Systems engineering applied to urban planning and development: A review and research agenda

Citation: Reid, Jack and Wood, Danielle. 2022. "Systems engineering applied to urban planning and development: A review and research agenda." Systems Engineering.

As Published: 10.1002/sys.21642

Publisher: Wiley

Persistent URL: https://hdl.handle.net/1721.1/146601

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Received: 25 April 2022 | Revised: 28 July 2022 | Accepted: 22 August 2022

DOI: 10.1002/sys.21642

REVIEW ARTICLE

WILEY

Systems engineering applied to urban planning and development: A review and research agenda

Jack Reid[1] | **Danielle Wood**[2]

[1]Media Arts and Sciences Program, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

[2]Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Correspondence
Jack Reid, Media Arts and Sciences Program, Massachusetts Institute of Technology, Cambridge, MA, USA.
Email: jackreid@mit.edu

SIGNIFICANCE AND PRACTITIONER POINTS

The use of systems engineering tools and methodologies for applications outside of the traditional engineered system domains is on the rise. In particular, systems engineering is seeing increased popularity in urban planning (commonly tied to the concept of the smart city), healthcare, and sustainable development. Many researchers and practitioners may be unaware of a previous boom in the popularity of such applications that occurred in the United States during the 1960s and 1970s. At the time, numerous unexpected challenges were encountered, leading to high profile failures and backlash from urban planners, politicians, and the public. This paper seeks to review that history, identify specific pitfalls, consider which ones are still relevant today, issue recommendations for how current practitioners may avoid them, and identify how ongoing research may help obviate the remaining pitfalls.

Funding information
MIT Media Lab Consortium, Grant/Award Number: N/A

Abstract

Systems engineering tools and methodologies are increasingly being used in urban planning and sustainable development applications. Such tools were previously extensively used for urban planning during the 1960s and 1970s in the United States, only to result in high profile failures and pushback from urban planners, politicians, and the public. In order to better understand why this occurred, what has changed, and how we can avoid such failures moving forward, this study conducts a systematic review and an integrative review of the systems engineering and critical literature. These reviews are used to identify eight common pitfalls and organize them into key themes. Technological and methodological developments that may address each of these pitfalls are considered and recommendations are made for future applications of systems engineering to planning contexts. Finally, examples are provided of systems engineering being used productively in a way consistent with these recommendations for sustainable development applications.

KEYWORDS
lessons learned, review, stakeholders, sustainabilitys, urban development, urban planning

1 | INTRODUCTION

Over the course of the past decade, the fields of systems engineering and systems architecture have increasingly found applications outside of the traditional engineering systems (aerospace, defense, major infrastructure projects, etc.). The digital twin concept has been extended to the smart city.[1–4] Systems architecture has been leveraged to design environmental monitoring and sustainable development systems.[5–7] Healthcare too has seen recent systems engineering applications,[8] including COVID-19 response.[9] Obviously, there is an increased interest among systems engineers in such applications. This is bolstered by the rise of many urgent issues in these same domains that systems engineering is well-posed to address.

Perhaps unknown to newer participants in the field, however, is the fact that this is not the first time that systems engineering has sought to apply its methods to pressing societal issues outside of the realm of traditional engineering. In the late 1960s and into the late 1970s, buoyed by the success of the Space Race, many sought to bring the tools, methods, and perspectives of systems engineering to development, urban planning, and societal welfare. These attempts were largely unsuccessful and, in some cases, actively harmful. As we seek to re-enter these application areas today, it is thus worth examining the sources of these failures and considering the extent to which they are (or are not) still applicable today. This is important for both veteran systems engineers who remember this history and are reluctant to return to planning applications and to new systems engineers who may not be aware of this history and need to avoid the mistakes of the past. If we fail to do so, we risk incurring the same damages to the public and harming the reputation of the field of systems engineering.

Since the terms *planning* and *development* are both commonly used in an engineering context, it is worthwhile to be clear about what we mean in this paper. *Urban planning* is the field that focuses on the design and enactment of urban land use, infrastructure, and services to promote the welfare of the community (typically either a municipality or metropolitan area). Municipal governments tend to be the primary, but by no means the sole, organizations that engage in urban planning. *Regional planning* is similar, but occurs on a larger geographic scale. *Development* is a closely related, but distinct field, that focuses on improving societal welfare of an area. Development can be focused at the urban, regional, national, or international scales. Historically, it focused primarily on economic welfare, but more recent and expansive forms are increasingly common, such as sustainable development. In this paper, the word "planning" will be used to refer to both planning and development at all spatial scales. This is done for conciseness, clarity, and because most (though certainly not all) of the systems engineering applications of the mid-20th century in these domains were concentrated in urban planning, but we believe that there are useful lessons learned for applications across both planning and development, as well as across a wide range of spatial scales. Finally, this paper focuses primarily on a particular period in the United States in order to focus the study on a specific phenomena.

In this paper, we conduct both a systematic review of the systems engineering literature as it pertains to planning and an integrative review of a broader disciplinary background, in order to identify several primary pitfalls. We organize these pitfalls into thematic groups and consider to what extent new developments in theory and methodology have addressed the pitfalls. We then propose an approach for productive collaborations of systems engineers with planners in sustainable development contexts.

2 | THE HISTORY OF SYSTEMS ENGINEERING AND PLANNING

While systems engineering certainly is connected to other, older engineering disciplines, most histories of the field start in the early 1950s and acknowledge that the field truly hit its stride with the Space Race of the late 50s and 60s.[10–13] The official formation of a professional society, the International Council on Systems Engineering (INCOSE), would follow much later in the early 90s.[14] These histories tend to focus on the technical development of the field, highlighting new methodologies and frameworks such as Model-Based Systems Engineering (MBSE), System of Systems (SoS), and so forth; or academic milestones, such as the formation of the IEEE Systems Journal or the promulgation of MIL-STD-499. The only consistently mentioned application of systems engineering is the Apollo program, though some of these histories occasionally mention other military or NASA programs such as Tracking and Data Relay Satellite System (TDRSS).

