Introduction to the Handbook of Systems Sciences

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Abstract

The Handbook of Systems Sciences reflects the work of scholars whose thinking and practice cross a wide spectrum of disciplines. The intent of this handbook is not simply to be an overview of knowledge domains, but is the marking of milestones in their development. The formal study of systems, cybernetics, and complexity all date back to the early twentieth century. The principles on which those domains were founded trace back millennia. The chapters contained in this handbook describe the evolution of theories, and applications in practice, across familiar disciplines including engineering,

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management, ecology, education, and design. The hope for this work is to provide foundations on which future researchers and scholars can build.

Keywords
Systems, Science, Cybernetics, Complexity, Models, Design, Management, Ecology, Engineering

This handbook is comprised of chapters which correspond to disciplines or areas of study that will be familiar to many people: systems modeling and methodology; complex systems modeling; management and organizations; social systems; design of systems; ecological systems; engineered systems; and systems research and education. The topics were chosen to provide points of access for those readers who might not be familiar with systems sciences or related fields. Different topics or chapters could have been used, still demonstrating the evolution in theories and concepts of these domains. The chapters in this handbook, however, represent the work of significant scholars in these fields, and summaries of their contributions over decades.

Readers may find challenges in varying uses of terminology across the chapters. Ludwig von Bertalanffy is referred to by many as the "founding father" of general system theory (GST) although, as will be seen in the opening chapter, he was by no means alone in his work. He did, however, make extremely important contributions. One set of distinctions that he created was between three aspects of systems: systems science, systems technology, and systems philosophy (von Bertalanffy 1969). Systems science was the use of systems theories in traditional disciplines, such as physics, biology, psychology, and sociology. This included a search for "isomorphisms" which would connect the disciplines at higher theoretical levels (part of the hope for a general system theory). Systems technology was Bertalanffy's way of addressing complexity, as he saw it arising in society through computerization and automation of many kinds, as well as the increasing amounts of data and concepts that had to be understood. Systems philosophy captured the deeper reorientation, or shift in paradigms, that was caused by thinking in these terms. Bertalanffy (1969) also referred to a "systems approach". He did not, to our knowledge, use the term "systems thinking", which has become a common, almost generic term, particularly in applied areas such as management consulting. Systems engineering is part of the field of engineering.

The greatest dilemma probably lies in distinguishing between systems science and systems philosophy. All the founders of systems, cybernetics, and complexity were scientists or researchers from traditional fields of study. Many worked to advance those fields using these more encompassing principles. A small number had formally studied philosophy, or even identified as philosophers, in addition to being scientists, researchers, or practitioners. They have generally been the few who have practiced both systems science and systems philosophy. They have advanced their individual fields as well as the larger domains of systems, cybernetics and complexity. They appear to know when they are working within their fields, and when they are stepping outside to challenge the very tenants on which those fields, and science in general, are based. As Bertalanffy (1969) described: "In one way or another, we are forced to deal with complexities, with ‘wholes’ or ‘systems,’ in all fields of knowledge. This implies a basic re-orientation in scientific thinking” (p. 5). Readers will find vestiges of these concepts and questions throughout the chapters of this handbook. As noted, the intention of some authors is to apply tools or technologies to specific problems, while others hope to document advances in a field of science, or in systems, cybernetics or complexity theories, more generally. Those are all different, but legitimate pursuits.

Historical Foundations

“Systems Science, Cybernetics and Complexity” (Metcalf and Kauffman) is an historical overview of the three domains of interest: systems, cybernetics and complexity. Debates about the nature of the world, including form, function and process, date back at least to Ancient Greece. Echoes of those debates continue in science today. In some ways, interest in systems, cybernetics and complexity all represent a change in focus, from the micro to the macro. Discovering and understanding the most fundamental aspects of matter and energy do not, by themselves, explain the world in which we live. Researchers and theorists began asking larger questions, and searching for ways to understand some of the many forms and behaviors that could emerge from the basic materials of the universe. The world was not random, nor was it predictive. Some theorists looked for answers in traditional forms (e.g., mathematical equations). Others challenged the prevailing assumptions of their disciplines. Two key figures, Stuart Kauffman and Robert Rosen, are compared as a way of tracing some of the influences which have driven the fields as they have developed over recent decades.

Systems Modeling and Methodologies

From the title of the section, readers might assume that these chapters would focus on specific tools and technologies. In fact, the authors in this section decided to challenge many of the problems posed by excessively narrow perspectives, which could either misinterpret or underestimate the situations being addressed, or apply tools and technologies without appropriately assessing the nature of the systems involved.

Allenna Leonard and her co-authors, Tom Scholte, Ken Shepard, Gabriele Harrer-Puchner, and Joe Truss, in their chapter “Cybernetics Approaches and Models” offer a window into the many ways in which the principles of these domains (in this case, cybernetics) can be used. Their chapter includes descriptions in theatrical works, in organizational applications, and in decision-making processes. They cover specific applications such as Sensitivity Modeling, Viable Systems Modeling, and Syntegration.

The chapter “Meta-Methodology for Risk Management” by Takafumi Nakamura considers the field of risk management. The author provides a broad overview of current strategies, and underlying theories, for managing risk. Each risk management strategy brings with it not only underlying assumptions, but often different sets of terminology or language. The first recommendation is for a more common language or framework for assessing systemic failures. Then, there need to be more holistic ways of understanding risk, as opposed to the current problem-solving approaches which lead to overly narrow solutions. Given the growing complexity of risks, both double-loop learning and meta-methodological approaches should be employed.

Michael Lissack offers a clear set of distinctions between first-order and second-order cybernetics, with respect to control in the chapter “Cybernetics and Control”. First-order approaches are consistent with the needs for machinery. Second-order cybernetics, as it appears in human settings, addresses issues of biased interpretations, cognitive limitations, complexity of varying contexts, and choices of individual agency. Control, then, becomes a matter of choices which guide influences, as affected by levels of awareness, and even the narratives created to make sense of the circumstances in question. Or as Lissack describes his conclusion: “Control in second-order cybernetics is the assertion of balance, the developing of a narrative and the exploitation of the resulting dominoes of relatedness. Feedback was the initial cybernetic concept. Narrative, communication, awareness, and reflexivity are its current successors.”

