engineering, not Systems Thinking.

The growing need for inculcating Systems Thinking into undergraduate and graduate engineering curricula is also being highlighted by industry. For example, Summerton et al. [8] note that Systems Thinking facilitates a more integrated understanding of related subject matter, as opposed to teaching disparate concepts. They claim that Systems Thinking improves student learning by promoting the consideration of a wide range of both positive and negative impacts within the context of multiple interacting systems, and Systems Thinking allows students to make predictions based on their understanding of how system outputs may change given changes in an input or parameter. They also observe that Systems Thinking prepares students more thoroughly for their future career paths.

Voorhees and Hutchison [9] state that in the Green Chemistry industry "industrial employers are looking to hire students with expertise in sustainable practices and an understanding of systems thinking and life cycle." In the lean manufacturing industry, Ballé [10] observes from his personal experience that his work with Systems Thinking concepts and System Dynamics simulations prior to studying lean practices facilitated his immediate application of lean practices, which was not the case for his colleagues that did not have a background in Systems Thinking.

The preceding publications substantiate a demand for Systems Thinking in engineering education both from industry and academia. While these works do well to expose the need, they necessitate follow up questions on optimal Systems Thinking content and how to practically teach it.

Davidz et al. [11] conducted a field study to determine the enablers, barriers, and precursors to Systems Thinking development in engineers. Their study focused on 205 aerospace industry employees with various levels of experience and tenure. They concluded that the primary enablers of Systems Thinking were experiential learning, individual characteristics, and a supporting environment. However, their analysis focused on practicing Systems Engineers as opposed to academic curricula or content. It is interesting that their survey responses indicated that in 2007, education was not considered a principal enabler of Systems Thinking in engineers. They offer the following suggestions for academia: 1) Offer Systems programs 2) Use feedback mechanisms to continually improve Systems programs and courses 3) Structure courses to emphasize experiential learning 4) Structure courses to emphasize context and knowledge integration and 5) Continue research on the mechanisms for effective Systems Thinking development. We agree with Davidz et al's proposals for academia and we expand on their proposal 4 by illustrating several Systems Thinking applications in the context of specific engineering disciplines.

Muci-Kuchler et-al. [12] note that student teams in undergraduate Mechanical Engineering courses often struggle when they have to design products with several components requiring multiple areas of technical expertise, due to the watering down of typical design problems to remove the complexity that is typically present in practical systems. Valenti [13] similarly underscores a need for reforms in mechanical engineering curricula to better meet the demands of industry. His proposed Systems Thinking topics include a Systems Perspective, Teamwork, Communication, Creative Thinking, and Professional Ethics. Based on the U.S. Department of Labor's Engineering Competency model [14], the Systems Engineering Career Competency Model (SECCM), [15] and the CDIO syllabus [16], Muci-Kuchler et al. offer a more extensive list of topics aimed at basic Systems Thinking and Systems Engineering KSA's. The primary topics include:

- System, Element and System boundaries
- System context and System of Systems
- System function, behavior and emergent properties
- System structure and decomposition
- System life cycle
- Basic types of system architecture
- Identifying Stakeholders
- Interfaces, interactions and dependencies

A typical undergraduate product design course was updated based on the aforementioned topics to include lessons in Systems Thinking and Systems Architecture. The emphasis here however was on Systems Engineering, and the subject of dynamic modeling (which is central to Systems Thinking) was not explored in detail.

A similar effort is offered in [17], targeted at Industrial Engineering students. Here the required topics were covered in two courses: an undergraduate and a graduate level course on Systems Engineering and Design. Students were first taught 'Classical Systems Engineering' topics, then later exposed to Sociotechnical System Theory (SST), Cognitive Systems Engineering (CSE) and Soft Systems Methodology (SSM). These methodologies were treated as complementary and useful in resolving a range of problems from "hard" to "soft" where all problem situations are presented on a continuum from well-structured to unstructured. This work offers an extensive coverage of the main ideas in the field of Systems Thinking, and it may serve as a useful template for a Minor in the field.

Rehman [18] describes the objectives of the E2020 Scholars Program at Iowa State University, which sought to have students become proficient in four pillar areas: leadership, innovation, global awareness, and systems thinking. Each pillar was introduced during three weeks in a freshman-level seminar followed by half of a semester in a year-long sophomore-level seminar. Students applied systems thinking to grand challenge problems by considering factors inside and outside of engineering and using three graphical tools. They identified connections between elements with rich pictures, explained relationships with causal loop diagrams, and sketched the behavior over time of key variables in the system. Qualitative observations and quantitative assessments suggested that the initial offerings were mostly successful. Most students stated that the activities helped them to appreciate the range of issues affecting an engineering problem. Students struggled most with identifying key variables and deriving the behavior over time from causal loop diagrams. This work offers some useful resources for implementing courses that offer an introduction and overview to Systems Thinking.

Degen et al. [19] provide an overview of a new course that was developed to help sophomore students in mechanical engineering develop skills in systems thinking. They provide details about an Engineering Systems Thinking Survey (ESTS) that was developed to assess systems thinking skills in specific areas and provide the results of the ESTS from implementation of the course during two separate semesters. The specific areas targeted by that survey were the identification of customer needs, establishing target product specifications, concept generation, and systems architecture. The survey results showed that the course was successful in improving students' self-efficacy on each of the four topics, particularly in setting target specifications and systems architecture. Comparisons of pre- and post-survey results showed improvements in student answers on the technical questions related to identification of customer needs, establishing target product specifications, and concept generation, with a slight decrease in the area of systems architecture. The survey results also indicated the need to strengthen students' awareness of concept implementation. Similar to [12] this work is more pertinent to Systems Engineering; the subject of dynamic modeling is not explored.

Robinson-Bryant [20] describes a Systems Thinking skills intervention developed for an online Project Management course for 3rd and 4th year engineering students. It describes the application of a vertical course thread approach, called a Conceptual Systems Thinking Integration approach, which outlines instructional events, learning events, knowledge features, and assessment events that can be applied to facilitate "robust" learning of Systems Thinking skills. It also provides a literature-based discussion of the growing importance of developing an orientation towards Systems Thinking skills for all engineers. Similarly, in [21] Cattano et al. describe their approach in teaching Systems Thinking to Civil Engineering students at Clemson University in 2009. They elaborate on teaching methodologies: which specific exercises, assessments, and lecture topics worked best. These papers are a good initial reference for how to teach Systems Thinking to engineers, but they do not address obstacles or an integrated approach.

While the offerings of standalone Systems Thinking courses described in references [17–21] are useful guides for what to teach, the concepts and tools explored in these courses may be more enlightening when applied to typical engineering problems. For this reason, we favor a more integrative approach that embeds the lessons and tools of Systems Thinking into the context of traditional engineering courses. Such an approach is suggested without much detail by Davidz et al [11] in their proposals for academia.

Kasi, Chi, and Padmanabhan [22] note the morphological analogy between groundwater flow (civil engineering) and electrical current flow (electrical engineering) using similar Laplace equations. They argue that using multiple "representations" in engineering education is beneficial: "Thinking about a problem through multiple representations and through translations within and among representations contributes to conceptual and application understanding of undergraduate students." Although they did not invoke Systems Thinking, their work supports the benefits of conceptual modeling in engineering education. The application of Systems Thinking tools like Causal Loop Diagrams and dynamic modeling tools might reveal systemic structure that helps students understand not only that fluid flow and electron flow are analogous, but *why* they are analogous.

The need for engineers to be trained in non-technical disciplines such as ethics, psychology, sociology, the environment, communication, economics, and a global perspective is discussed by Rüütmann, Parts, Teichmann, and Kipper [23]. They added many of these topics to the engineering curriculum at the Tallinn Institute of Technology in Estonia, and they note the obstacles encountered. Student surveys confirmed the value of the non-technical subjects. However, the authors do not articulate these competencies as components of a broader Systems Thinking perspective.

In her paper [24] on engineers' systems intelligence, Lappalainen discusses the need for engineers to consider global societal and social issues along with traditional engineering issues. She calls for the practice of "systemic capabilities" using positive psychology and socio-emotive frameworks to stimulate new ways of thinking. The paper is not a comprehensive case for incorporating Systems Thinking into engineering education; however, it supports the perspective that engineers should be trained on non-technical socio-economic, psychological, cultural, and environmental topics as well as on traditional engineering topics.

Stoica and Islam [25] describe their experience integrating systems engineering and software engineering in computer engineering education. Their course instruction was supplemented by real-world software projects for industry. Their work emphasizes the benefits of teaching non-technical topics to undergraduate engineers, but it focuses on systems engineering as opposed to Systems Thinking.

Hung et al. [26] describe a case study in which they assessed the ability of eight students to apply Systems Thinking concepts both before and after the students had taken a one semester modelling course. They argue that systems modelling is a cognitive tool that helps students understand Systems Thinking concepts. They found a statistically significant increase in students' utilization of systems thinking through interrelationships, causal relationships, and feedback processes, and concluded that teaching System Dynamic models is effective in increasing students' knowledge of and ability to apply Systems Thinking concepts. They mention several models that were used (population, thermostat regulating room temperature, growth of a city on limited land, prey and predator) but they do not discuss the specific details of the models.

On application of Systems Dynamic modeling for analysis of physical systems, Fuchs [27] advocates for integrating Systems Dynamics into undergraduate courses. He identifies Physics courses as a suitable starting point and discusses a sample course in solar energy engineering that applies this approach. He notes that introducing Systems Dynamics to students earlier on equips them with the tools for exploring complex engineering problems, without getting bogged down in the mathematical details that are usually required. Fuchs offers a more extensive list of examples of System Dynamics applications in physics pertinent to engineers in [28].