Typically lacking in these histories is discussion of notable application lessons learned, particularly from failures or shortcomings. Such a lack can lead to each new generation of engineers using new tools to replicate the mistakes of the past. This is not to say that the systems engineering field has wholly ignored failures. Talbott summarized systems engineering insights from several hundred system failures across several disciplines including aerospace engineering (e.g., the Hubble Telescope mirror defects), civil engineering (e.g., the Tacoma Narrows Bridge collapse), and telecoms (e.g., a worm on ARPAnet).[15] Bahill and Henderson conducted a similar review, though they also (unusually) included a couple of social systems, namely the US war in Vietnam and the failure of US counterintelligence to prevent the September 11, 2001 terrorist attacks.[16] Petroski has written extensively on lessons learned from civil engineering failures (primarily bridge and other structural collapses) that are generalizable to engineers of all disciplines.[17,18] A 2011 panel of senior practitioners in the field examined multiple aerospace failures from a systems engineering perspective.[19]

A neglected source for such lessons learned, however, are the attempts to apply systems engineering to planning, particularly urban planning, in the 1960s and 1970s. In 1964, the state of California commissioned four aerospace companies to conduct studies and develop models of the state's transportation needs for the coming decades.[20] US Vice President Herbert Humphrey said in a 1968 speech that "The techniques that are going to put a man on the Moon are going to be exactly the techniques that we are going to need to clean up our cities".[21] In the same year, the RAND Corporation established the New York City—RAND Institute (NYCRI) in an attempt to bring systems analysis and engineering to urban planning. Around the same time, the American Institute of Aeronautics and Astronautics (AIAA) hosted meetings on urban technologies to bring aerospace expertise to bear on the urban crises of the time.[21] In 1970, NASA established the Urban Development Applications Project,[22] followed by a New York City Applications Project in 1972, and an NSF Urban Technology System Experiment in 1973.[23] Also in 1970, Jay Forrester published his seminal paper "Systems Analysis as a Tool for Urban Planning"[24] which in 1972 would be expanded upon with the World3 model used in the (in)famous book *The Limits to Growth*.[25] System dynamics, the modeling approach underlying both of these, would go on to have major impacts on business management, urban development, and environmentalism.[26] The very same year, the US federal government established the Urban Information Systems Inter-Agency Committee (USAC) to bring systems engineering and analysis tools to municipalities across the country.[27] Outside of the United States, the London-based think-tank, Centre for Environmental Studies, was advocating for the use of multiscale and multidomain urban models as early as 1968.[28] It was a heady time, with engineers feeling 'that, having reached the moon, they could now turn their energies to solving the problem of growing violence in cities along with other urban "crises" [Ref. 29, p. 33]. These applications were justified by several different rationale, chief among them were[21]

1. Computer simulations and related techniques were simply advances on the statistical models already widely used by the urban planning profession.
2. The rise of cybernetics, with its cross-disciplinary control analogies, promised to unify disparate fields within urban planning and analysis, resulting in a unified understanding of cities.
3. The use of these military innovations would transform urban planning and decision-making into scientific endeavors.

Almost immediately, however, such grand ideas met with difficulties. The New York City-RAND Institute (NYCRI) was forced to close in 1975 in the face of resistance from the civil service, unions, and the public at large due to perceptions of RAND's elitism, secrecy, and lack of regard for the side effects of their proposed reforms.[21] As early as 1972, RAND acknowledged that the NYCRI attempt had met numerous difficulties due to such issues as the NYCRI's secrecy (the New York City council "grew annoyed" that "under the terms of our contracts [they have] no right of access to the studies" [Ref. 30, p. 159]) and NYCRI's failure to "provide these groups [local interest groups] with the means of participating in public debate in a more informed and more rational way." [Ref. 30, p. 161] The USAC was shut down in 1977 after significant criticism for spending large amounts of money on projects that failed to deliver.[27] NASA's efforts lasted somewhat longer, continuing to encourage the use of remote observation data by urban planners as late as 1980[31,32] before retreating from the urban development domain in the early 1980s largely due to a lack of interest from municipal governments and planners.[21] Perhaps the most ambitious application of systems engineering methodologies to economic development was the 1971–1973 Project Cybersyn, a distributed decision-support system (DSS) based on an economic simulator and cybernetics intended to facilitate the management of Chile's national economy.[33] Unfortunately Project Cybersyn is not particularly useful for understanding the benefits and limitations of systems engineering as it was abandoned following the nation's military coup in 1973, though even in prototype form, it did yield some initial successes (and ran into various challenges).[34]

Meanwhile, much of the US planning profession strongly rejected the new systems engineering entrants:

> "The systems engineers bring some expertise and substantial pretensions to the problems of the city. Their principal system expertise seems to be relative to complex organizations that are mission oriented. There is in any case a good deal of difference between the mission of reaching the moon, and the mission of survival and welfare for society and the city. The systems engineer can in general deal best with subsystems and specific tasks, and he therefore suboptimizes. This is a charitable description." [Ref. 35, p. 12]

> "Trying to solve 'earthly problems,' especially urban problems through aerospace innovations had shown that 'transporting the astronauts from terra firma to land on the lunar sphere, travel hither and yon over its surface, and then back home to Houston' was a comparatively simple task." [Ref. 21, p. 144]

This skepticism continues to the present day. Urban planner John Friedmann considered systems engineering to be among the intellectual schools of urban planning, but stated that the field "look[s] to the confirmation and reproduction of existing relationships of power in society. Expressing predominantly technical concerns, they proclaim a carefully nurtured stance of political neutrality. In reality, they address their work to those who are in power and see their primary mission as serving the state" [Ref. 29, p. 19]. Similarly, Marcuse, another urban planning scholar, referred to systems engineering as primarily concerned with efficiency and highly deferential to existing relations of power.[36]

In short, systems engineering poured immense resources into planning in the 1960s and 1970s, only to face numerous difficulties and a quickly disenchanted public, leaving lasting impacts on the reputation of the field. This history leads us to asking why systems engineering did not achieve all that it hoped. While we cannot change the past, we can learn from it and use its lessons to improve our current practice.

It should be noted that the above history focuses almost entirely on the United States. This is due partially for reasons of scope: We would like to draw concrete lessons learned from a specific cycle of popularity in the United States. It is also partially due to the language limitations of the authors and to a genuine concentration of publications in the United States during this period (as is demonstrated later in this study). Similar (or opposing) trends at the same time in other countries, such as the USSR,[37] may also be worth examining in a future study. This study also focuses primarily on "push" factors inside the planning field that drove the decline of systems engineering involvement. It does not address the possibility of external "pull" factors that could have drawn systems engineers to other fields (such as financial services).

3 | METHODS

The objectives of this paper are to identify and classify the primary pitfalls of systems engineering as applied to planning; seek to determine to what extent this pitfalls continue to be relevant; and issue

TABLE 1 Systematic review search terms

A: Field	B: Application Domains	C: Pitfall Keywords
systems engineering	urban development	difficulty
	urban planning	difficulties
	regional development	failure
	regional planning	unsuccessful
	international development	challenge
		challenges
		inadequate
		limitation
		limitations
		lessons learned

recommendations on how systems engineering practice can be improved. To address the first of these objectives, we conducted two parallel reviews of the literature. The first was a systematic review based on boolean searches for specific phrases in the text and tags of publications in the systems engineering literature. This search was conducted using Engineering Village, a search engine that includes both Compendex and INSPEC, making it one of the more comprehensive databases for engineering literature. Web of Science was not used as it contains a much wider set of fields and publications than is necessary for this search. IEEE Xplore was also considered but ultimately not used as it output in less than 10% of the results of Engineering Village and even less during the critical period during the 1960s and 1970s.