In “Knowledge Construction Systems Methodology”, Yoshiteru Nakamori describes principles for knowledge creation, focusing primarily on intuition, or tacit knowledge. His model is comprised of five abilities (intelligence, involvement, imagination, intervention, and integration) across four domains (scientific-actual, social-relational, cognitive-mental, and intuitive-creative). He then applies the model to the marketing promotion of a traditional, Japanese craft item.

Gerald Midgley and Raghav Rajagopalan in “Critical Systems Thinking, Systemic Intervention and Beyond” summarize extensive earlier work, describing three “waves” of systems thinking, which led to the development of Critical Systems Thinking and methodological pluralism. They explore the practical and philosophical debates which shaped those waves, and the resulting developments in systems thinking over time. Finally, they propose two new efforts which seem promising for taking the current state to next stages. One is the work of Cabrera, built around the concepts of distinctions, systems, relationships, and perspectives (DSRP), and the other is their own recent work, incorporating philosophical traditions from India and challenging long-standing Western ideas.

Jifa Gu in “Oriental Systems Thinking” departs from the traditional approach to systems methodologies and models, in order to trace more ancient roots of systems ideas. He describes concepts including Yin-Yang, eight trigrams, five elements, great learning and Traditional Chinese Medicine. Through several research efforts, Gu and his colleagues consolidated many of the traditional approaches into an Oriental system methodology, later referred to as Oriental systems thinking. Gu’s chapter brings together many of the ancient traditions into one convenient source of reference.

Complex Systems Modeling

This section spans a variety of topics and approaches by the authors. Some focus on modeling, per se; others on specific models; and still others on applications of concepts and models in systems settings.

Hajime Kita explores fundamental questions about the nature of complex systems in the chapter "Complex Systems". This is done across domains including physical systems, biological and ecological systems, artificial systems (developed by humans), and social systems. Kita focuses on processes of emergence, self-reproduction, and adaptive mechanisms.

Yasuo Sasaki in "Multi-agent Decision System" addresses multi-agent decision systems, defined as systems in which several autonomous agents interact and make decisions according to their "internal models." This is applied to hyper-game theory (Bennett 1977; Bennett and Dando 1979) where agents can interpret the game from each of their own internal models (as in societal systems).

Simple hyper-games assume that agents see each other's internal models as common information. Hierarchical hyper-games allow for more complex formulations, e.g., "my view about your view about her view," etc. This level of complexity affects assumptions of equilibria, used in traditional game theory. An important aspect is the ways in which agents may change their internal models, and how this affects later outcomes. Finally, drama theory, a game-theoretic model, is introduced (Howard 1994). Hyper-games deal with the subjective, internal models of agents, while drama theory is more concerned with the dynamic processes arising from interactions among those internal models.

Belov and Novikov in "Methodology of Complex Activity" are concerned with formal models. Specifically, they describe a methodology of complex activity (MCA), which they define as "a system of formal models that, from a systems science perspective, generalizes nontrivial human activity and the operation of enterprises and complex (socio-technical) systems." Complex activity involves "a non-trivial internal structure...with multiple and/or changing actors/players, methods, and roles of the subject matter of activity in its relevant context." MCA deals with coupled pairs of complex activities and sociotechnical systems. As they summarize, "the subject matter of this study is complex activity, and the research topic is the general principles underlying its organization and management." In application, MCA attempts to formalize typical processes in organizational work.

In "A Perspective on Agent-Based Modeling in Social System Analysis", Takao Terano explores the use of agent-based modeling as an interdisciplinary research method. It is proposed as a means of simulation, which could be an alternative to traditional scientific research in social systems.

In the chapter "Systems Modeling", Shingo Takahashi addresses systems modeling as the explicit topic of the chapter. A defined process is presented in which modeling has three purposes: to express a current system state as a model, to express an ideal state of the system, and to represent existing problems. The framework used describes the relationships between "subject S, objective A, prototype T, and model M." Systems are classified as machine, organic, cybernetic, or complex adaptive. And finally, "the modeling process consists of five phases: understanding problem situations, identifying relevant systems, clarifying the modeling purpose, identifying and structuring model components, and identifying parameters."

Hironobu Matsushita in “Translational Features of Competencies in Healthcare Innovation” focuses on healthcare as an area of application. Specifically, “the purpose of this chapter is to clarify the translational features of human competencies in healthcare innovation by analyzing some features of nursing managers as a potential agent of innovation through a perspective of complex adaptive systems.” The quantitative study on which the work was founded revealed discrepancies between what nurses perceived as personal strengths, and attributes that would be necessary for the adoption of innovation. The study points to a need for new models to be developed and implemented in healthcare settings, in order to create the skills needed for innovation.

Management and Organizations

Systems theories have been used by management scholars since the 1940s, starting with Barnard’s (1938) discussions of the functions of an executive from a practical perspective. Since then, several prominent management scholars have contributed to the advancement of management and organizational theories using systems approaches, including social systems theories, sociotechnical systems, contingency theory, open systems, and the application of General System Theory (von Bertalanffy 1969). One of the recent works in applying systems theories to management is the social systems theory of Luhmann (1995), which contributes to the institutional theory of organizations. According to Jackson (1991), systems theories applied to management overcome the weaknesses of traditional approaches to management by looking at “organizations as wholes” (p. 41).

Leadership has received much attention in the field of management, as well as having many of its own books, journals, and organizations. Complexity is a topic that has been more recently incorporated into management. Peter Senge’s The Fifth Discipline (1990) was an influential book which connected systems thinking to (learning) organizations. Nancy Southern in “Creating Leaders for Systems Complexity” takes up the cue from Senge’s work on how complexity affects the nature of leadership in organizations. She urges leaders to view organizations as complex adaptive systems bringing diverse people (agents) together towards a shared vision and goals. She suggests that looking at organizations from a systems perspective helps by dynamically engaging with others, and by moving away from a command-and-control mode of leadership. She urges modern leaders to create conditions for collective creativity, leading to collaborative action. The chapter also includes examples of systemic approaches to building leadership capacity.