Beyond system dynamic modeling there is a growing call for an early adoption of modeling and simulation in undergraduate engineering education with the goal of balancing theory, simulation, and project-based content [29]. Li et al [30] describe a simulation-based teaching mode for a mechanical engineering design. A broader application of simulation technology for training undergraduate mechanical engineers is detailed in [31]. A more project focused approach is proposed by Pirinen [32], who advocates the adoption of an applied research and development culture in engineering education termed “Learning by Developing” (LbD). We believe Systems Thinking as an underlying framework can support an implementation of these disparate themes in engineering education by balancing theory, simulation, and project-based methods.

The literature emphasizes the need for Systems Thinking in engineering education with a number of publications proposing courses on the subject. However, there is some diversity in the topics proposed; ranging from Systems Engineering, Systems Architecture, System Dynamics, and Soft Systems Methodology to Critical Systems Thinking. More significantly it is not clear from these proposals how Systems Thinking concepts can be applied in the context of the various engineering disciplines. All these factors contribute to the lack of a mainstream adoption of Systems Thinking in engineering education. To address this, we argue for the need for a comprehensive, convincing case for Systems Thinking in engineering education that addresses why, how, a proposed approach, and obstacles hampering its adoption.

We hope to initiate such a discussion in this paper. We demonstrate here that Systems Thinking concepts can be applied to concepts from most engineering disciplines. We argue that incorporating systems modeling approaches into existing courses exposes students to analysis tools flexible enough to address real world problems that are often ill-structured, incomplete, and ambiguous. Additionally, we show that existing project-based course work can be extended with Systems Thinking concepts to better address environmental and socio-cultural issues and foster interdisciplinary collaboration.

3 Systems thinking overview and tools

Systems Thinking has been characterized as a perspective, a language, and a set of tools [33]. It is a holistic perspective that recognizes that the relationships among system components and between the components and the environment are as important as the components themselves. It is a language of feedback loops, emergence, complexity, hierarchies, self-organization, dynamics, and unintended consequences. Systems

Thinking tools include the Iceberg model, causal loop diagrams, behavior-over-time plots, stock-and-flow diagrams, systemic root cause analysis, dynamic modeling tools, and archetypes. See [33] for a more comprehensive explanation of Systems Thinking.

We distinguish between Systems Thinking and Systems Engineering, which is an emerging discipline and profession that focuses on the successful engineering of complex man-made systems [34]. Systems Engineering entails a systematic process of translating stakeholder needs into increasingly detailed design specifications, ultimately leading to the realization of physical/cyber-physical systems that are deployed, operated, and retired in time, in accordance with stakeholder expectations.

In our teaching, we have found it convenient to split the Systems Thinking tools into three categories:

1. Conceptual Modeling Tools to articulate and frame issues, elicit knowledge and beliefs, and meaningfully organize information to appreciate underlying causal structures.
2. Dynamic Modeling Tools to assess the dynamics of those causal structures, and to evaluate potential interventions.
3. Holistic Thinking Tools to ensure that complex problems are not addressed using unidimensional solutions.

Each of these is explained in the following sections.

3.1 Conceptual modeling tools

Robinson [35] defines Conceptual Modeling as a non-software specific description of a simulation model that is to be developed, describing the objectives, inputs, outputs, content, assumptions and simplifications of the model. This definition is mostly suited to the context of simulation development. In this paper we apply the term more loosely, from the perspective that Conceptual Modeling may not necessarily lead to a simulation model. Conceptual Modeling entails framing a problem precisely enough to allow for more rigorous analysis, but also transparently enough to engage a broad base of stakeholders and capture their perspectives on the problem. This should ideally inform a common baseline of what the problem entails, deepen stakeholders' understanding of the problem and its context, and support further analysis to inform how the problem should be addressed.

Conceptual Modeling tools offer a language to describe issues in general concepts that are accessible to a broad range of stakeholders, while also abstracting the details of constructs required for dynamic analysis. For example, constructs such as Stocks, Flows, and Causal Loops offer a simple way to visualize the structure and dynamics of systemic problems ranging from machine control to the spread of disease.

There are several Conceptual Modeling approaches incorporating tools such as general graphical modeling languages, simulation framework-specific languages, Behavior-Over-Time plots, Stock and Flow diagrams, Causal Loop Diagrams, the Agents Modeling Language (AML), and the Iceberg Model.

3.2 Dynamic modeling tools

Dynamic models may be mathematical or simulation models, used to assess how a system changes over time. These allow us to exercise and test our assumptions, hypotheses, and knowledge of a system especially in situations where experimentation on the actual system is infeasible and/or prohibitively expensive. Systems Thinking heavily emphasizes understanding the dynamics of systems before any interventions are made, as it is often true that the problems of today are the result of the fixes of yesterday.

Differential equations are currently the dominant dynamic modeling approach in engineering. The power and limits of calculus, however, must be weighed carefully. While calculus is rigorous and effective for making generalizations about system behavior, it is an arcane language, unintuitive to most, and often too restrictive in the nature of problems that can be modeled. Furthermore, some differential equations are just unsolvable in closed form. Given the emphasis on dynamics in Systems Thinking we argue for the adoption of simulation/computational models as adjuncts to (not replacements for) differential equations. These are more expressive, flexible, and applicable to a broader range of problem contexts, albeit with some limitations in the generalization power.

There are several simulation methodologies available. System Dynamics [36] is the predominant simulation methodology in Systems Thinking. According to Forrester, [37] it is a necessary foundation underlying effective thinking about systems. Recently the field has embraced a broader perspective on dynamic modeling tools including other frameworks such as Cellular Automata, Discrete Event Simulation, and Agent Based Modeling.

3.3 Holistic thinking tools

Politicians, businesspeople, and bureaucrats often attempt to solve complex problems unidimensionally: that is, by throwing money at the problem. An example is the 2008 U. S. bank bailout after the financial/housing crisis. These unidimensional "solutions" sometimes address short-term symptoms, but often do not solve the underlying causes and may lead to other problems. The 2008 bailout, for example, led to the enrichment of bank executives who had made poor decisions and created incentives for managers to take unreasonable risks with the knowledge that they will be bailed out by taxpayer dollars; it also retarded economic development by rewarding failure.

Technocrats and engineers make a similar mistake by assuming that complex problems such as poverty, hunger, terrorism, climate change, pollution, and the lack of potable water can be solved by technology alone. But technology alone does not address the political, economic, environmental, ethical, psychological, and cultural aspects of the situation. In many cases, these non-technical aspects dominate system performance. For example, in the 2014 Ebola outbreak in Guinea, Liberia, and Sierra Leone, the control strategy involved isolating and avoiding contact with sick people. However, the West African culture involved strong family values, which mandated that the ill be cared for by family members who also wash the bodies of their dead [38]. These traditions proved to be major obstacles to the strictly technical solution.

Another example involves the Amish, whose traditions eschew motorized vehicles, the use of electricity, and the taking of photographs. Electric vehicles would not be successful in that culture. Yet another example involves vaccination. Many vaccines are stabilized with pork-derived gelatin. Orthodox Jews and conservative Muslims cannot use pork products, so conventional vaccines are not suitable for them.

Engineers must therefore be trained to think holistically. Specific Systems Thinking tools that facilitate holistic thinking include System Breakdown Structures, System Interrelationship Matrices, and Causal Loop Diagrams. But a well-written paragraph may be all that is needed. Also, the ability to identify and understand worldviews and mental models is a skill critical to holistic thinking. This capacity is facilitated by tools (such as the Iceberg Model) that help discover, expose, assess, and revise our ubiquitous (and often incorrect) Mental Models.

4 Description of systems thinking tools

In this section we elaborate on specific Systems Thinking tools discussed in the previous section and provide examples of their application. The aim is to show how these tools offer a complementary approach for framing and understanding typical engineering problems and how to apply them to address complex societal problems.

4.1 Conceptual modeling tools and applications

Causal loop diagrams. According to Monat and Gannon [39] one of the first steps in attempting to understand system behavior is the construction of a causal loop diagram, which graphically portrays systemic causes and effects and helps to identify reinforcing and balancing feedback loops. A simple temperature control causal loop diagram for heating is shown in Figure 1.

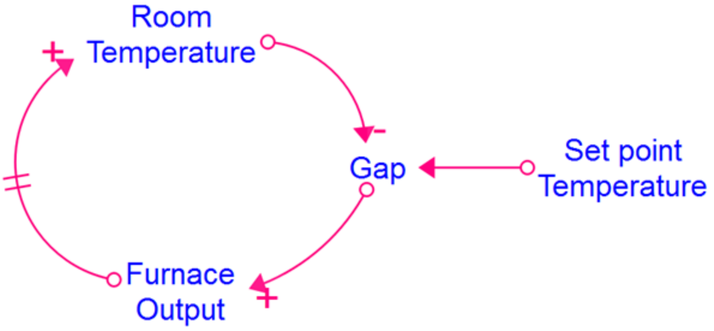


Fig. 1. Temperature control causal loop diagram

Stock-and-flow diagrams. Systems usually require the storage or accumulation of things, which may include physical quantities such as the volume of liquid, quantity of electric charge, number of deer in a field, number of clients of a company, or amount of money in a bank account. Those accumulated things can also be non-physical things such as love, greed, anger, or lust. These quantities of things in systems are called stocks, which can increase or decrease due to flows into or out of them. Stock and flow diagrams illustrate the stocks, inflows, and outflows of things in a system. These diagrams are usually developed in concert with causal loop diagrams and are important first steps in system dynamics modeling. Stock and flow diagrams, along with causal loop diagrams, provide valuable insights in understanding system behavior. A simple stock-and-flow diagram showing logging impact on a forest [36] is shown in Figure 2.