The initial search (**S1**) was for all publications containing the term "systems engineering" (Column A of Table 1). It should be noted that systems engineering was and is not the only term used when referring to the application of systems engineering methodologies in a planning setting. In the mid-20th century, other commonly used terms included *systems analysis* and *policy analysis*. Both of these terms were advanced by the RAND Corporation in particular. One definition of systems analysis was "an orderly analytic study designed to help a decisionmaker identify a preferred course of action from among possible alternatives" and explicitly tied the field to "the defense community" and "weapon development" [Ref. 38, p. 1]. Over time, however, the term systems analysis was largely replaced by policy analysis and the field developed on its own trajectory. More recently, the term *systems thinking* has become more popular in reference to the combination of systems engineering, systems dynamics, and other related fields in application to business, the environment, and public sectors.[39] A review that tracked the rise and fall of such terms, along with their degree of connection or distance from systems engineering, is beyond the scope of this paper. For this reason, only the term "systems engineering" is used to constrain search **S1**.

To identify relevant applications of systems engineering in the domains of interest, we then searched the **S1** corpus for publications that contained one of the relevant domain phrases (i.e., Column B of Table 1). This search is termed **S2**. No searches were conducted for co-occurrence with "development" or "planning" without additional descriptors as these are commonly used terms (with different meanings) within systems engineering. The first **S2** result was from 1963 and we terminated search results at 2020, since, as of time of writing, that is the last year whose complete publications have been including in the Engineering Village database. This period was used to define the study period for all of the subsequent searches.

To further refine this into those publications likely to contain discussion or examples of failures or shortcomings, we then searched within **S2** for publications with at least one term from Column C of Table 1. This search is termed **S3**. Obviously many of these terms are commonly used in systems engineering literature, including in publications irrelevant to this search. For this reason, a final refinement (**S4**) was conducted in the form a manual review. Four exclusion criteria were applied:

Criteria 1: The actual publication was unavailable.
Criteria 2: The publication had little to do with systems engineering.
Criteria 3: The publication had little to do with development/planning in the senses used in this survey.
Criteria 4: The publication either recorded a completely successful application of systems engineering in the relevant domains or did not discuss challenges in application.

Note that these criteria were applied in sequence and if a publication met one exclusion criteria, the later criteria were not evaluated. Publications that met all four criteria and were thus included in **S4** were coded for implementation pitfalls. By *pitfall*, we mean a typically unforeseen factor that is largely under the control of the systems engineer and is likely to significantly and negatively impact the success of a project. These pitfalls were generated organically, by reading through the publications and identifying commonalities. As the list grew, previous publications were re-evaluated. This was an iterative process, with the set of pitfalls growing, splitting, and merging before the final list was converged upon. Finally, the pitfalls were grouped into themes.

The term "pitfall" is chosen intentionally, as each was (and is) essentially a trap for an unwary systems engineer. Several can be ameliorated or partially circumvented via technological means, but all require the engineer to identify the presence of the pitfall and consciously choose a different path.

In addition to coding for pitfalls, the various systematic search results were also examined for any trends over time, to determine to what extent the purported 1960s–1970s boom and subsequent bust is borne out in the literature.

There are certain limitations to any systematic search, however, and particularly for this one. For one, systems engineering as a field has evolved significantly over the relevant period (1963–2020) and has changed definitions multiple times (compare[40–42]). Similarly, there is no clear set of phrases to describe the planning domain that does not also encompass a certain number of irrelevant topics. The set listed in Column B is likely to result in both false positives and false negatives. Finally, we are primarily interested in failures, shortcomings, and limitations, all of which are likely to be less well-documented in the

TABLE 2 Search results and criteria violations counts

	S1	S2	S3	C1	C2	C3	C4	S4
# of Publications	347,490	1261	96	9	23	16	6	36

engineering literature than successes. This is both because of a longstanding publication bias in favor of positive results across numerous fields[43] and also because when a engineering endeavor is disbanded, there often is not the time or funding to commission a retrospective. Such documentation is left to the veterans of the project or historians to complete on their own time, and this often only occurs for particularly high profile projects. For example, the previously referenced NYCRI commentary was a mid-program review, not a post-mortem.[30]

For all of these reasons, it is worthwhile to supplement the systematic review of the systems engineering literature with an integrative review of notable relevant reviews, histories, and critiques. Eleven such publications were identified. Most are focused specifically on the relevant boom period (late 60s and 70s). For some, this is because they were written during or just following this period.[27,44–48] For others, it is because they are historians investigating this period.[21,49] Some are focused on some technical subfield of systems engineering, such as multicriteria decisions,[50] system dynamics models,[51] or large integrated models.[46] It is hoped that these publications can provide the more critical perspective of an outsider to the field, more detailed context on the nature of the pitfalls identified, and suggestions for how to move forward.

One piece originally selected for the integrative review[52] was returned as a result in the systematic search. It was decided to count it in the systematic review and not among the (now ten) integrative review publications, in order to avoid double-counting.

Following the identification of the pitfalls, we consider what new developments (theories, methods, practices, etc.) have occurred and how these developments interact with the pitfalls. This set of developments is not exhaustive and is intended primarily to be illustrative of how the relevant aspects of systems engineering have changed. Finally, we use the combination of pitfalls and new developments to map out recommendations for the future.

4 | RESULTS: WHAT HAPPENED AND WHY?

The number of search results and criteria violations are summarized in Table 2. The historical rise and fall of systems engineering in planning contexts can be clearly seen in across **S1** and **S2**. Figure 1 presents both the raw study counts as well as the ratio of **S2** to **S1**. The United States publications are shown overlaid on the global publications (which also include the US publications). The initial 20th century boom, lasting roughly 1968–1976 and largely US-driven, is evident. This is followed by the long, subsequent fallow period, and then by a more recent surge occurring largely, though not entirely, outside of the United States. The spike in 2004, for instance, was driven primarily by the Systems Engineering Society of China electing to co-sponsor the Fourth International Conference on Traffic and Transportation Studies, which was held in Dalian, China.[53] This more recent phenomena could be the result of the lack of professional memory of previous failures outside the United States and further motivates the need for a historical review of those failures.

Of the 96 **S3** results (the corpus that included the application domain terms and on which a manual review was conducted), **C1** (publication availability) was violated by nine publications, primarily government and nongovernmental organization (NGO) reports from the 60s and 70s that do not appear to have been digitized or widely disseminated (e.g., Refs. 54, 55). **C2** (relevance to systems engineering) violations were primarily due to alternative uses of "systems engineering," such as in longer phrases (e.g., "biological systems engineering"[56]) or by the National Technical Information Service (NTIS). The latter seems to use "systems engineering" in a way that does not always align with contemporary definitions of the field (e.g., the 1966 Model Plumbing Code was tagged as systems engineering[57]). **C3** (relevance to planning) violations typically occurred because one of the application domain terms was being used in a different, more colloquial sense (e.g., "international development" referring a multination collaboration on a combat aircraft[58]). The relatively large numbers of **C2** and **C3** violations (24% and 17% of the **S3** set, respectively) raise questions of the accuracy of the original **S1** and **S2** searches. This concern is partially alleviated by the fact that 20 of the 23 **C2** violations and 15 of the 16 **C3** violations occurred after 2010, suggesting the dilution of "systems engineering" and the application domain terms is fairly recent. The 20th century trends of Figure 1 are thus unlikely to be impacted by this source of error. Finally, the **C4** (contained discussion of pitfalls) violations were primarily in purely technical pieces that were proposing or demonstrating a model or methodology, but not applying it in an actual planning setting (e.g., Refs. 59, 60).