While there are systematic approaches for creating technical systems, such as the *vee* models in systems engineering, working with sociotechnical systems requires a different mindset. Sociotechnical systems have been of great interest to management, dating back to the work of the Tavistock Institute in the early 1960s. They were used to deal with issues arising from the introduction of automation in the textile mills in Ahmedabad, India, and later at Volvo’s Kalmar and Uddevalla car plants in Sweden. Alison McKay, Mathew Davies, Helen Hughes, Rebecca Pienazek, and Mark Robinson, from the sociotechnical research center at Leeds University, offer a process to design sociotechnical systems in the chapter titled “Designing Socio-technical Systems: A Multi-team Case Study”. They argue that designing sociotechnical systems requires a new branch of systems science that helps to integrate human behavior into systems behavior. They illustrate their approach by using a systems design process vee-model to develop a multi-team customer-service system. They suggest that their approach can be used as a practical framework to design sociotechnical systems, more generally.

Governance has become increasingly important as corporate scandals have plagued organizations such as Enron, WorldCom, and Lehman Brothers, and contributed to the global financial crisis. Governance is also of great concern to systems scientists with questions about governing during the Anthropocene (Ison et al. 2018). Recently, an interest in Stafford Beer's (1984) Viable Systems Model (VSM) has come about, for developing a Viable Governance Model for information technology projects, and in the field of Systems Engineering. Ralf Müller, Nathalie Drouin, and Shankar Sankaran discuss the application of the VSM to Organizational Project Management (OPM) and megaprojects, in the chapter titled "Governance of Organizational Project Management and Megaprojects Using the Viable Project Governance Model". These authors have also recently developed a seven-layer model for OPM to integrate all project management-related activities in an organization. In doing so, they linked the five subsystems of the VSM to the seven layers of their OPM model. They have also explained how VSM is applicable to megaprojects, which are large complex undertakings that have great impacts on the environment and society, posing problems for sustainable development. A case study of a megaproject is used to show how their proposed viable governance model can be applied in practice.

An important activity in organizations is the development of a strategic plan. The strategy is typically formulated or revised annually, but it is unclear how that ritual contributes to the organization's outcomes, despite consuming valuable resources. This is the dilemma addressed by Steven Wallis and Kent Frese in the chapter "Reaching Goals with Structured Strategic Plans: A Fresh Approach to an Annual Leadership Dilemma". The authors propose an innovative approach, using the example of the strategic planning process in a regional catering company. As they explain, it became an exciting and enjoyable exercise that also resulted in organizational cohesion, providing flexibility while maintaining analytical rigor. The process proposed by the authors takes less time than common approaches used in strategic planning while leading to increased organizational success.

Can systems science and systems engineering help enterprises to make better decisions (which is one of the main functions of management)? Keshav Vithal Nori, Swaminathan Natarajan, Anand Kumar, and Doji Samson Lakku try to capture the nature of an enterprise and its evolution over time, to create software models and tools. Using systems science and systems engineering principles, they describe their work in the chapter "A Systems Engineering Approach to Modelling Enterprises". Their approach helps to understand an enterprise in terms of its morphogenic structure and how the epigenesis of an enterprise captures its evolution over time. They illustrate their approach using an information technology enterprise, which is concerned with the information, processes, and knowledge that enable the functioning of its business systems.

Sustainable management is one of the challenges faced by both developed and developing countries. The challenges are even more daunting in an underdeveloped economy, particularly in disadvantaged, rural communities. Nam Nguyen, Ockie Bosch, Tuan Ha, and Kwamina Banson discuss the successful application of their innovative systems-based framework, the Evolutionary Learning Laboratory, which uses participatory approaches to help some of the poorest regions in the world. The study presented in their chapter, “Sustainable Management: Case Studies of Applying an Innovative Systems-Based Framework in Southeast Asia and Sub-Saharan Africa”, uses community-based studies in the rural areas of Haiphong, Vietnam and Accra, Ghana, to support small-holder women farmers making practical and sustainable decisions in complex situations. The two cases demonstrate the effective development of systemically defined management plans. The cases show how the framework provided by the Evolutionary Learning Laboratory serves as a powerful management tool to address complex problems, where the relationships between natural (environmental) elements, human factors, cultural and socioeconomic aspects, and stakeholders are intrinsically interwoven.

Change management is one of the challenges faced by organizations needing to implement strategies for both survival and growth in rapidly changing environments. Several rational models have been proposed by management scholars. Sam Wells and Josie Mclean examine the application of living systems theory, using a garden metaphor, as an alternative to engage with change in organizations, using a holistic rather than a reductionist approach. Their chapter, “Organizational Change as Emergence: A Living Systems Perspective”, explains how their approach takes into account uncertainty, nonlinear causation, self-organization, and emergence. This can help managers understand change as an expression of life rather than as a strategy that gets imposed on an organization. The practice that they explore, along with stories they share, make their perspective accessible to practitioners.

Organizations in government and the public sector are concerned with development and implementation of policies that can address complex challenges faced by nations. Food and nutrition security are some of the challenges affecting countries across the world. Robert Dyball and Bronwyn Wilkes propose a human ecological systems framework that can help policy makers analyze, critique, and design interventions in complex human environments in the chapter “A Human Ecological Approach to Policy in the Context of Food and Nutrition Security”. Their framework considers interactions and feedback between components of a complex system in four main categories. They propose that their approach is applicable to a variety of policy-related situations to study how different paradigms can influence policy making, giving rise to systems that impact outcomes for human and environmental wellbeing.