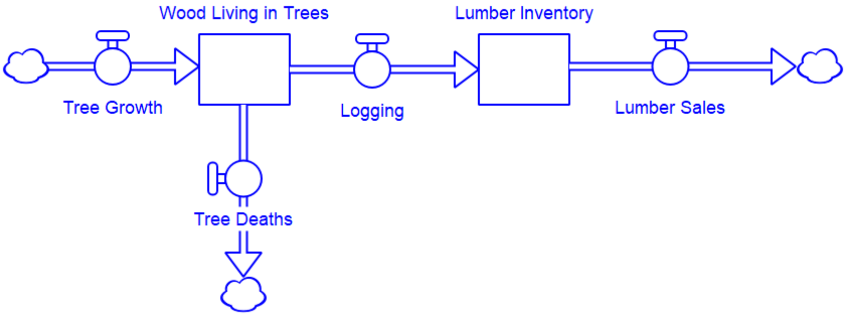


Fig. 2. A basic stock-and-flow diagram [36]

Behavior-over-time plots. When one first comes upon a system, it can be very difficult to understand the way the system works or the systemic structure. Behavior-Over-Time (BOT) plots are therefore useful. BOT plots simply show the value of one or more system parameters over time. Several examples are shown in Figure 3.

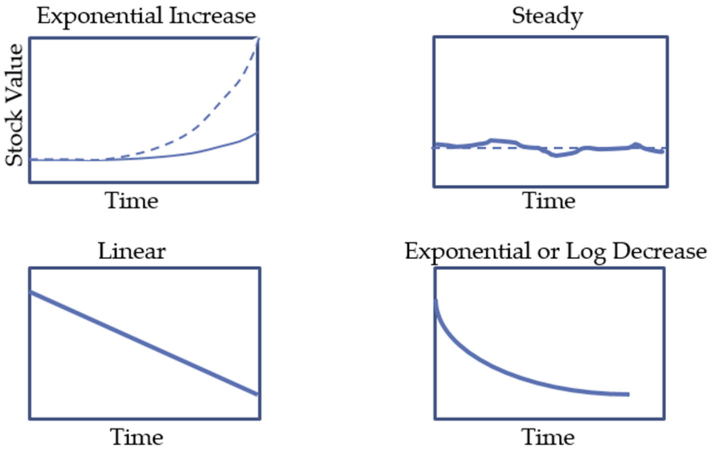


Fig. 3. Behavior-over-time plots

A parameter that increases or decreases exponentially indicates the presence of a reinforcing feedback loop. A parameter that oscillates indicates the presence of feedback loop with delays. A linear parameter indicates either the absence of feedback loops or broken feedback loops. A parameter that remains constant over time indicates the presence of a stabilizing feedback loop. Thus, simple observation of BOT plots provides insight into the systemic structure.

The Iceberg model. The Iceberg Model is a convenient uber-tool for understanding the systemic big picture. It posits that repeated observable events are patterns that are caused by systemic structure (hierarchies and feedback loops), and that structure is caused by underlying forces (mental models in human-designed systems; natural forces such as gravity and electromagnetism in natural systems). The Iceberg Model is depicted in Figure 4.

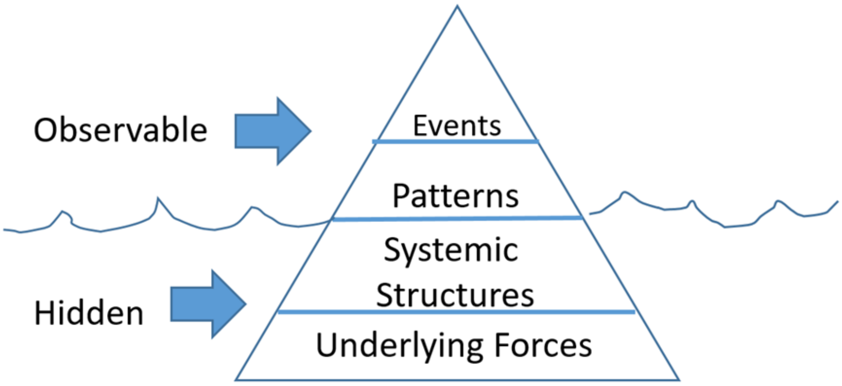


Fig. 4. The Iceberg model

Events and patterns are typically observable while the underlying systemic structures and mental models are not and must be uncovered.

4.2 System dynamics tools and applications

System dynamic tools. System Dynamics was developed in the 1950’s and 1960’s, mostly through the work of M.I.T.’s Jay Forrester who adapted the mathematics of control theory to the dynamic modeling of business decisions and subsequently to urban and global policy analysis [40–42]. According to Forrester, System Dynamics involves interpreting real life systems as computer simulation models that allow one to see how the structure and decision-making policies in a system create its behavior.

Monat and Gannon [39] state, “In their most basic form, System Dynamic models are typically control volume analyses: an initial quantity or stock increases over time due to an inflow and decreases due to an outflow” as shown in Figure 5.

Fig. 5. Control volume analysis

In the above example, t is time and dN/dt represents the instantaneous change in the quantity of stock N with respect to time. Given that N_o represents the initial value of the stock, this model implements equation 1, which is used to calculate the population N as the simulation advances in time increments Δt.

$$N(t) = N_o + [(dN/dt)_{in} - (dN/dt)_{out}]\Delta t \tag{1}$$

Modeling the dynamics of a system usually starts with developing a causal loop diagram and then translating into a stock and flow diagram. Next, links between stocks and flows are added along with initial values for each stock. Algebraic equations are then developed to quantify the inflows into and outflows from the stocks, and a simulation is run and debugged. Behavior-Over-Time plots are usually used to display the results, which must then be compared with reality to validate the model. After the results are validated, control points may be identified, and experiments conducted to see how to best influence the system. Detailed instructions on how to model the dynamics of a system are provided by Richmond [43].

In the following subsections we apply System Dynamics to several engineering problems that are traditionally solved using differential equations. We argue that System Dynamics is especially well-suited to such problems due to its flexibility in adjusting model parameters and intuitive graphical language supporting conceptual modeling. This approach scales better for real world dynamic analysis and should be considered as a valuable addition to traditional differential equations for teaching dynamic engineering analysis.

Examples of the application of systems thinking tools to major engineering disciplines. It is important to show that System Dynamics modeling can be beneficially applied to a broad range of engineering disciplines. Therefore, we include eight examples demonstrating its application to fluid mechanics, heat transfer, mechanical engineering, electrical engineering, nuclear engineering, and environmental engineering.

Radioactive decay. A typical decay or depletion process can be described by the simple Causal Loop Diagram (CLD) shown in Figure 6.

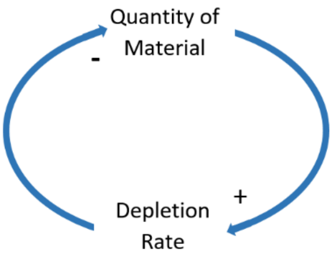


Fig. 6. Causal loop diagram for depletion

The CLD indicates that a greater quantity of material increases the depletion rate but that a higher depletion rate reduces the quantity of material. Figure 7 shows the corresponding stock-and-flow diagram indicating that the rate of uranium decay is proportional to the quantity of uranium remaining. Once this schematic is entered into ISEE Systems' Stella Architect software, one need only enter an initial concentration for the starting stock of uranium and that the decay rate is equal to a constant time the concentration of uranium per the equation $dN/dt = -kN$ (where N is the concentration of a radioactive species such as U 238, t is time, and k is the radioactive decay constant); the model then yields the familiar exponential decay curve shown in Figure 8.

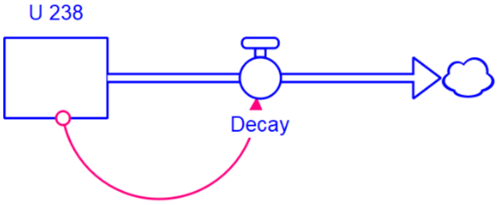


Fig. 7. Stock-and-flow for U-238 spontaneous decay

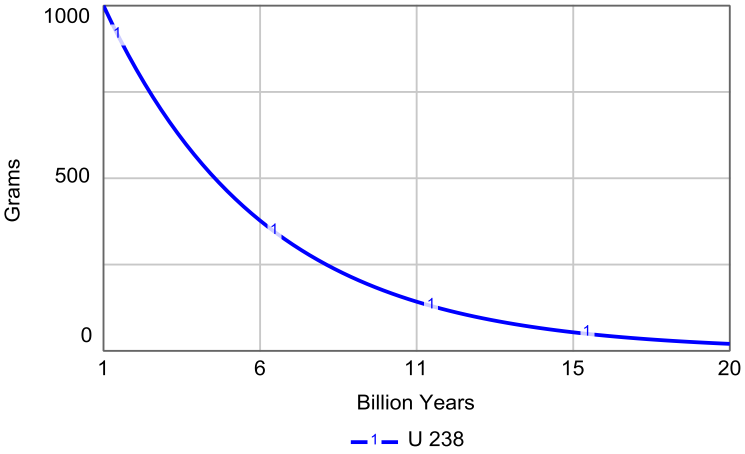


Fig. 8. Radioactive decay

A conventional engineering solution to this problem would require the integration of the equation $dN/dt = -kN$ which is far less descriptive and intuitive than the System Dynamic perspective.

Fluid mechanics: Tank drainage. A simple tank drainage model exemplifies the weakness in conventional engineering education and the benefits of Systems Thinking. Figure 9 shows a cylindrical 5000-gallon tank filled with V gallons of water. At time zero, a valve near the bottom of the tank is opened, allowing the water to gush out at rate dV/dt. What is the volume of water in the tank as a function of time?