Ultimately, across both the **S4** systematic review and the integrative review, eight pitfalls were identified (**P1–8**) which were then organized into three themes (**T1–3**). These, along with the portion of the reviews that noted each pitfall, are summarized in Table 3. The full set of **S3** and **S4** publication references, along with their **C1–4** and **P1–7** codings are available as an online appendix. These pitfalls and themes are not the only possible way to categorize the pitfalls present across the literature, nor are they wholly independent from one another. These were selected and organized so as to facilitate useful lessons learned and actionable responses.

P1: Data and metrics and **P2: Theory and methods** represent primarily technical limitations in data, metrics, and methodologies, coupled with the general intransigence of social systems to measurement and modeling. The first of these deals primarily with the much more limited and fuzzy data that systems engineers had to work with in planning contexts during the mid-20th century, as well as limited performance metrics for social wellbeing at both the individual and community scales. The latter refers to limitations in modeling methods and theoretical frameworks for grappling with the complicated dynamics of human societies. Such limitations encourage simplifying assumptions in order to make the problems tractable. One of the most common of these simplifications was selecting an efficiency metric for an existing

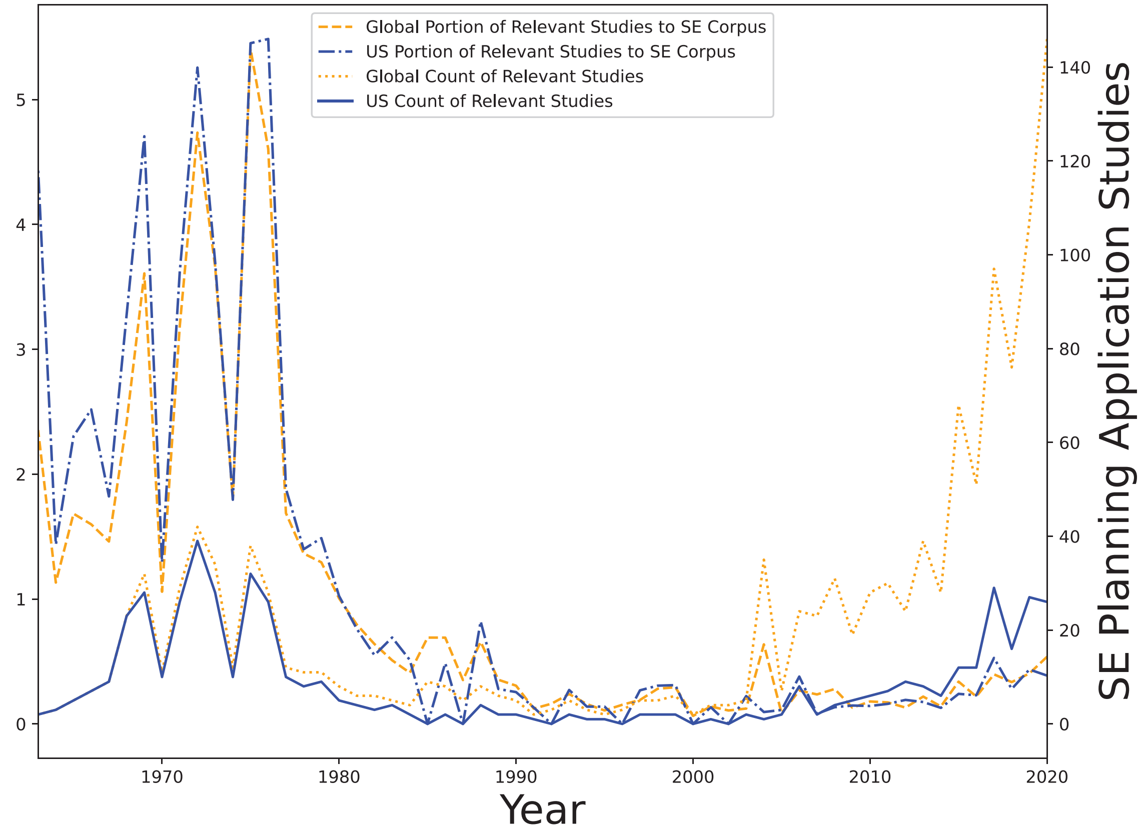


FIGURE 1 Frequencies of the co-occurrence of "systems engineering" with "urban planning," "urban development," "regional planning," or "regional development" (**S2** both in absolute count and relative to the systems engineering corpus (**S2**/**S1**). US publications include all those published in the United States regardless of affiliation of the authors. Global publications include all publications, including the US publications

system to optimize, rather than more critically considering the goals and design of the system as a whole.[29,36] Both of the **T1** pitfalls were commonly identified in both reviews, likely because identification of technical limitations, along with proposals for how to address them, constitute a major mechanism for research progress. Beyond this, however, some issues, particularly around social questions, have no single, encompassing metric, regardless of the level of data availability.

This directly leads into **T2**, which includes **P3: Siloed knowledge**. As was discussed previously, planning literature abounds with complaints of systems engineers not considering disciplinary expertise or other forms of knowledge. Urban planners sometimes felt as though engineers sought to replace them rather than collaborate.[21] Perhaps due to the data and computational limitations at the time, engineering models tended to focus on the abstract and universal, ignoring local context. Forrester's system dynamics model of a city, for instance, was critiqued for being "not spatially disaggregated," "of an abstract city," and for "us[ing] no data" [Ref. 46, p. 174]. **P4: Singular solution**, regarding the extent to which a single objective function representing a single stakeholder's preferences is even appropriate, is an issue the systems engineers have had to grapple with even outside of planning contexts. This issue was recognized early on, though productive means of addressing were only developed much later. Smith in 1968 wrote that "It is relatively easy to answer the question: 'Who and what is missile XYZ being designed for?' It is significantly more difficult to answer the question: 'For what users and what purposes is the city to be designed?"' [Ref. 20, p. 34] Similarly, Rider, in a 1975 NYCRI paper demonstrating a parametric model for the allocation of fire companies, readily recognized that "Far from involving the optimization of some well-defined criterion, the pursuit of such a goal requires the delicate integration of several often conflicting objectives… These questions have no universally acceptable solutions" [Ref. 61, p. 146-147].