For-profit corporations are often criticized on many fronts: for caring only about money; for neglecting the good of workers and the communities they affect; for harming the natural environment; and so on. The chapter by Jean-Claude Pierre, “Developing a Sustainable Employee-owned Chemical Company”, offers a firsthand account of an alternative. Pierre served as the head (comparable to CEO) of a company that would appear to be the antithesis of other corporations. As implied by the chapter’s title, he led an employee-owned chemical company which focused on environmental sustainability. That did not, however, leave the company without challenges, as he explains in his account.

Social Systems

Like many topics in this handbook, social systems could be understood as extremely broad, or as confined to a small number of theories and theorists. In a broad sense, social systems encompass the collective behaviors of species from insects to humans. Termites and ants display divisions of roles and labor, as well as collective efforts in the building of elaborate nests. Swarm theory (including swarm behaviors and swarm intelligence) describes specific patterns, across species from insects to birds to fish, and applicable in some ways to humans. It includes mathematical models to simulate the patterns and interactions. Animals hunt in packs and survive in herds. Primates display many common behaviors as familial groups. Disciplines including sociology, anthropology, economics, and political science, among others, describe human behaviors at aggregate levels of organization. In terms of theory, however, there are actually few theorists who have focused on human social systems, per se.

Families and organizations are not simply collections of individuals any more than bodily organs are simply collectives of individual cells. They remain individual and collective, in different ways; described as holons, or systems of systems, or in other terms. Social systems have identities and distinctive behaviors, however, at their levels of wholeness. Notable theorists who have attempted to define those systems, in their own rights, include Talcott Parsons and his student, Niklas Luhmann.

Given the potential breadth of this topic, there is no way that one section in this handbook could cover or summarize the possibilities. The chapters included address particular aspects of social systems, which represent a small sampling of particular interests. They serve, however, as an introduction, which will hopefully lead to further exploration.

Paul Lillrank in “Declining Society and Systems Productivity” addresses the current convergence of economics, and technologies, and demographics in human social evolution. The particular focus is healthcare, and the challenges posed by aging populations in contrast with the expectations for care, and the abilities of societies to deliver that care, economically and logistically. Lillrank explains that healthcare is a service industry, but not a typical one. It cannot be managed or improved simply like another industry of a different type. Technologies may help, and there are improvements to be made in efficiency and productivity. Given current trends in human populations, change is critical.

Hiroshi Deguchi uses a play on Herbert Simon’s book, The Sciences of the Artificial, as the entry point for his chapter “Social Sciences as the Artificial: Toward Constructive Social Systems Theory”. Deguchi introduces the idea of “constructive social systems sciences” as a way of capturing the collective construction of social reality for humans. This involves individual, internal models and their interpretations (echoing ideas from Michael Lissack’s chapter “Cybernetics and Control”). Deguchi compares the development of theory between natural and social sciences, including the development of models, and uses of natural languages and mathematics. He then applies his ideas to the realm of public health, and explores distinctions between macro and micro models of social systems. He argues for a multi-layer, multiaspect, reflexive process of building theories and understanding in societies.

Susumu Ohnuma in “Consensus Building: Process Design Toward Finding a Shared Recognition of Common Goal Beyond Conflicts” explores the potential for building consensus in public decision-making from social dilemmas. This is done using concepts from game theories as frameworks, including the Illegal Waste Dumping Game, Emissions Trading Game, and Consensus Building of Wind Farm Game. Much of the value comes from the process of cooperating towards a common goal.

In “Social Systems Theory”, Saburo Akahori deals directly with social systems theory, coming from the perspective of sociology. Fittingly, the theories of Talcott Parsons and Niklas Luhmann are prominent, but ideas from Ross Ashby and Ludwig von Bertalanffy are also included. Social systems as second-order observers is introduced, incorporating concepts from second-order cybernetics.

Engineered Systems

The section on engineered systems is one of the more significant for this handbook, both in terms of the number of chapters included, and in terms of perspectives which these chapters add. There have been formal, collaborative efforts between the systems science and systems engineering communities since at least 2010, as evidenced by agreements between the International Society for the Systems Sciences (ISSS) and the Systems Science Working Group of the International Council on Systems Engineering (INCOSE). It would be easy to assume that while ISSS focused on the development of theories, INCOSE was interested in implementing them. In fact, both groups have been involved in theory as well as application since the outset. The authors included in this section represent some of the most pioneering and active systems engineers in this work.

The value of these collaborations has been significant, evidencing the need that theory and practice must work together for mutual benefit. Untested theories are just good ideas. Practice without a theoretical basis (even tacit) is just a series of trial-and-error activities.

Special note needs to be made of Harold (Bud) Lawson, who passed away during the production of this handbook. His chapter “Understanding the Systems Solution Landscape” is included with the generous agreement of his family, and the help of James Martin (editor of the section “Engineered Systems”) in completing the final writing. Bud was a pioneer in crossing the domains of systems science and systems engineering, as a writer, editor, and long-time practitioner.

While the chapters in this section come from authors who have practiced systems engineering, there is nothing homogeneous about the ideas or the examples. Like other sections, the chapters span great territory.

Brian White in “Enterprise Systems Engineering” focuses on enterprise systems engineering (ESE) and issues of complexity. Enterprises may be formal organizations, or self-organizing collaborations of many kinds. ESE recognizes the need to treat enterprises as systems, per se, and as human systems, specifically. As such, White notes many societally related issues (e.g., population size, education, etc.) as contributing problems, and the need for stakeholder involvement. He rebuts, in fact, recent suggestions for systems engineers, which do not adequately address stakeholders. As he states, “They don’t identify, characterize, and intentionally include all the key stakeholders as intrinsic, non technological components of the system to be improved or developed.” That absence leads to inadequate solutions.

In “Handling Uncertainty in Engineered Systems”, Azad Madni and Terry Bahill explore ways of dealing with uncertainty in engineered systems. Uncertainties are sometimes measurable, and not always destructive. They may be caused by challenges within a system itself, or by external factors. A focus of the chapter is on tradeoff studies (or trade studies), which address compromises that customers often have to make in design or production. Engineering processes historically begin by stating customer requirements, but those can be plagued by “biases, cognitive illusions, emotions, fallacies and the use of simplifying heuristics,” which make the choices and decisions difficult. The authors explore these problems in some depth, along with possibilities for resolving them.