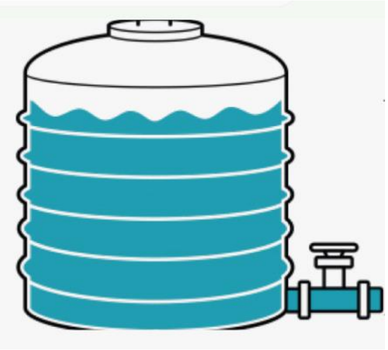


Fig. 9. Tank draining. There are V gallons of water in the tank and the drainage rate is dV/dt

A conventional solution to this problem would argue that the drainage rate, dV/dt equals some constant k times the instantaneous volume of water in the tank V, *i.e.* $\frac{dV}{dt} = -kV$. Solving this by rearranging terms and integrating yields the exponential relationship $V = V_o e^{-kt}$. Where Vo is the initial volume of water in the tank. A plot of the water volume vs time is shown in Figure 10.

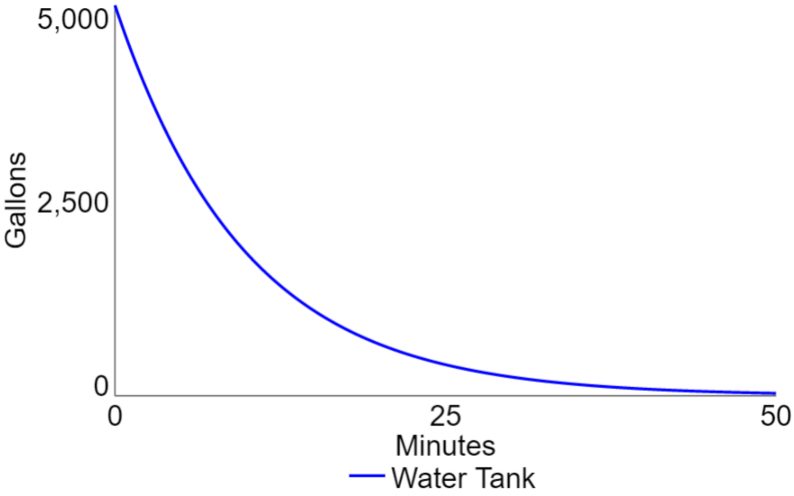


Fig. 10. Tank volume vs time

Yet in our introductory course on Systems Thinking, many engineering students get this plot wrong, drawing a linear decay of volume over time. When this occurs, we ask the students to consider a smaller cylindrical tank on a tabletop, as shown in Figure 11.

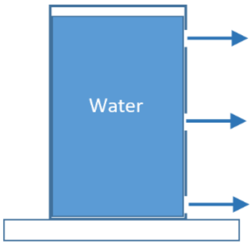


Fig. 11. Tank on table

We ask the students to imagine three small holes drilled into the side of the tank at various elevations and ask the students to sketch the trajectories of the water exiting from the 3 holes. They eventually figure out that the water spurts vigorously out of the bottom hole, less so out of the middle hole, and barely trickles out of the top hole. When we ask why this is so, they reply that the pressure increases toward the bottom of the tank because of the greater volume of water pressing down due to gravity. We then take them back to the draining 5,000-gallon tank and ask them to re-plot the tank volume vs time, and this time they get it right. Systems Thinking provides an interactive conceptualization that allows a student to visualize the dynamics of a situation as opposed to a differential equation which often leaves students stuck with the mathematical mechanics of the problem. A stock-and-flow diagram for this situation is shown in Figure 12 and the corresponding Causal Loop Diagram is provided above in Figure 6. The System Dynamic model output is shown above in Figure 10. The stock-and-flow diagram indicates that the rate of water draining is proportional to the volume of water remaining in the tank.

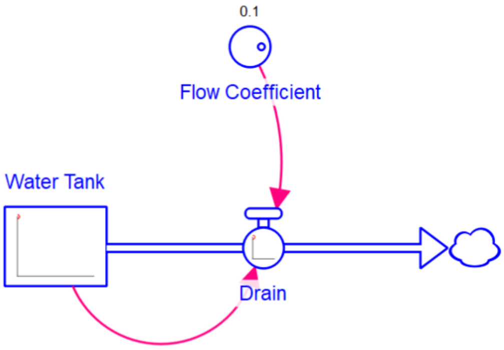


Fig. 12. Drainage stock-and-flow diagram

Here again the System Dynamics approach provides insights not afforded by the conventional differential equation solution.

Heat transfer: Ice freezing on a pond. In winter, how fast does ice buildup on the surface of a pond, and when will it be thick enough to walk on safely? Consider the schematic shown in Figure 13 in which a newly forming volume of ice of area A and thickness dx is forming just under the surface of existing ice on a pond.

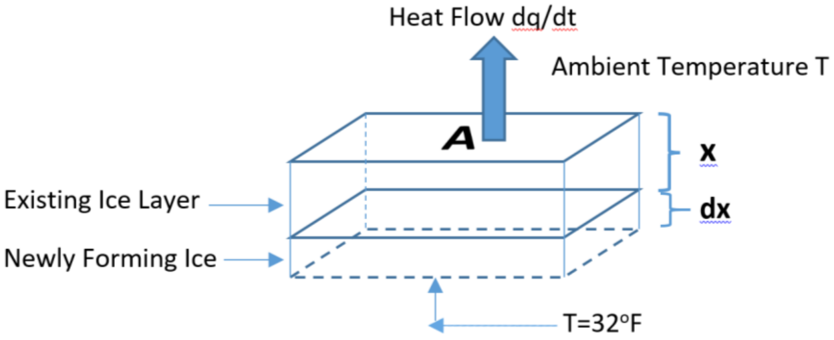


Fig. 13. Schematic of ice freezing at the surface of a pond

Define:
ρ = density of ice = 0.036 lbm/cubic inch
$\varDelta H_f$ = Water heat of fusion = 143 BTU/lbm
k = thermal conductivity of ice = 2.3 BTU/(day-inch-degree F)
x = thickness of ice in inches
A = area in square inches
t = time in days
T = temperature in degrees F
dq/dt = heat flow in BTUs/day

The rate of heat flow through the ice, dq/dt is provided by the standard conductive heat flow equation $dq/dt \ = \ kA(32-T)/x$.

And dq, the amount of heat transferred in time dt is then:

$$dq \ = \ kA(32-T)dt/x \tag{2}$$

The amount of heat that must be extracted to freeze a volume of water with dimensions $A \cdot dx$ is given by $A \cdot dx \cdot \rho \cdot \varDelta H_f$. Equating this to dq in equation 2 yields:

$$\rho \, \varDelta H_f \, A \, dx = \ kA(32-T)dt/x \tag{3}$$

Which may be rearranged and simplified to yield:

$$dx/dt \ = \ k(32-T)/(x \, \rho \, \varDelta H_f) \tag{4}$$

which is the rate of ice growth over time. A conventional solution to this equation would involve multiplying both sides by dt and integrating to obtain a square root dependence of ice thickness on time. But System Dynamics obviates the need for integration. Instead, one may draw a very simple stock-and-flow diagram for this situation as shown in Figure 14.

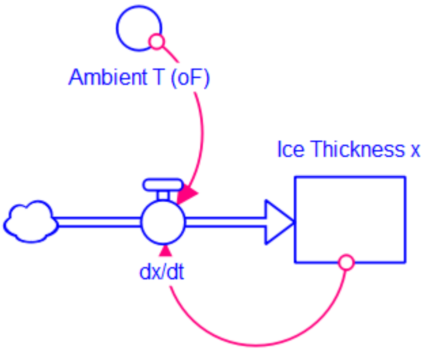


Fig. 14. Stock and flow diagram for Ice Freezing on Pond Surface

Then all one must do is enter $k(32 - T)/(x\ \rho\ \Delta H_f)$ for dx/dt in the Stella Architect model and run the model, plotting x, the ice thickness over time. The result is the graph shown in Figure 15.

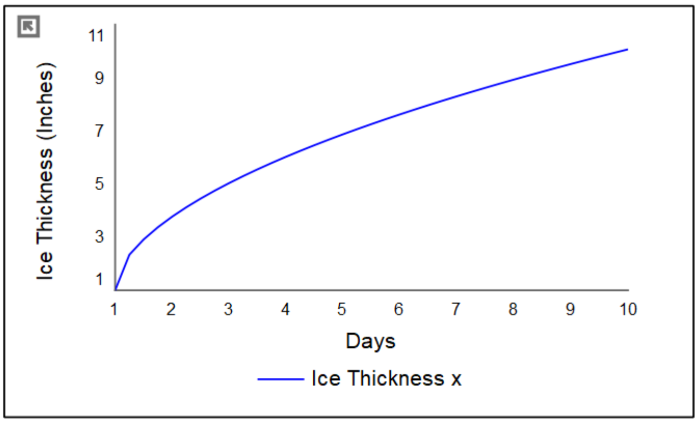


Fig. 15. Ice thickness vs time

Mechanical engineering: Simple harmonic motion. A simple harmonic oscillator subject to both gravitational and spring forces is depicted in Figure 16.

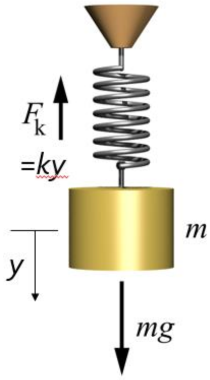


Fig. 16. Spring-mass system

Traditional methods of solving for the mass's position as a function of time involve guessing a solution of the form: $y = Ae^{i\omega t}$. Where y = the mass's vertical position, $i = \sqrt{-1}$, k = the spring constant, t = time, m = the mass of the oscillator, and $\omega = (k/m)^{.5}$. The expression is then differentiated twice and substituted into the expression $F = m\ddot{y} = mg - ky$, the imaginary term is disregarded, and one obtains the solution $y = Acos[(k/m)^{.5}\, t]$. This method of solution is not intuitive to most students, and it is hard to understand why a solution must be guessed, as well as what the guess should be. In addition, since the solution is not analytic, might there not be other solutions that also work?