Some of the notable differences between the systematic review and the integrative review are worth discussing. **P5: No user focus** was mentioned in approximately half of the systematic review publications but almost all of the integrative review publications. Two primary causes of this pitfall were noted in the literature. The first is that many of the systems engineering applications were more focused on research, including developing and demonstrating new tools and techniques, rather than on responding to the immediate needs of decision-makers. The second was an emphasis on secrecy both towards decision-makers and the public at large. Both of these were likely disciplinary norms inherited from systems engineering's origins in military and private industry.

P6: Cost and time, which refers to higher than anticipated startup costs for systems engineering studies and models, was noted by only 9% of publications in the systematic review but was noted in 50% of the integrative review publications. This difference is likely due to two sources. First, scholarly research publications do not often complain

TABLE 3 Identified themes and pitfalls from **S4** coding, including the proportion of systematic and integrative review publications that contained each pitfall

Theme	ID	Pitfall Description	Systematic Review	Integrative Review
T1: Technical Limitations & Simplifying Assumptions	**P1**: Data & Metrics	Lack of relevant and low uncertainty data and indicators. This historically has been particularly severe in the case of social wellbeing. This lack of good metrics can result in optimizations based upon narrow metrics.	60%	80%
	P2: Theory & Methods	Lack of understanding, theory, or methodologies to handle the complexity of cities and societies. This can result in overly simplified models and the design of simple, controllable systems that do not work well in the field.	43%	70%
T2: Stakeholder & Contextual Consideration	**P3**: Siloed Knowledge	Lack of integration across fields of research and other forms of knowledge. This can lead to a lack of regard for subject matter experts (e.g. urban planners, social scientists, etc.), historical context of intervention areas (i.e. assuming every city can be treated the same), and local expertise (e.g. long-term residents or community organizers).	40%	80%
	P4: Singular Solution	The assumption that there is a single objective function to be optimized, that there is a singular 'optimal solution', or that the needs of all stakeholders except the client can be safely ignored.	54%	50%
	P5: No User Focus	Lack of collaboration or interaction between the engineer/analyst and decisionmakers, system users, and/or the public. This can result in prioritization of basic research over the needs of the actual system stakeholders.	53%	90%
	P6: Cost & Time	Development of systems engineering analyses and tools either lagging the urgent need for a particular policy decision or being too costly to pursue and maintain.	9%	50%
T3: Self-Awareness	**P7**: Lessons Learned	Lack of learning from past failures and experiences	14%	50%
	P8: Hype	Overstating systems engineering capabilities or using engineering terminology to justify unscientific methods/actions.	3%	30%

about their own lack of funding or compressed deadlines, preferring to restrict themselves to technical results (with perhaps an appeal for future research support in the future). The second, noted in a number of publications found in both reviews, was a combination of general optimism with an expectation that tools and techniques developed in an aerospace or defense context could be directly ported over to urban and regional development with minimal additional resources. This ultimately proved to not be the case, and while both civilian and military aerospace projects could be assured of immense funding and institutional support during the Space Race era, these urban development applications often lacked such long term, invested support. Furthermore, if the development of a spacecraft was delayed, the launch date would be pushed back. In a policymaking setting, if the model development was delayed, a decision would simply be made without the model.

P7: Lessons learned also has a significant gap between the systematic and integrative reviews. It should be noted that almost all of the publications included some amount of background or a review of the literature, as is to be expected. These typically focused on specific technical limitations of previous work that the new publication seeks to address. **P7** does not refer to this, but to a broader consideration of what impacts, positive or negative, that previous impacts had on decision-makers and public. Such consideration was infrequently found in the systematic review.

Another noticeable difference is the least commonly noted pitfall, **P8: Hype**. This was only discussed once in the systematic review but was raised in several of the integrative review publications. This is perhaps because this is a critique that would rarely, if ever, be levied against one's own field. The systems engineering literature is populated by actual practitioners presenting primarily on their own results and thus, quite reasonably, believe in the validity and scientific merit of their own activities. Outside critics, however, are more prepared to identify hyperbole and deep methodological flaws. Forrester's system dynamics model of a city[62] was criticized for "bur[ying] what is a simplistic conception of the housing market in a somewhat obtuse model, along with some other irrelevant components. He then claims that the problem cannot be understood without the irrelevant complexity" [Ref. 46, p. 174]. The one systematic review paper to discuss **P8** positioned itself as seeking to preserve the systems analysis/systems engineering field from “overblown promotion” by “opportunistic converts” who bring “discredit to both the convert and his new-found meal ticket.” [Ref. 63, p. 1-3] Scott, meanwhile, pointed out that, regardless of the intellectual rigor of the underlying analysis, decisionmakers who commission a study can, through their influence of the study, direct its outcome in much the way that Forrester’s model was accused. These decisionmakers can then drape themselves in the authority of a “a scientific report” to justify their already decided upon course of action.[49] This is of course closely connected to stakeholder considerations posed by the **T2** pitfalls.

5 | DISCUSSION: WHAT HAS CHANGED?

The frequency and content of publications in the literature records the gradual rejection and retreat of systems engineering from planning applications. As early as 1973, planning scholars were (perhaps preemptively) eulogizing the death of large-scale models and other tools of the systems engineer.[46] The subsequent decades saw the fields of systems engineering and development planning grow largely independently of one another.

With regard to **P1: Data and metrics**, numerous quantitative economic and social indices have been developed for the planning field[64–68] and available data sources have greatly expanded, including telecoms-based mobility data, distributed sensors, remote observation, and demographic statistics. Mathematical tools such as cellular automata and agent-based modeling have become popular.[69,70] Digital models underlie the popular subdiscipline of scenario planning.[71,72] Interdisciplinary, integrated models have even started to re-emerge.[73–75]

At the same time, systems engineering has changed. As early as 1981, systems engineers were incorporating some of the more critical perspectives into their work, as seen in soft systems methodology (SSM), which sought to shift emphasis from directly engineering social systems to leveraging a systems perspective during a process of inquiry.[76] The greater popularity of SSM in the UK and Europe when compared to the United States has been suggested as a reason why the extra-US increase in planning-related systems engineering publications in the early 2000s seems to lead the intra-US rise in the 2010s (as seen in Figure 1).[77] In general, the belief that systems, even human systems, can be made simple, rational, and controllable (**P2: Theory and methods**) has been largely outmoded. Instead, systems engineers have adopted theories of complex systems. This change puts systems engineers in line with critical development planner Jane Jacobs, who argued that “intricate minglings of different uses are not a form of chaos. On the contrary they represent a complex and highly developed form of order” [Ref. 78, p. 222]. Complex systems, emergence, “ilities,” systems-of-systems, and complex adaptive systems have all become popular fields of study within systems engineering,[79–89] with numerous frameworks being proposed for how to classify and handle such systems.[90–95] Faced with such systems, engineers have had to recognize their own inability to definitively predict the future and have turned to probabilistic and flexible methods that instead “manage” complexity over longer time scales, such as epoch-era analysis[96,97] (which has many similarities to the aforementioned urban planning method called scenario planning) and fuzzy probabilistic programming.[98,99] This can be seen in a recent set of definitions promulgated by INCOSE, which includes terms such as “transdisciplinary,” “integrative,” “socio-technical systems,” and “complex systems,” as well as a recognition that systems are conceptual abstractions with a chosen focus.[100]