Kenneth (Ken) Lloyd explores a branch of mathematics known as Category Theory in the chapter “Category Theoretic Foundations for Systems Science and Engineering”. (This is the form of mathematical modeling used by Robert Rosen. See the section on “Ecological Systems”.) As explained by Lloyd, “a category exclusively refers to an abstract collection of objects, upon which a structure has been added or imposed.” Further, and a reason that Category Theory is proposed as an exceptionally good approach for describing systems: “A category is a particular realization of a formal (mathematical) construct that can precisely, but indirectly represent all the feature details of any system – by a single reference.” Category Theory also translates well into computer modeling. Lloyd then provides a primer to Category Theory, interspersed with concepts and examples of systems. The chapter is challenging, but a valuable addition to the work in this section.

Hillary Sillitto addresses the fundamental nature of engineered systems in “Nature of Engineered Systems: Illustrated from Engineering Artefacts and Complex Systems”. This is important so that human designed systems can be compared to, and distinguished from, natural systems writ large. He situates engineered systems within a larger taxonomy, including distinctions between conceptual and physical systems, and discusses the increasingly complex systems with which engineers are faced; highly-networked, and potentially autonomous. He then applies these concepts of engineered systems to numerous kinds of examples, including products, services and enterprises. He highlights the differences between engineered and natural systems, and lastly, contrasts the various approaches that systems engineers use in working with engineered systems, from those that systems scientists use in studying natural systems.

Duane Hybertson's chapter "Systems Engineering Science" serves as a ready companion to that from Hillary Sillitto, by focusing on the scientific foundations underpinning systems engineering. As Hybertson explains, "the chapter describes the changes in SE and in science-based engineering (SBE), and then describes the SE Science (SES) resulting from the changes in nature and scope of SE." As the realms of systems engineering expand, so do the needs of the science on which it depends. Traditional areas included defense, transportation and energy. Current and future areas encompass healthcare and other social systems, as well as autonomous and intelligent machine agents, which will require SE to expand into other existing realms of science.

In "General Schemas Theory: A New Basis for Systems Engineering Practice", Kent Palmer reaches into philosophy to define a "General Schemas Theory that can be used as a basis for the science of systems." He begins with the nature of schemas, tracing back to Kant, and covers an impressive range of philosophers and theories. He moves into the application of schemas as templates for design, and into the realm of meta-systems. He incorporates Pascal's triangle as a framework on which to build his theory, ending with a challenging but impressive chapter on which others might begin to build.

Anand Kumar offers his perspective on the creation of value in "Delivering System Value: A Systematic Approach". As he explains, building quality into a system does not always equate with delivering the value needed or required by all stakeholders. He presents an approach involving four aspects: value understanding, value characterization, value proposition, and value realization. This creates an interesting companion to the chapters by White, and by Madni and Bahill.

William (Bill) Schindel explores patterns in systems and in science in the chapter "System Patterns in Engineering and Science". As he describes, "In addition to providing a unifying perspective to historical accomplishments of specialized disciplines, system patterns also simplify the complexity of existing engineering environments while advancing ability to develop new scientific and engineering disciplines for more complex domains, including markets, networks, distribution systems, the Internet of Things, communities, and the innovation process itself." Interestingly, rather than building on the concepts of isomorphies from General System Theory, or Pattern Language (though referenced), he works up from the S*Metamodel as a foundation. This creates a unique contribution to the discussion of patterns, while it parallels and complements several other chapters in this section (particularly "Nature of Engineered Systems: Illustrated from Engineering Artefacts and Complex Systems", "Systems Engineering Science", and "General Schemas Theory: A New Basis for Systems Engineering Practice").

The late Bud Lawson contributed his chapter describing a "systems solution landscape." As he summarized, "Working toward a solution (response) first involves understanding the problem or opportunity situation space, the potential response and the system assets that are available or can be developed to provide a response." In clear and simple language, Lawson summarizes basic concepts of systems, and processes of change in his chapter "Understanding the Systems Solution Landscape". He then covers the Essence approach, which is derived from software engineering, systems architecture, cybernetic applications for change management, and issues of enterprises. (It is a privilege to publish this final chapter from Bud given his many foundational contributions in the field.)

Design of Systems

The many relationships of design in systems engineering, philosophy and social sciences have been identified from the early years of systems science. Ross Ashby's "Ashby Box" was an artifact designed to demonstrate cybernetic relationships in electronic experiments. Ranulph Glanville wrote on the mutual necessity of design processes in understanding and designing for complex systems. Herbert Simon's Sciences of the Artificial (1969) deeply addresses the relationship of design as intent in the development of artificial systems and practices. Fernando Flores developed a practice of "ontological designing" and demonstrated its use in theory and tools such as the early email system, The Coordinator. The systems discipline of social systems was envisioned from the roots of the discipline as a design practice, from Hasan Özbekhan's normative planning, to Eric Jantsch's Design for Evolution, Alexander Christakis' Dialogic Design and Warfield's generic Design Science, and of course Bela Banathy's work. Russell Ackoff's Idealized Design was an explicit design process, and so on.

Design has advanced considerably in complexity the information age, and systems design has evolved into an interdisciplinary intersection of service and systemic design for complex systems.

The chapters in this section, curated by Peter Jones reflect some of the leading intersections of systems and design. Peter Jones, a social scientist by training and designer by profession, provides a foundational overview of Systemic Design, a thriving practice developed in the last decade and taught in over a dozen universities, in the chapter "Systemic Design: Design for Complex, Social, and Sociotechnical Systems". Jones defines systemic design as a design-led field, relying on creative design epistemology and drawing on systems theory and method as instrumental functions in the design process for complex social systems. As an emerging practice in the last decade, systemic design differs from traditional systems design, a field that views systems as the site of engineering or sociotechnical design, as developed through systems engineering. Jones takes readers through a brief history of design, and of the recent emergence of systemic design. He covers theory and principles, practices and methodology, and incorporates adjacent fields of practice, de such as Structured Dialogic Design, a practice he has incorporated into graduate design education. Dialogic Design, and social systems design, are conceived as stakeholder-driven practices, which is consistent with the direction of advanced design for policy, social services, and human systems. This leads to considerations of what John Warfield called generic design, not only for how human systems can be designed, but how they should be designed, incorporating stakeholders of the future systems.