System Dynamics provides an alternative (and perhaps more intuitive) methodology. First, a Causal Loop Diagram (see Figure 17) is drawn.

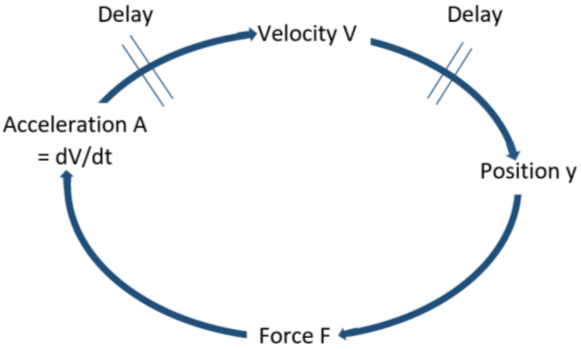


Fig. 17. Spring-mass causal loop diagram

The mass's vertical position y determines the magnitude of the force that acts upon it while simultaneously the force on the mass impacts the mass's acceleration which impacts the mass's velocity which impacts the mass's vertical position y. However, while the position instantaneously changes the force, the force does not instantaneously affect the mass's position; there is a delay as the force produces an acceleration that changes the mass's velocity and, over time, its position. It is this delay that causes the oscillation. This is a rule of thumb for Systems Thinking: feedback loops with delays typically cause oscillation. Therefore, if one observes an oscillation in nature, it behooves one to figure out the systemic relationships and identify the causative feedback loops. A stock-and-flow diagram (see Figure 18) may then be drawn for this situation.

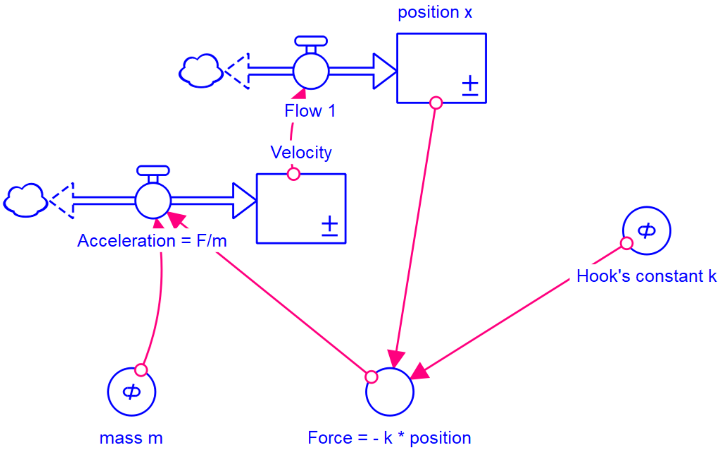


Fig. 18. Spring-mass stock-and-flow diagram

The right side of this model shows the Hooke's Law force (the spring force) resulting from spring compression and gravitational force: $F = mg - ky$. But also, $F = ma$, so the spring and gravitational forces cause an acceleration of the mass m, which is shown on the left side. The force responds instantaneously to the position and so does the acceleration, since $F = ma$. But the acceleration causes a velocity change over time (velocity does not respond instantaneously to acceleration), and the velocity causes a position change over time (position does not respond instantaneously to velocity.)

A sample set of parameters for this model could be:
Initial Position y = 50 mm
Hooke's Constant k = 0.5 N/mm
Force = (-1)(Hooke's Constant k)(Position y) + (9.8)(Mass m) (N)
Mass m = 1 kg
Acceleration = (-k)(position y)/(mass m) (m/s^2)
Initial Velocity = 0 m/s
Flow 1 = Velocity m/s

This model was entered into ISEE Systems' Stella Architect system dynamics modeling software, and yielded the following plot (Figure 19) of the mass's position vs time:

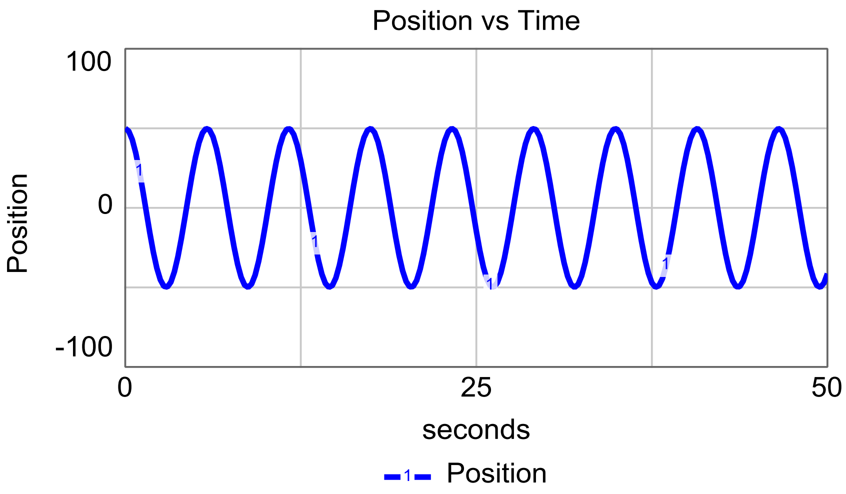


Fig. 19. Stella model output

This is an intuitive, simple method of solving for the position of the mass over time involving only fundamental concepts of force, mass, acceleration, and velocity.

Electrical engineering: Oscillating circuits. LC circuits, like the one depicted in Figure 20, are common in radio, TV, tuners, oscillators, signal generators, mobile phones, power systems, and electronic filters. In the figure, V is voltage, L is inductance, and C is capacitance.

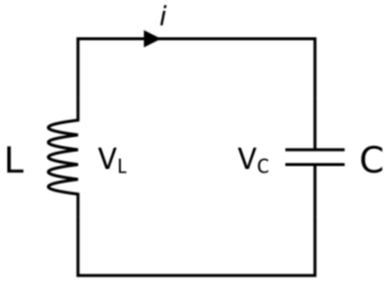


Fig. 20. Simple LC circuit

Traditionally, the current flow over time in these circuits is solved using differential equations analogous to those used for the simple harmonic mechanical oscillator described above. Defining V = voltage, q = charge, i = current, and t = time, we have:

$$V_{\mathrm{C}} = -q/C \tag{5}$$

$$V_{\mathrm{L}} = L\, di/dt \tag{6}$$

$$di/dt = V/L \tag{7}$$

$$i = (di/dt)dt \tag{8}$$

$$q = idt \tag{9}$$

The conventional solution for the current flow in this circuit is quite involved, involving a second-order differential equation for which we guess a solution of the form $i(t) = Ke^{st}$ where $i(t)$ is the current, K and s are constants, and t = time. This is then differentiated twice and substituted into the Kirchoff's law equation $V_l + V_c = 0$, leading to a solution of the form: $i(t) = K_1e^{j(1/LC)^{0.5}t} + K_2e^{-j(1/LC)^{0.5}\,t}$ where $j^2 = -1$. Euler's formula is then used to replace the exponential terms with trigonometric terms, the imaginary terms are disregarded, and one obtains the solution : $i(t) = (C/L)^{0.5}V_o sin[(1/LC)^{0.5}t]$ where V_o is the voltage at time zero. This method of solution is not intuitive to most students and is quite elaborate.

A Systems Thinking approach to this problem would start with a Causal Loop Diagram as shown in Figure 21.

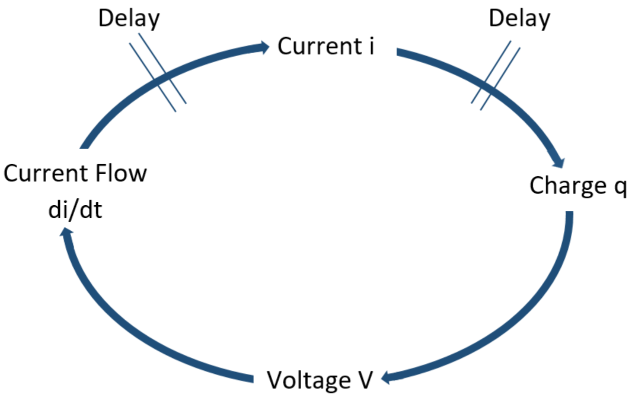


Fig. 21. LC circuit causal loop diagram

The circuit's charge q determines the magnitude of the voltage across both the inductance and the capacitance while simultaneously the voltage impacts the circuit's current flow which impacts the circuit's current which impacts the circuit's charge q. However, while the charge instantaneously changes the voltage, the voltage does not instantaneously affect the circuit's charge; there is a delay as the voltage produces a current flow that changes the current and, over time, its charge. It is this delay that causes the oscillation. A stock-and-flow diagram for this situation is shown in Figure 22.

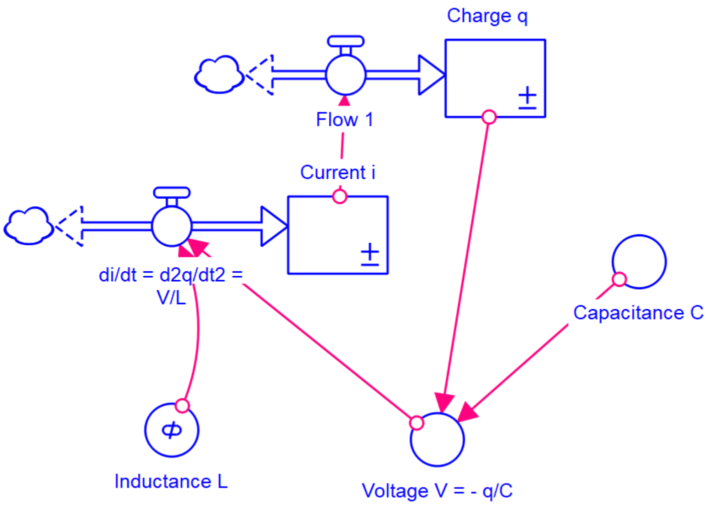


Fig. 22. LC circuit stock-and-flow diagram

The right side of this model shows the voltage generated across the capacitor $V_c = -q/C$ as a result of the charge q. But also $V_c = V_L = L \cdot di/dt$, so that voltage causes a change in the current flow di/dt through the inductor, which is shown on the left side. The voltage responds instantaneously to the charge and so does the di/dt, since V=L di/dt. But the current change di/dt causes a change in current i over time (current i does not respond instantaneously to di/dt), and the current i causes a charge q change over time (charge q also does not respond instantaneously to current.) Hence current and charge are represented as stocks.