Parallel to this, systems engineers have moved away from narrowly implementing the directives and priorities of an individual client (**P4: Singular solution** and **P5: No user focus**) to identifying, mapping, and analyzing the various stakeholders in a system in order to inform the architecture of the system and its requirements. Stakeholder analyses can involve both qualitative and quantitative tools, such as the Stakeholder Requirements Definition Process,[101] Stakeholder Value Network Analysis,[102] and interviews of representatives from different stakeholder groups. This change in focus can also be seen in the rise of human- and user-centered design perspectives, which have spawned numerous specific methodologies and seen application in healthcare,[103] Industry 5.0,[104] MBSE,[105] and other fields.[106]

Such changes also serve to address **P3: Siloed knowledge** by accepting information from a wider range of disciplinary sources and methods. In order to translate these complicated networks of stakeholders into designs, systems engineers have developed methods for handling multistakeholder negotiation and[107–109] tradespace visualization and exploration,[107,108,110–112] the latter of which demonstrates an increased willingness to appreciate the psychology and experience of the user. Multiple of these techniques can even be linked together, such as when Sparrevik et al. combined participatory stakeholder engagement with multicriteria decision analysis for the management of a harbor, emphasizing the lateral learning and trust that can develop through such a transparent process.[113] Such techniques can thus been seen as a response to a common historical critique that systems engineers assume “complex controversies can be solved by getting correct information where it needs to go as efficiently as possible,” that “political conflict arises primarily from a lack of information,” and that “if we just gather lack the facts… the correct answers to intractable policy problems like homelessness will be simple, uncontroversial, and widely shared” [Ref. 114, p. 124]. Systems engineering thus has potentially useful tools and perspectives to contribute to the such endeavors as collaborative planning theory[115] and participatory development.[116]

With regards to **P6: Cost and time**, significant infrastructure has been put in place to support the urban planning profession. Interactive DSSs abound.[117,118] The use of geographic information system (GIS) has become the norm,[119–121] including more participatory variants.[122] Systems engineering likewise has seen a heightened emphasis on reusable tools and infrastructure in the form of both specific modeling languages like Object Process Methodology (OPM)[123] and in general approaches such as MBSE.[124] Beyond planning and systems engineering, computational power has increased by orders of magnitude (which has then found use in new simulation techniques) and the public in general has become much more familiar with computational tools. All of

TABLE 4 New developments for the identified pitfalls

Theme	ID	New Developments	Relevant Publications
T1: Technical Limitations & Simplifying Assumptions	**P1**	Improvements in in-situ data collection (e.g. telecoms, distributed sensors, statistical agencies) and remote observation; new indices of societal and personal wellbeing	[63–67]
	P2	Complex systems, biomimicry, emergence, systems-of-systems, complex adaptive systems, epoch-era analysis, fuzzy probabilistic programming, agent-based modeling	[68–75, 78–88, 95–98]
T2: Stakeholder & Contextual Consideration	**P3**	Stakeholder Value Network Analysis, qualitative interviews for use in requirement definition; general expansion of interdisciplinary teams	[101, 146]
	P4	Multi-attribute and multi-objective optimization methods; multi-stakeholder negotiation, tradespace visualization and exploration	[106–111]
	P5	Stakeholder Requirements Definition Process; Human-centered and user-centered design perspectives; open source software; end of the Cold War; increased role of non-military stakeholders in systems engineering discipline	[100, 102–105, 114, 115]
	P6	Advances in computing power; Decreases in computational cost; Increased public familiarity with computational tools; Development of re-usable tools and infrastructure (OPM, MBSE, etc.); independent development of urban planning models	[116, 117, 122, 123]
T3: Self-Awareness	**P7**	Better histories of the field	
	P8		

these together have supplied the basic analysis infrastructure that is common to the field. As a result, new applications do not necessarily require immense resources.

These developments are summarized in Table 4. Taken together, they suggest that the fields of systems engineering and planning are perhaps closer to each other than ever before, even showing some elements of convergent evolution. This can be seen in the use of the term complex adaptive system in both fields,[125] as well as in the rise of industrial ecology.[126] This latter field is bringing insights from systems engineering (among other fields) to bear on cities and the environment once more. Examples include thermodynamics and entropy modeling,[127,128] metabolism,[129] and scaling laws.[130] Some of this work is explicitly picking up avenues of research from the 1970s that were abandoned in the 1980s.[129] Furthermore, many of the pitfalls from half a century ago identified by this paper have been significantly addressed in the literature. Much benefit could be gained through more direct dialog and collaboration between systems engineering and planners. At the same time, none of these pitfalls have been wholly obviated, none of the new developments have achieved universal adoption, and the dangers of **P8: Hype** are always present, regardless of methodology. Some of the methods for addressing these pitfalls are in tension with one another. For example, the new modeling techniques aimed at addressing **P2** can increase opacity and inexplicability, thereby inhibiting the ability to involve decision-makers and the public in their development and build trust in its results (**P5**).

So how can we make use of the opportunity for constructive collaboration, avoid falling prey to the same pitfalls as the past, and navigate these inter-pitfall tensions? The next section will lay out a multipronged approach.

6 | RECOMMENDATIONS FOR MOVING FORWARD

We propose three tactics for collaboration between the fields of systems engineering and planning:

1. Adopt the new developments that address certain historical pitfalls (as summarized in Table 4) and continue to pursue new opportunities to address the remaining dangers.
2. Explicitly grapple with the history of systems engineering in planning. Use this to expand the sphere of collaboration.
3. Select an application domain that can benefit greatly from both systems engineering and planning, preferably a relatively novel domain, then put together multidisciplinary teams to address that domain.

The first is straightforward. As has been discussed, 50 years ago, systems engineering lacked the disciplinary tools and perspectives necessary to successfully tackle many areas within planning. While significant gaps remain, new methodological developments in both fields mean a new opportunity for collaboration.