Following this introduction, systems scientist Thomas Flanagan develops a chapter on Structured Dialogic Design (SDD) titled "Structured Dialogic Design for Mobilizing Collective Action in Highly Complex Systems", further elaborating the relationship to systemic design and design with and for systems stakeholders. This includes the formulation of deeply reasoned methods and engagement technologies, the development of cognitive and language models for democratizing the design process, and the challenges of decision making with shared interpretations and meaning for stakeholders. Flanagan details the methods and concepts of SDD, providing readers with a quick introduction to a complex engagement process based on principles of generic design and dialogic design science.

Senior policy advisor Nenad Rava takes systemic design into the realm of public policy, an emerging discourse and application for engagement and system change proposals. The chapter "Systems Design Approach to Public Policy" introduces policy as a design discipline and develops the systems concepts relevant to policy design. This expands into complexity, and then systemic design. Finally, Systemic Design Policy is presented, including basic principles for guidance. Public policy is not a context typically associated with design, nor with the kinds of stakeholder involvement advocated by authors in this section. Yet with a new journal (Journal of Policy Design) and systemic design practitioners heading up new government policy "labs" there are significant developments emerging in this field. Rava skillfully shows is the approaches and opportunities that make systemic policy design an area ripe for further study and development.

Physician Joachim Sturmberg applies systemic design and complexity science to healthcare reform in the chapter "Systems Design for Health System Reform". The case is made that most attempts at reforming healthcare have failed, due at least in part to inadequate approaches. Sturmberg summarizes key issues for reform: "The design of a true system facilitating health, i.e. a real health system (Sturmberg 2018) hinges one a clear understanding of three key concepts: (1) the nature of health and disease, (2) the epidemiology of health, illness/dis-ease and disease, and (3) the nature and function of organizations." The chapter then covers basic principles of systems and complexity, and explains why healthcare systems have been resistant to change. Finally, implications for putting systemic design into practice are presented, along with examples.

Ecological Systems

This section is about systems science and its application in ecological theory. It takes a broad look at theoretical and applied systems ecology from a natural systems perspective, reviewing traditions in the history of ecology and new complexity theories that are emerging. Ecology represents one of the truly complex disciplines and one argument made in this section is that theoretical ecology can provide foundational concepts for natural science in general. A basic question addressed in these four chapters is if ecological processes are determined only by physical constraints or if, in addition, there must be something acting more at the systems level. Historically, there has not been a clear theoretical framework to unify these two views. The authors navigate the history of ecological modeling methods to suggest pathways toward synthesis; considering thermodynamic drivers and constraints ("Systems Ecology and Limits to Growth: History, Models and Present Status"), loop causality ("Putting More 'System' into Ecosystem-Based Management Using Qualitative Analysis"), holon theory ("Relational Systems Ecology: Holistic Ecology and Causal Closure") and model coupling ("Relational Systems Ecology: The Anticipatory Niche and Complex Model Coupling").

Charles A. S. Hall, known for his work on socio-ecological systems and energy analysis of both natural and industrial systems within the frameworks of Eugene and especially Howard Odum, sets the stage for this section with a broad but vivid review of systems ecology in "Systems Ecology and Limits to Growth: History, Models and Present Status", describing the development of the field from the perspective of energetics, including turning points and great actors (which certainly include Hall). Throughout this history, Hall reminds us that the journey has often been about our own survival as a civilization, dependent on resources and constrained by energy. He points out that we have survived this battle so far, but only because of continuing discoveries of new energy supplies, chiefly petroleum; perhaps a risky game of brinksmanship. What happens when we can no longer expand our energy sources?

Hall, like Odum and others (Hall 1995; Odum 2007; Sibly et al. 2012), takes energy and related measures as perhaps the most important diagnostic factor in the dynamics of ecosystems and modern civilization in relation to the ecology of the planet, its resources, and how we as people and governments manage it. In this chapter, he eloquently demonstrates the strength of this perspective in work that has been done to date, reminding us that as sophisticated as we may become in our mathematical modeling, there are still basic physical and chemical laws that are not going away. These laws can be seen as either driving system behavior or establishing constraints, but either way, complex possibilities seem to stay within established physical boundaries. In the face of modern crises affecting global civilization, from accelerating climate change to emerging pandemics and sociopolitical upheaval, Hall argues for a return to basic realism that can ground us in verifiable processes that have been well-studied in ecology for nearly a century, reminding systems thinkers that many socio-ecological issues would benefit from considerations of how energy has governed much if not all of biotic interactions with nature, including human ones.

In "Putting More 'System' into Ecosystem-Based Management Using Qualitative Analysis", Patricia Lane, working in network analysis, marine food webs, and the evolution of ecosystem chimeras as an ecosystem ecologist, approaches socioecological assessment from the perspective of "loop analysis," which has been an important tool for understanding feedbacks in many ecological traditions; for example, in "self-organizing holarchic open" (SOHO) systems (Kay et al. 1999), climate change studies (Lyubchich et al. 2020), and most recently the study of pandemics (Tonnang et al. 2020). Loop causality itself is characteristic of "relational biology" and "anticipatory systems" introduced by the mathematical biologist Robert Rosen (Rosen et al. 2012), who is often considered a revolutionary genius for his ability to take us to a more foundational level of complexity. Lane's own colloquium of Rosen scholars for the journal "Ecological Complexity" has introduced relational theory to ecology in a way that cannot be overlooked (Lane 2018).