Modeling this system in ISEE Systems' Stella Architect software yields the behavior-over-time plot depicted in Figure 23, showing the sinusoidal oscillation of both current and voltage. No differential equations were involved.

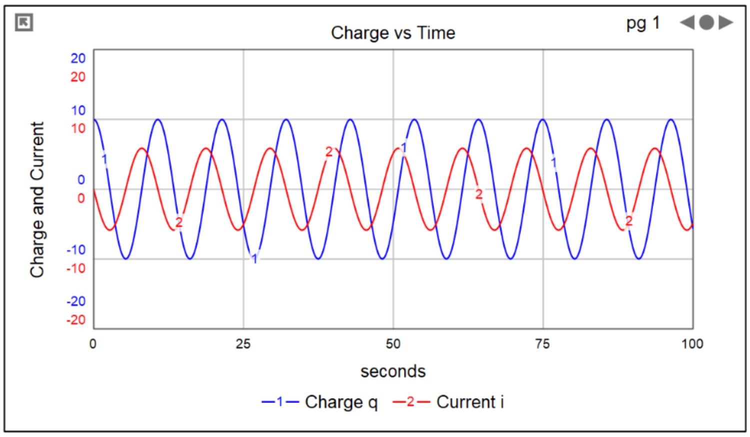


Fig. 23. Stella model output for LC circuit

The similarities between the mechanical engineering spring-mass system and the electrical engineering oscillating circuit are noteworthy: the behavior-over-time, causal loop, and stock-and-flow diagrams are morphologically identical. One may infer that the systemic structure of both systems is similar, and one may then question if the systemic structure for other oscillating systems (hydraulic, pneumatic, acoustic, building and bridge oscillations in the wind) are also based on similar systemic structure. This is the beauty of Systems Thinking: it exposes and provides insight into the underlying structure of systems. In the case of oscillations, systems will oscillate whenever there is a stabilizing feedback loop with delays.

Environmental engineering: Population dynamics/epidemiology. Bacteria Growth. Bacterial growth dynamics are classically described using differential equations.

Definitions:

N = population of bacteria
N_o = initial population
C = carrying capacity in units of population
t = time
k = a rate constant

The rate of change of population N is then written as $dN/dt = kN\,[1 - N/C]$ which is a non-linear differential equation. This equation is hard to solve using calculus and requires the use of partial fractions. After much effort it eventually leads to the classic logistic solution.

$$N(t) = C/\left[1 + \left(\frac{C-N_o}{N_o}\right) e^{-kt}\right] \tag{10}$$

But System Dynamics provides a much easier and more intuitive solution. A very simple stock-and-flow diagram describing this situation is shown in Figure 24.

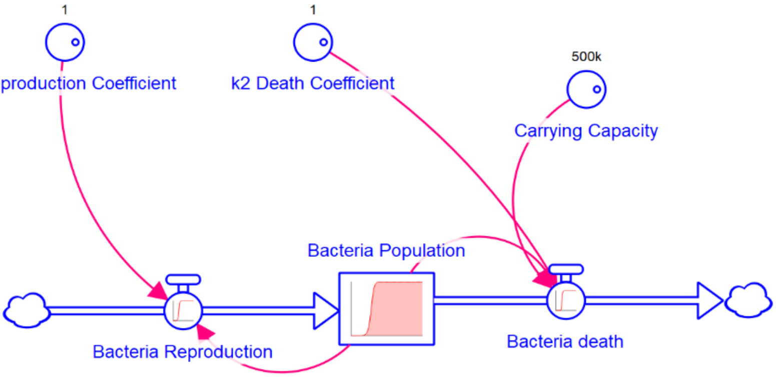


Fig. 24. Bacteria growth stock-and-flow diagram

The bacteria population N is increased by bacteria reproduction and decreased by bacteria death, both of which are impacted by the existing population N. And using the isee Systems Stella Architect software permits the solution of this problem without any differential equations or calculus as depicted in Figure 25.

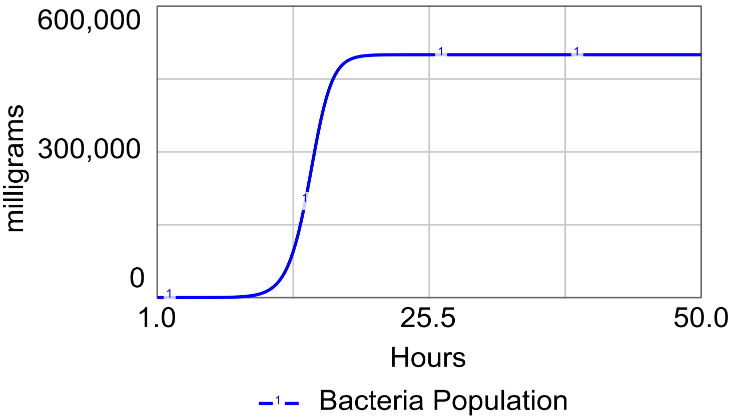


Fig. 25. Stella model output for bacteria growth

Environmental engineering: Population dynamics/predator-prey relationships. The relationships between predators and prey have been studied extensively by environmental engineers and ecological biologists. The populations of the various species have been described by the Lotka-Volterra differential equations. Where x is the population of prey, y is the population of predators, and b, p, r, and d are constants, these equations are:

$$dx/dt \;=\; bx - pxy \tag{11}$$

$$dy/dt \;=\; rxy - dy \tag{12}$$

These equations *cannot be solved* in closed form; analysists must resort to computer-generated numerical solutions, which typically yield an oscillation in the populations of both predators and prey, with the two populations out of synch by a constant amount.

A System Dynamics solution to this problem, on the other hand, is straightforward. We use an example involving cabbages (prey) and rabbits (predators). The stock and flow diagram is presented in Figure 26.

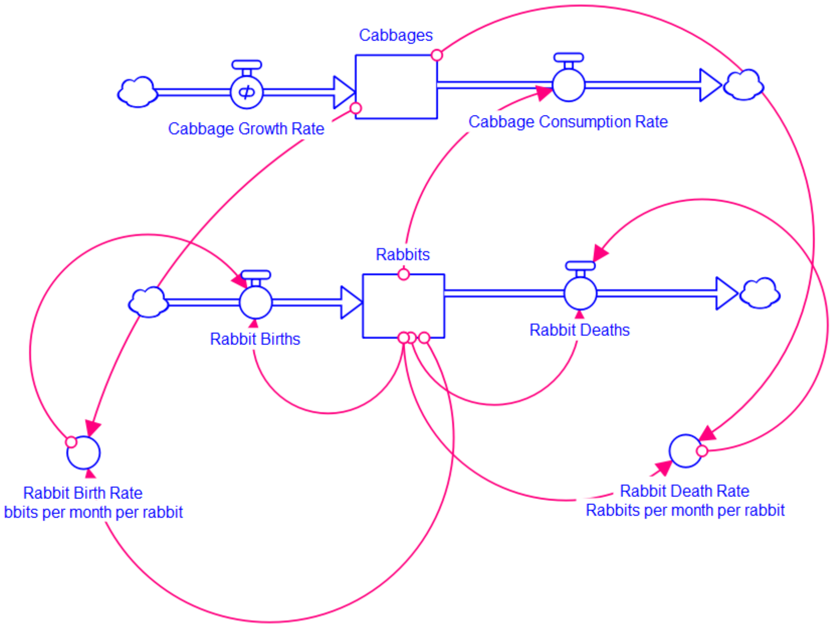


Fig. 26. Predator-prey stock-and-flow diagram

In this model, both cabbages and rabbits are born and die. But the rabbits prey upon the cabbages. When the rabbits have depleted the cabbages, the rabbits decline due to starvation, and the cabbages recover. The new crop of cabbages yields a surge in the rabbit population, and the cycle continues. Modeling this in isee's Stella Architect yields the output shown in Figure 27. The oscillations of the populations of both species are clearly shown.

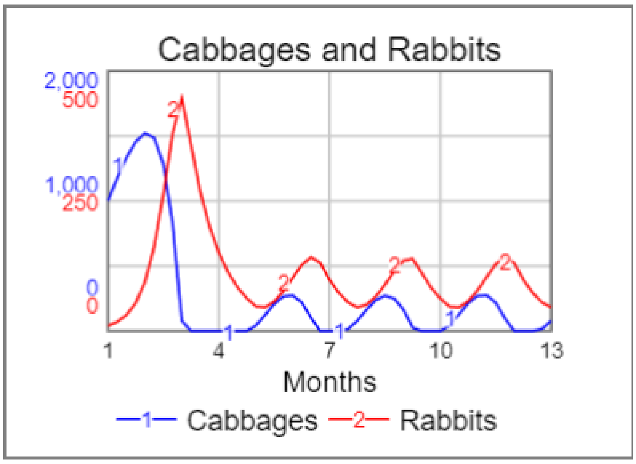


Fig. 27. Stella model output for predator-prey

Nuclear engineering: Nuclear chain reaction. The nuclear fission chain reaction is a reinforcing feedback loop, in which neutrons generated by fission impact atomic nuclei and release more neutrons, which subsequently also impact other nuclei to release even more neutrons. Not all neutrons are active, though: some leak out of the system while some are absorbed by cadmium or boron control rods to control the nuclear reaction. The ratio of Neutron Production Rate to the sum of Neutron Leakage Rate and Neutron Absorption Rate is called K_{eff}. If K_{eff} <1 the reaction is sub-critical and the quantity of neutrons decreases exponentially. If K_{eff} =1 the reaction is critical and self-sustaining. If K_{eff} >1 the reaction is super-critical and yields an explosion. A highly simplified stock-and-flow diagram is shown in Figure 28.