The second is necessary to avoid new generations of systems engineers being educated in ignorance of past mistakes. None of the pitfalls listed in Table 4 were based entirely on technical shortcomings and most were primarily nontechnical in origin. Many had to do with perspective and personal approach, often characterized by a certain disciplinary hubris. The urban planners of the 1970s felt that systems engineers wanted to replace them, rather than collaborate with them. Much of the public felt that the systems engineers were the servants of entrenched powers rather than the community at large. Regardless of the truth of these perceptions, their mere presence significantly hampers the ability of systems engineers to effectively implement their projects. Both can be addressed via a certain professional humility and a willingness to engage in true multistakeholder decision-making. In many ways, this is an extension of an already present norm within systems engineering. From its beginnings, systems engineers have depended upon multidisciplinary teams of engineers. After all, systems engineers are largely unnecessary for projects that can be accomplished by a single engineer and for a single stakeholder. Teamwork, communication, and collaboration are thus fundamental to the field. Over time, the boundaries of these collaborations expanded to include multiple organizational stakeholders in a single project, including multiple clients, government agencies, and nonclient beneficiaries. What we are now proposing is to expand this still further, by including both technical experts such as environmental scientists, ecosystem services economists, and anthropologists; and nontechnical members of the communities in which our systems operate. Such a proposal has been previously advanced, particularly with regard to the inclusion of social scientists, in the form of emphasizing the importance of the "ologies".[131] Beyond this however, we are arguing for a participatory systems engineering, taking a page from the fields of GIS and planning that have been building participatory frameworks and tools for the past couple decades.[116,122 132–134] This is also in line with the field of remote sensing, which has a similar Space Race military origin and has recently seen a more participative research agenda mapped out.[135] Systems engineering already has many of the tools for this, in the form of multistakeholder negotiation methods and tradespace exploration tools. These can be readily adapted to incorporate community perspectives and be used as part of existing collaborative scenario planning processes common in urban planning.

The third approach is appropriate not only because it allows for plenty of research opportunities, but it avoids one field (systems engineering or planning) dominating the other due to historical entrenchment. Urban planner Scott Campbell recognized a similar need within his own field:

> The danger of translation is that one language will dominate the debate and thus define the terms of the solution. It is essential to exert equal effort to translate in each direction, to prevent one linguistic culture from dominating the other… Another lesson from the neocolonial linguistic experience is that it is crucial for each social group to express itself in its own language before any translation. The challenge for planners is to write the best translations among the languages of the economic, the ecological, and the social views, and to avoid a quasi-colonial dominance by the economic *lingua franca*, by creating equal two-way translations… Translation can thus be a powerful planner's skill, and interdisciplinary planning education already provides some multiculturalism. [Ref. 136, p. 230]

The question then, is what domain would be fruitful for this endeavor? Campbell suggests that "the idea of sustainability lends itself nicely to the meeting on common ground of competing value systems." We tend to agree with him, while noting that just because sustainable development is an apt proving ground, it does not mean that it is the only domain well suited for such collaboration.

Sustainability first enters the engineering literature in the 1970s and its frequency rises in an exponential fashion over the course of the subsequent decades.[137] Computational models have been closely linked to the pursuit of sustainability and with its definition, stemming from the World3 system dynamics model underlying the Club of Rome's *The Limits to Growth* report in 1972.[25] The rise of sustainability in engineering is mirrored by a similar rise in other domains (such as architecture) and in the popular consciousness. As de Weck et al. have noted, sustainability is the fastest growing of the "ilities" in the engineering literature.[138] More recently, the term *sustainable development* has become increasingly commonplace. It is often defined as the integration of three previously separate fields: economic development, social development, and environmental protection.[139] These fields are alternately described "as interdependent and mutually reinforcing pillars" [Ref. 139, p. 2][Ref. 140, p. 5], and as "conflicting" [Ref. 136, p. 216], as seen in Figure 2. Sustainable development is now a powerful enough framework and a pressing enough issue that the United Nations (UN) followed up their 2000–2015 Millenium Development Goals (MDGs)[141] with the 2015–2030 Sustainable Development Goals (SDGs)[142] in order to coordinate development action globally.

The rise of sustainable development, with its interconnected systems, has also been paralleled by the (rightfully) expanded number of stakeholders involved in decision-making processes and an increased recognition of linkages across multiple geographic scales.[143] This increase in complexity is something that systems engineering is well posed to address, while still being well within the purview of urban and regional planning. Economist Jeffrey Sachs argues that "sustainable development is also a science of complex systems," and that two specific tools are important for implementing the UN SDGs: backcasting and technology road-mapping [Ref. 140, p. 7]. Systems engineering is well-equipped to support both. Two other such areas are the transition to a low-carbon energy system[144] and general urban climate resilience as environmental and social perturbations intensify in the coming decades.

Recent years have seen promising efforts made in this vein. In 2020, Honoré-Livermore et al. sought to address the SDGs in arctic coastal regions via an approach grounded in socio-environmental

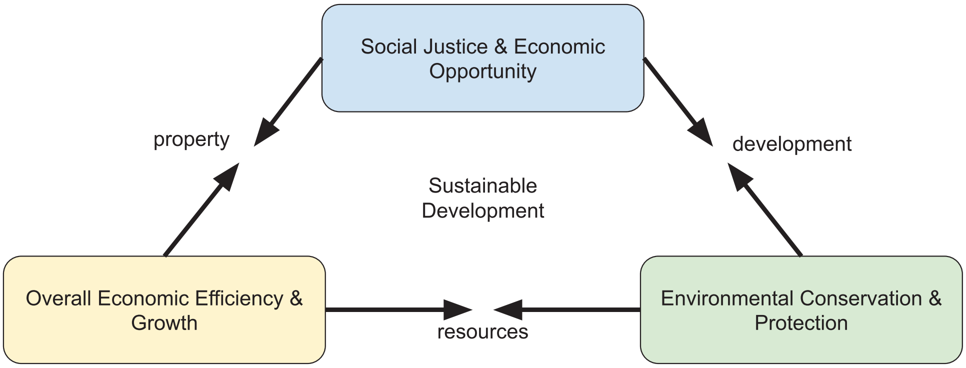
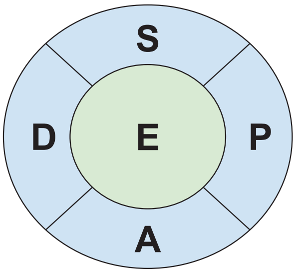


FIGURE 2 The triangle of conflicting goals of sustainable development. Adapted from Campbell[136]



Non-linear Steps	Relevant Systems Engineering Methods
Stakeholders	Social network analysis
Problem	Concept maps; Consensus building; Negotiation; Scenario analysis
Alternatives	Backcasting; Interactive management; Specialized trade studies
Decision-Making	Decision-making under uncertainty; Systemigrams; Group model building
Evaluation	Key performance indicators; Evaluation matrix; Pareto analysis

FIGURE 3 The stakeholders-problem-alternatives-decision-making-evaluation (SPADE) methodology and associated methods. Adapted from Haskins[145]

system (SES) and the Stakeholders, Problem, Alternatives, Decision-making, Evaluation (SPADE) methodology.[6] The SPADE methodology was developed specifically for sustainable development applications. The five components of its name constitute five nonlinear steps, each of which has various specific associated methodologies,[145] as shown in Figure 3.