Relying on Rosen's category theory approach, Lane explains and applies Causal loop analysis, giving us a roadmap to a relational understanding of ecology, while retaining the footing that ecological science has provided to-date. She explores causal loop diagrams as an analytical capability that may have been missing in physical theory; processes that otherwise seem to characterize the surprise and unpredictability of complex and living systems. This analysis is especially relevant to socio-ecological systems (SES), which strongly involve a human cognitive component. Loop causality is emerging as a major avenue of investigation.

Closed loops of natural entailment have been known for a long time in terms of positive and negative feedback systems that tend to form in living and non-living systems, both carrying information and recycling resources as they dissipate energy. Basic ecology teaches us about carbon, water, nitrogen, and many other cycles, which are loops in physical causation that can be observed. The idea of dynamic attractors can also be associated with causal loops. But a problem arises in explaining why such phenomena exist: What gives rise to or selects for causal loops? Complex causal loops must logically require another "organizational" phenomenon, which Rosen called system "genericity," a new kind of meta-causal loop between behavior and existence itself that is involved in the prior organization of physical/material processes in living systems. There is an emerging trend to explore ways of combining such mechanistic and complex views (e.g., (Rissman and Gillon 2017; Schlüter et al. 2019).

John J. Kineman, physical scientist and systems theorist, and Carol A. Wessman, ecosystem/global ecologist, address this last question in two co-authored chapters. They apply a recent synthesis of Robert Rosen's complexity (Kineman 2011) in a retrospective study of ecological holism and niche theory. The first in this pair of chapters, "Relational Systems Ecology: Holistic Ecology and Causal Closure", examines four-cause ontology of the holistic framework, an ancient and perennial concept of holism and symmetry in nature that is also derivable from Rosen's theories as a causal loop of the second kind mentioned above. This four-cause cycle relates structure and function, or behavior and origin, within systems, and provides a new analytical tool for complexity science. To introduce this metaframework, the authors examine higher causation in nature, arguing that misunderstanding Aristotle's 'final cause' as 'purpose' has prevented its incorporation into natural science. Final-formal cause entailment, in this view, is "functional entailment" (Louie 2013), having a natural basis in the anticipatory effect of prior conditions – the concept of 'karma' in the East and the inverse causality that Ervin Schrodinger called for in his famous book "What is Life". The result is to propose a rigorous causal synthesis in the concept of "holon" – a unit of system wholeness interconnecting and transcending nature as something different from 'the sum of the parts'.

The second chapter by these authors, "Relational Systems Ecology: The Anticipatory Niche and Complex Model Coupling", associates final cause with the abstract ecological niche as described by G. Evelyn Hutchinson, tracing the success of this concept in ecological theory, its abandonment for heuristic and practical reasons, and now it's possible return as a key model type in coupling human and natural system informatics. The adaptive ecological niche is presented as the missing factor that has been shyly hiding in ecological theory and that "closes the loop" of cyclical causality, according to Rosen. The authors suggest that developing niche-based "causal closure" will allow ecology to rigorously define holism, life, and sustainability in meta-causal terms. Similarly, their proposed model coupling architecture is meant to meet the aims of current high-priority research into "Coupled Human and Natural Systems" (CHANS) that is desperately needed to understand global to local socio-ecological systems presently in crisis. One very important point regarding general model coupling that all the authors of this section stress, is that each kind of model needs to be built properly in its own domain; then the coupling will work best. In that sense, problems arise from two directions; (1) when logically different types of model are conflated, and (2) when causal types are eliminated for the sake of arbitrary simplicity.

One topic of concern for every ecologist is how the discipline can affect policy. Ecology as a discipline has traditionally maintained a keen interest in providing advice or recommendations to manage and take care of the ecosystems that support us and all life on Earth. Ecologists can observe what is happening to those systems more keenly than most because they have the observing instruments and know how to interpret the data. Undeniably, ecosystems are degrading. But now we must ask, if ecology has done its job of informing humanity, why is that still the case? The traditional view has been that a pure scientist should have a certain kind of professional detachment from policy decisions, but increasingly all of us are humbled, if not humiliated, by our inability to affect policy.

Each author contributing to chapters discussing “Ecological systems” has made some attempt to comment on this issue, both here and elsewhere. Kineman and Wessman point out how scientific detachment has isolated ecologists from critical decisions and from that absence has encouraged the development of would-be “brokers” (the “policy analyst”), meant to form a dialog based on their own professional independence from both science and policy. But, in the end, such independence does not work as it only establishes a third actor, equally incapable of coupling science and policy. Clearly there is a communication breakdown creating systemic dysfunction in a “post-truth” world that discredits expert advice, and no longer receives the scientist’s message. The emerging alternative is “to develop co-productive relationships with decision makers...to engage with people on a personal level” (Peters and Besley 2019). This means becoming more engaged in society and policy by encouraging things like citizen science; sharing not just expert advice but methodology to arrive at that advice, and thus to build personal bridges from science to motivation without conflating the two.

These three views of theoretical systems ecology go from the practical world of proven mechanisms and physical limits into the abstract world of relational complexity and then down the rabbit hole into a wonderland of general holism. Readers should not, however, see these views as contradictory, but as identifying different aspects of modeling that should work better together. These chapters provide a review of ecology as a unique field of science, essentially an integral science. The many practical developments can be praised while the lack of progress criticized, on holistic levels; but perhaps this is symptomatic of the leading edge of science itself. Nevertheless, it appears that if some revolutionary change is needed in science to better couple natural and human systems, that might also require more integral modes of participation. We need a more synthetic, systems-oriented perspective both for Ecology’s own sake and for the relatively complex issues facing humanity.