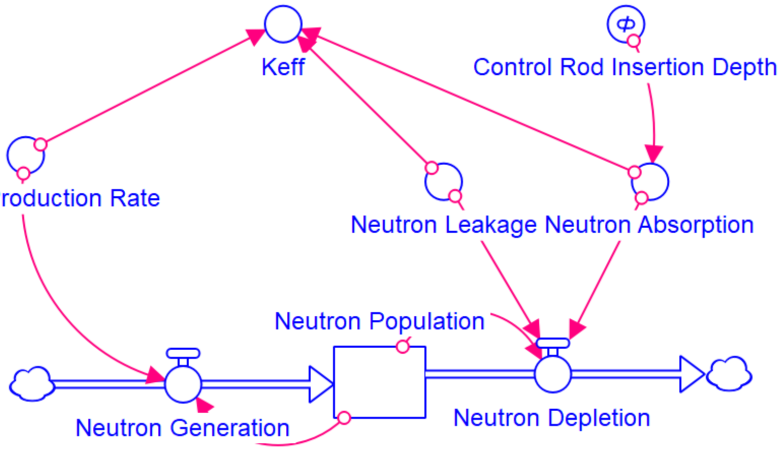
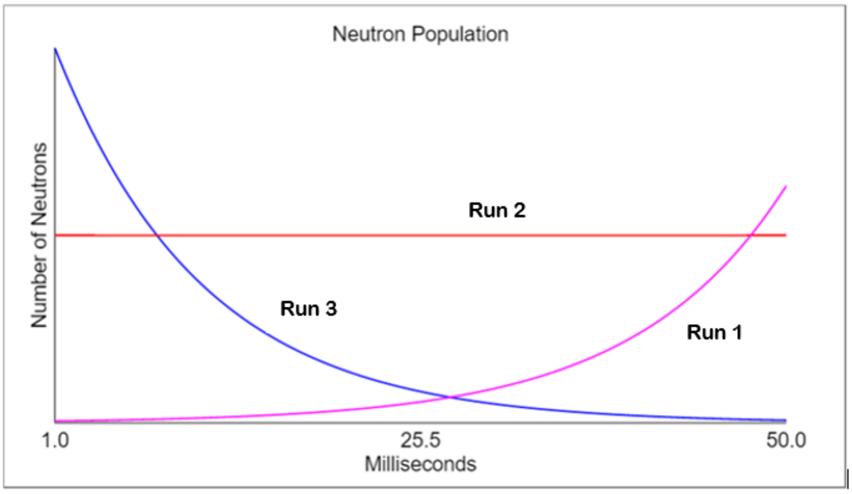


Fig. 28. Stock-and-flow diagram of a nuclear reactor

This is a very simplistic model of a nuclear reactor. However, experimenting with the variables is instructive. By adjusting the insertion depth of the control rods, one can cause the reactor to go sub- or super-critical (see Figure 29).



Run 1: Control Rod Insertion Depth = 1.7; K_{eff} = 1.05
Run 2: Control Rod Insertion Depth = 1.8; K_{eff} = 1.0
Run 3: Control Rod Insertion Depth = 1.9; K_{eff} = 0.952

Fig. 29. Results of nuclear reactor dynamic model

In Run 1 with $K_{eff} >1$ the system is super-critical and the number of neutrons increases exponentially, yielding an explosion. In Run 2 with $K_{eff} =1.0$, the system is critical, and the number of neutrons is stable. In Run 3 with $K_{eff} <1$, the system is subcritical, and the number of neutrons declines exponentially.

In contrast with the simplicity of this model, El-Sefy at al. [44] have constructed a detailed system dynamics simulation of the thermal dynamic processes within different systems in a pressurized water nuclear reactor and have validated the model against other simulations.

For a more in-depth study on applying System Dynamic modeling to typical Engineering science problems, the cited paper [27] and book [28] by Hans Fuchs are suggested.

4.3 Holistic thinking tools and applications

Systems Thinking recognizes that technology alone cannot solve complex socio-economic problems. Approaches for addressing world hunger, the need for potable water, transportation systems, the environment, waste management, and many other current issues require more than just technology: solutions to these issues also require consideration of sociological, cultural, economic, philosophical, moral, and political issues: a holistic perspective. An excellent example of the holistic application of Systems Thinking to a real-world potable water issue is provided by *The Water of Ayolé* [45].

Ayolé is a small rural village in the West African country of Togo. The water source for the village in the 1970s-80s was the Amou River, which was infested with the guinea worm *Dracunculus medinensis*, a parasite that infects a human host and causes excruciating pain. To address this issue, government engineers and international aid organizations installed wells in the village. While those wells served the needs of the village for several years, the wells eventually broke down due to normal usage. Unfortunately, no spare parts were available, no technical expertise was available to fix or maintain the pumps, and no money was available to pay for the repairs. As a result, the people of Ayolé went back to using the contaminated water from the river. The government engineers had interpreted this as a purely technical/engineering problem, when in fact this problem was much broader. Fortunately, local Togolese extension agents applied Systems Thinking to address the larger systemic issues. They established a repair parts supply chain via the local Togo hardware store; they trained some of the villagers in well maintenance and repair; and the women of the village developed a farming system that produced and sold agricultural products to generate money for the parts. Several Systems Thinking tools were used to address the Ayolé issue [46].

System Thinking tools that encourage holistic thinking include System Breakdown Structures, System Interrelationship Matrices, and Causal Loop Diagrams. However, a simple awareness of the presence of these non-technical factors resulting in a clearly written paragraph may be just as useful. Many of these issues involve disparate mental models among the various stakeholders. The Iceberg Model (described above) is a useful tool for discovering, exposing, assessing, and revising our ubiquitous (and often incorrect) Mental Models.

Bounding and defining the system. Appropriately defining and bounding the system of interest is vitally important. Several tools are available for this including simple diagrams, tables showing what is in and what is out, or a clearly written paragraph. Had the engineers who installed the well at Ayolé included the villagers and their culture in their system definition, things would likely have proceeded more smoothly.

The System Breakdown Structure (SBS) is a hierarchical pictogram showing the components of a system. It is wise to include in a SBS not only the system proper, but also the environment, users, and support systems that are required to operate and maintain the system; including these exogenous factors results in the depiction of the "suprasystem" and is helpful in identifying the non-technical issues that are likely to impact the system's performance. An example of a SBS applied to *The Water of Ayolé* is shown in Figure 30.

In Figure 30, the well system itself is shown in on the left while the exogenous factors are on the right. Had the government agents responsible for the project used a similar SBS, many of the obstacles might have been identified and addressed before problems occurred. The SBS itself is not magical, but if done well it forces engineers to consider non-technical issues affecting the system.

The System Interrelationship Matrix (SIM) is also a pictogram; however, it displays the interrelationships among the system components. A preliminary but incomplete SIM for the highest-level components of *The Water of Ayolé* is shown in Figure 31.

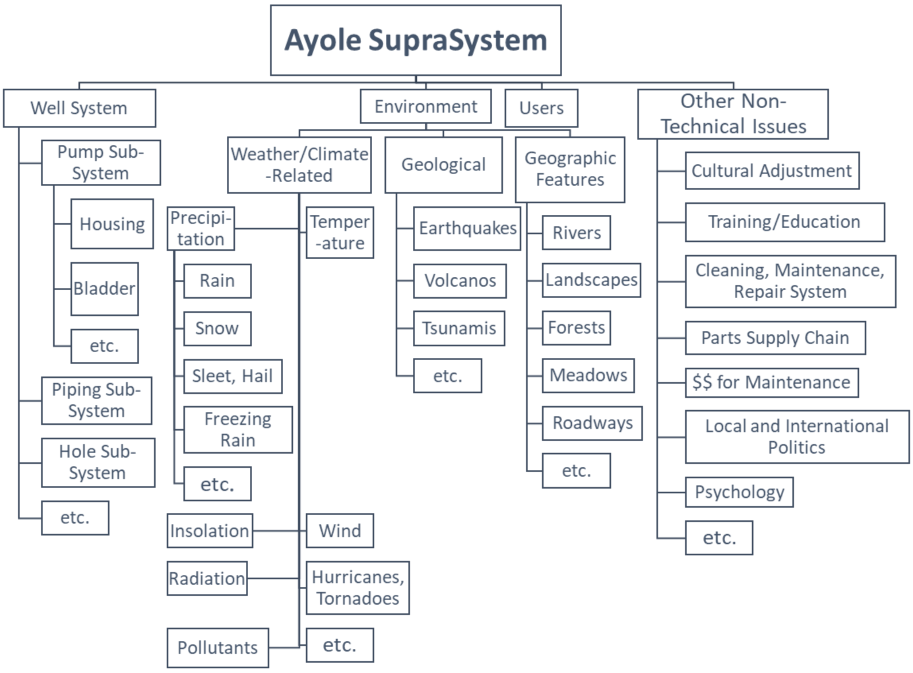


Fig. 30. System breakdown structure for Ayolé

	Pump	Hole	Mainte-nance	Repair Parts	$$	Village Culture	Education	Etc.	Etc.
Pump	-	X	X	X		X	X		
Hole	X	-			X				
Mainte-nance	X		-	X	X	X	X		
Repair Parts	X		X	-	X				
$$		X	X	X	-		X		
Village Culture	X		X			-			
Education	X		X		X		-		
Etc.								-	
Etc.									-

Fig. 31. System interrelationship matrix for Ayolé

The Xs the figure above indicate where there is a relationship; more detail may be added to each cell to indicate the type of relationship (e.g., electric-mechanical; electric-chemical; mechanical-psychological.) In addition, SIMs may be developed for lower levels of the system to show greater detail at sub-levels. A simple SIM like this would have demonstrated (for example) the interactions between the well maintenance system and the village culture.

Additional tools such as the Causal Loop Diagram may be applied to capture different perspectives. Figure 32 shows Causal Loop Diagrams describing two perspectives on the Ayolé scenario.

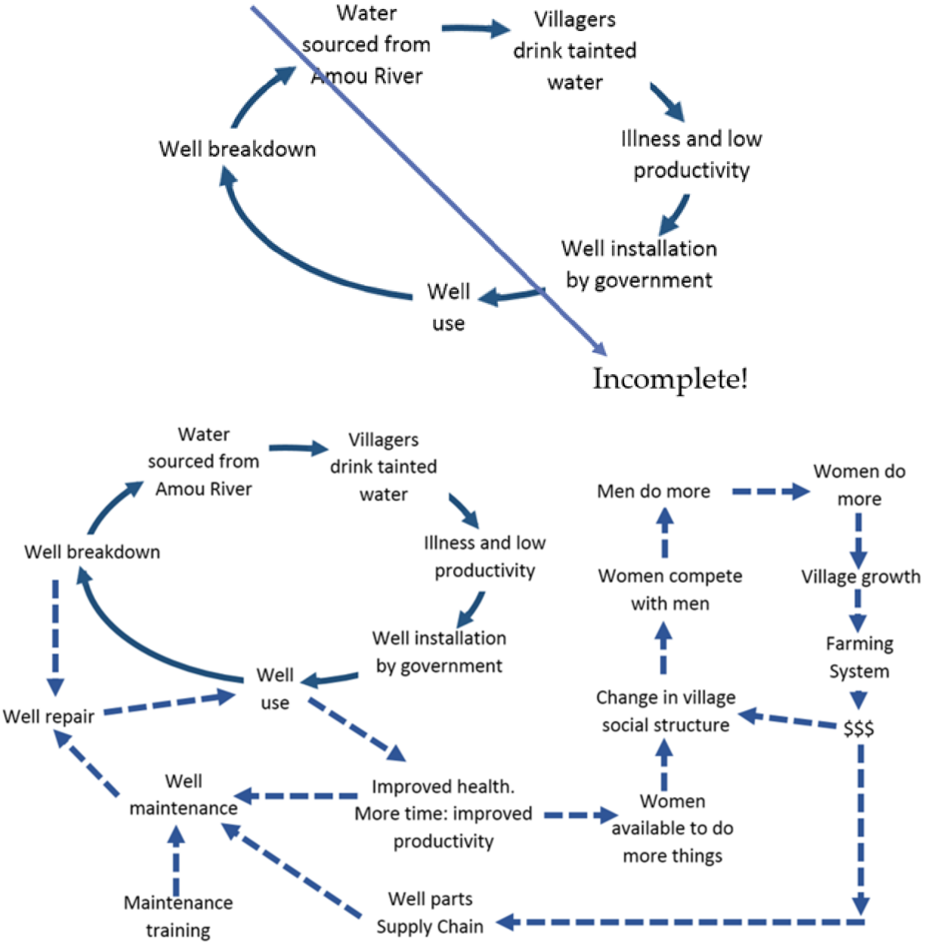


Fig. 32. Initial (upper) and final (lower) causal loop diagrams for the water of Ayolé

What was thought to be a simple engineering problem was really an engineering/socio-economic/logistics/ psychological problem, as illustrated in the Causal Loop Diagrams above in Figure 32 [47].

The Iceberg Model has been described above. It is especially useful for discovering, exposing, assessing, and revising mental models. Figure 33 shows an Iceberg Model for Ayolé from the engineers' perspective.

Fig. 33. Ayolé Iceberg model—Engineers' perspective

Figure 34, on the other hand, shows the corresponding Iceberg Model from the villagers' perspective.

Fig. 34. Ayolé Iceberg model—Villagers' perspective

Clearly, the disparate mental models conflict and must be resolved. Other Iceberg Models from the perspectives of politicians, the U.S. A.I.D., and others are also relevant and should be included.

One cannot say with certainty that the application of these Systems Thinking tools would have prevented the Water of Ayolé problems. However, they would have facilitated the consideration of non-technical issues and would have exposed the confounding mental models, thus increasing the probability of success. Engineers should be taught these tools to facilitate holistic thinking.

5 Preliminary assessment and field study

We have not performed a controlled experiment to validate our position, nor have we yet conducted a case study or attempted to adapt the curriculum at Worcester Polytechnic Institute per our recommendations. However, we have developed and taught an undergraduate Systems Thinking course 3 times, and the feedback from those offerings is supportive. SYS540 *Introduction to Systems Thinking* was taught during the early springs of 2019, 2020, and 2021; Table 1 shows student evaluations.

Table 1. Results of first 3 offerings of *Introduction to Systems Thinking*

Term	Enrollment	Average Student Rating of the Overall Course Quality (out of 5.0)
2019	20	5.0
2020	20	4.8
2021 (Remote)	24	4.6

Student comments include, “Fascinating course, should be required for most majors, gives you important insights about how many things in the world work, and how to avoid pitfalls in products/designs you make,” “It's a fascinating subject and one I think can apply to many fields, not just civil engineering,” “Systems Thinking is an extremely exciting field that is often overlooked at WPI. It was great to have a course that studies this topic that is relevant in all our lives,” “I learned so much taking this course and now I feel like I look at the world around me with a Systems Thinking perspective, which I didn't have before,” and “New class was handled well and the subject matter was made relevant to all majors.” These results are not a statistical validation of our proposals; however, they represent an initial assessment of the perceived value of Systems Thinking to undergraduates. Future plans include a quantitative assessment of our positions.

6 Conclusions: Proposal for integrating systems thinking into engineering education

Many administrators attempt to include Systems Thinking in engineering education by simply adding a Systems Thinking course or two to their undergraduate engineering curriculum. In our opinion, this is a necessary but not sufficient approach. Although undergraduate engineering curricula should certainly include Systems Thinking courses, instructors need to demonstrate the application of Systems Thinking to engineering problems in traditional engineering courses.

Like calculus, Systems Thinking is a perspective, a language, and a set of tools that can and should be applied to most engineering problems. And like calculus, it should be used whenever engineering disciplines are taught, not as a replacement for traditional engineering approaches, but as an adjunct to them.

In their regular courses on Mechanical, Chemical, Electrical, Civil, Environmental, and Aerospace Engineering, instructors must seek opportunities to demonstrate the application of Systems Thinking. Systems Thinking is applicable in the following situations:

a) Whenever a differential equation is used, a System Dynamics model may be used in addition.
b) Whenever a solution is sought to an infrastructure or design problem, Systems Thinking should be applied, as complex socio-economic problems cannot be solved by technology alone.

We acknowledge that there are several factors that contribute to the lack of adoption of Systems Thinking in engineering education:

a) Its methodology and tools are not well-understood by instructors.
b) Its benefits are not understood.
c) It is perceived to be a substitute or replacement for (as opposed to an adjunct to) conventional, tried-and-true engineering approaches.
d) Engineering curricula are full and cannot accommodate additional courses.

We address items a and b in this paper by reviewing some central concepts, tools, and methods in Systems Thinking and by providing examples applying these to typical engineering problems. We hope that this initial effort engenders more comprehensive work in each engineering discipline.

With respect to item c, we do not advocate Systems Thinking as a replacement for any conventional engineering approach. Instead, we advocate it as an adjunct: a different approach that can provide more insight.

Finally, to overcome resistance to inculcating Systems Thinking into undergraduate engineering education, we recommend the following:

a) Engineering instructors and administrators should educate themselves about Systems Thinking tools and their application. Several courses are available, as are several good books on the subject. We recommend *Thinking in Systems* by Dana Meadows [36], *An Introduction to Systems Thinking* by Daniel Kim [47], *An Introduction to Systems Thinking with iThink* by Barry Richmond [43], and *Using Systems Thinking to Solve Real-world Problems*, by Jamie Monat and Thomas Gannon [39].
b) College administrators should invoke the teaching of Systems Thinking as a means to support ABET standards.
c) Systems Thinking researchers and practitioners should continue to demonstrate and publish the beneficial results accruing from the application of Systems Thinking to engineering problems. Initial applications can focus on incorporating conceptual modeling approaches (such as Causal Loop and Stock and Flow diagrams) into typical engineering texts that address dynamic modeling of systems such as [48] and [49].
d) College administrators should require that Systems Thinking be taught as a part of every engineering program---not as a stand-alone course or courses, but integrated with the other engineering disciplines, just as calculus and physics are.
e) K-12 Teachers should introduce Systems Thinking concepts to their students so that the expectation is set to learn Systems Thinking in college.
f) Industry advisory boards to university engineering departments should stress the importance of Systems Thinking concepts in undergraduate engineering education.

The role of engineers is changing. No longer can they make engineering decisions independent of psychological, sociological, and environmental impacts. The interconnectedness of all things and people mandates that engineers take a holistic view, understand the second and third-order impacts of their designs, and recognize that there is usually not a "best" design but instead several acceptable designs involving various trade-offs. Traditional engineering educational methods involving algebraic plug-and-chug formulas, static models, and differential equations do not provide this holistic view or the insights and sensitivity required by today's engineers. Systems Thinking addresses these deficiencies and should be an integral part of every undergraduate engineering curriculum. We hope that this paper initiates a discussion focusing on this end.

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