Systems Research and Education

This section of the handbook encompasses contributions from diverse sectors of the systems sciences. It represents educators and researchers whose work includes fundamental concepts and experiential learning in teams; from career management to action research. Taking a broad view of the mission of education, its purpose goes beyond the immediacy of vocational preparation to embrace enduring preparation of minds, envisioning their futures as contributing members of societies through the development of critical and systems thinking. In short, education prepares people for the challenges of today and tomorrow through development of adaptive capacities and competencies for acquiring knowledge, skills, and abilities to thrive in a changing and uncertain world. Conceptually, this approach to learning, as well as a commitment to life-long learning, is akin to the adage about the vital benefits of teaching a man to fish as opposed to feeding a man a fish. Systems research and education are not merely about the economics and politics of reducing poverty. Research and education using systemic approaches can comprise ethical commitments to civic engagement, for the lifting of societies for betterment of the quality of life. The compelling question driving this section is, "How can systems research and education help us understand our complex world and respond to it in timely and effective ways?" The chapters in this section reflect the essence of being a systems scholar/practitioner.

Research and education using systemic approaches can comprise ethical commitments to civic engagement for the lifting of societies for betterment of the quality of life. Indeed, it was this recognition of a need to see whole systems, as they are, to understand complexity beyond science's reductive observation, that compelled Bertalanffy, Boulding, Gerard, and Rapoport to organize the Society for General Systems Research in 1954, now the International Society for the Systems Sciences (Hammond 2003).

This section, "Systems Research and Education," applies a systems view of research and education to inquiry and learning. The six authors' contributions share this vision, yet they come from different perspectives. Those perspectives help to construct a view of education and research as a whole system. This aligns with Bela H. Banathy's (1992) approach to education as a human activity system (Checkland 1999). In a handbook such as this, readers naturally ask, what does a systems perspective contribute to our understanding of our world's complexity through research and education? Here are some of Banathy's thoughts about this question:

> What can we expect to attain by the development of the systems view? I suggest that the systems view helps us understand the true nature of education as a complex, open, and dynamic human activity system (designed social systems organized for a purpose that they attain by carrying out specific functions) that operates in ever-changing multiple environments and interacts with a variety of societal systems. Beyond such understanding, once we develop the systems view, we have developed ways of knowing, thinking and critical reasoning that empower us to organize a system of comprehensive, disciplined inquiry capable of addressing all issues of educational practice (Banathy 1992, p. 17).

According to Walton (2004), Banathy recommended a three-lens approach for comprehensive modeling of social systems, like those in research and education. Walton emphasized that Banathy distinguished product models, which describe outcomes of an inquiry, from process models, which describe the activities for conducting an inquiry. Systemic inquiry uses both. It is important to note that these lenses are rarely independent of one another in organizations. They are perspectives, a plurality, which help inform the model of the system(s) represented.

Banathy (1992) introduced three lenses as general representations of social systems:

1. Systems-Environment – this view provides a framework for describing educational activity systems in the context of their communities and society. Banathy describes this as the "bird's-eye-view" (p. 22) or the landscape in which the system is embedded. Relationships, interactions, and interdependence mark the concepts and principles of this view. One of the interdependencies this lens explicates is a set of inquiries as a general description that guides assessment of the environmental adequacy and responsiveness of the educational activity system and vice versa – the responsiveness of the environment toward the system.
2. Functions/Structure – this view considers the educational activity system in a moment in time, a "still picture" (Banathy 1992, p. 22), or snapshot. This lens enables description of the goals, purpose, function, relationships, components, and organization of those elements as they are integrated into the system. Through this lens, a set of inquiries can guide researchers and participants toward understanding the adequacy of the educational activity systems in terms of its function/structure.
3. Process – this view considers the activities and actions of an educational activity system or what it does over time. (e.g., longitudinal research). Like a behavior over time graph, akin to those used in Systems Dynamics (Sterman 2000); this perspective presents the dynamics of the system. It is a "motion picture" (Banathy 1992, p. 22) illustrating how the educational activity system changes in the context of community and society. It describes how the system receives, screens, assesses, and processes inputs, as well as transforms this data for use and engages in operations that fulfill the purpose and goals of the system to produce expected outcomes. These are continuous processes guiding the transformation of operations with ongoing assessment and adjustment based upon feedback from the environment to ascertain its adequacy or fitness.

Banathy (1992) was keen to emphasize that each of these lenses, while robust on their own, render partial pictures of the essence of an educational activity system. When used in concert with one another, their vibrancy amplifies. Banathy stated:

> What is important for us to understand is that no single model or lens can provide us with a true representation of an educational organization as a complex social system. Each lens portrays certain characteristics, but not all, that we need to describe an educational activity system as a whole system. Only if we consider these three descriptions jointly, as if overlaid upon each other, do the lenses help us to provide a comprehensive image and reveal the real

> story of an educational organization as a system. (p. 23).

In this section of the handbook, the authors' contributions about "Systems Research and Education" fall into one or more of these lenses. Each article describes philosophies, perspectives, processes, and practices that inform our vision of educational activity systems in terms of inquiry and learning. For example, Rowland sets a conceptual foundation in "Making Inquiry More Systemic." In doing so, Rowland addresses Banathy's three lenses of environmental context, structures, and processes of education through systemic inquiry. In "Violence Prevention Education - Problem Structuring for Systemic Empowerment in Health Settings", Stephens and Liley use an action research approach to address the intractable issue of domestic violence. Their action research approach integrates relationships in context aligning with Banathy's Systems-Environment lens. McIntyre's "Systems Research and Education: A Conversation About a Critical Systemic Approach to Creativity and Design", aligns with Banathy's Functions/Structures lens in her own research and analysis of several student projects. McMahon and Patton's "Career Development from a Systems Perspective: The Systems Theory Framework" combines Banathy's Process lens with the Systems Environment lens to understand career development for individual success in competitive environments. Finally, in "Team Systems Theory: Building Stakeholder Value through a Learning Culture for Organizational Resilience", Edson uses Banathy's Process lens to analyze and recommend that leaders view project teams as valuable agents of change, leadership, and resilience in educational, commercial, governmental, and social service organizations. Banathy's comprehensive approach to modeling social systems complements others like rich pictures (Checkland 1999). As a whole, the authors in this section provide a vision of the potential realized through systemic research design and pedagogy for theoretical and experiential learning that cumulatively endures. In sum, it is the value of systemic approaches in research and education.

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