Van Zyl and Root meanwhile used a transdisciplinary approach involving Wilbur's integral systems theory[146] and the Customers, Actors, Transformation process, Worldview, Owners, and Environmental constraints (CATWOE) framework from SSM[147] to design sustainable agricultural principles in New Zealand.[7]

Over the past few years, the authors of this study and others have been building upon Maier's[41] and Crawley's[148] work to apply systems architecture to international collaborations[149] and sustainable development.[5] This currently takes the form of the Systems Architecture Framework (SAF) and the Environment, Vulerability, Decision-Making, Technology (EVDT) framework, both pictured in Figure 4. These frameworks seek to center the full network of stakeholders, invite them into a collaborative development process, and organize that development process around four central questions, essentially combining of the established fields of sociotechnical systems[150–152] and SESs[153]:

1. What is happening in the natural environment?
2. How will humans be impacted by what is happening in the natural environment?
3. What decisions are humans making in response to environmental factors and why?
4. What technology system can be designed to provide high quality information that supports human decision making?

SAF and EVDT have seen recent applications in the design of an invasive aquatic plant management system,[5] a COVID-19 DSS,[154] and a mangrove conservation policy DSS.[155] A future publication will lay out the steps of EVDT in more detail, along with guides for its application.

Other recent approaches focus on scenario planning and education for understanding evolution of the urban form,[156] sustainable land-use planning that relies upon multilevel stakeholder partnerships,[157] a synthesis of participatory planning with systems engineering for sustainable regional planning,[158] and leveraging human-centered design to address the SDGs.[159]

Common across all of these methods emphasize significant consideration of a wide set of stakeholders and then adopt different systems engineering techniques for integrating these stakeholder needs into the system design and development process. While none are fully developed or widely adopted, they are evidence of an active interest in applying systems engineering to sustainable development while avoiding the pitfalls of the past.

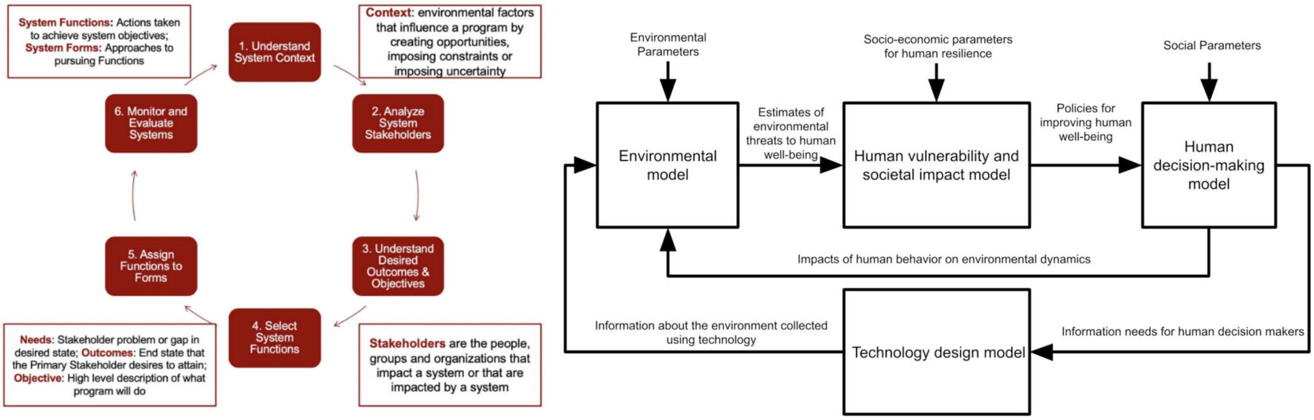


FIGURE 4 Left: The systems architecture framework (SAF) provides six steps to design and evaluate a complex SES. Right: The Environment-Vulnerability-Decisionmaking-Technology (EVDT) Framework seeks to organize the linkages and feedbacks of sustainable development systems.

7 | CONCLUSION

One of the foundations of engineering is the use of past failures and shortcomings to iterate and innovate, what Petroski calls "one of the fundamental paradoxes of engineering." This can be difficult when the gap between a failure and a subsequent attempt is half a century, enough time for "a new period of optimism and hubris" [Ref. 18, p. 166]. As systems engineering is increasingly finding applications in planning contexts, this review seeks to span that gap and provide useful lessons learned for both practitioners and researchers. Despite all of our technological, methodological, and professional developments over the past several decades, the identified pitfalls still pose dangers to the unwary systems engineer. It is only by recognizing these pitfalls and taking conscious actions to avoid them that we can avoid turning the trend identified in Figure 1 into an undamped sinusoid.

Among the key lessons from this review are the need for multidisciplinary teams and centering stakeholders (ideally a wide set of stakeholders) in the design and development process of any intervention. This requires intentionality and a willingness to adapt and extend systems engineering methods to work well with those of other fields. We have presented three methods that intend to do precisely this, each in their own way, and referred to several others. While a detailed examination of these discussed methods is beyond the scope of this review, they (and other such methods) warrant further consideration, particularly with regards to their differences and effectiveness. It may also be worthwhile to conduct a similar systematic review of specifically sustainable development applications of systems engineering. A recent such review for the related field of systems dynamics highlighted several gaps in the literature. Some, such as lack of stakeholder engagement, overlap with those highlighted in this study. Others are not included here, such as inconsistent validation and a poor understanding of the impacts of model boundaries on model behavior.[51] A review of sustainable development applications might thus highlight new gaps and new avenues for research. Between the examples cited in this article, those included in a recent special issue of *Sustainability*,[160] and those found in Yang and Cormican's search,[161] there is likely already a sufficient corpus for such a review.

ACKNOWLEDGMENTS

The authors would like to acknowledge the helpful critiques and input from Prof. Sarah Williams, Ufuoma Ovienmhada, and Caroline Jaffe. This manuscript contains brief quotations from other publications and figures adapted from information in other publications. Both of these fall under fair use. The only direct reproductions of previously published figures are in Figure 4, which were created by the authors of this manuscript.

CONFLICT OF INTEREST

The authors have no conflict of interest to disclose other than that both authors work on the applications of systems engineering to planning/development and thus have a desire to see the subfield succeed.

DATA AVAILABILITY STATEMENT

The full set of publications considered in both the systematic and integrative reviews, along with their codings, will be made available with this publication in online article supplementary material.

ORCID

Jack Reid https://orcid.org/0000-0002-8854-826X

REFERENCES

1. Austin M, Delgoshaei P, Coelho M, Heidarinejad M. Architecting smart city digital twins: combined semantic model and machine learning approach. *J Manag Eng*. 2020;36:04020026.
2. Francisco A, Mohammadi N, Taylor JE. Smart city digital twin-enabled energy management: toward real-time urban building energy benchmarking. *J Manag Eng*. 2020;36:04019045.

3. Ruohomäki T, Airaksinen E, Huuska P, Kesäniemi O, Martikka M, Suomisto J. Smart city platform enabling digital twin. In: *2018 International Conference on Intelligent Systems (IS)*, 2018:155-161.
4. Haberfellner R, de Weck O, Fricke E, Vössner S. Case Study 3: Smart City and Science Tower, Graz. In: *Systems Engineering: Fundamentals and Applications*. 2nd ed. Birkhäuser; 2021.
5. Ovienmhada U, Mouftaou F, Wood D. Inclusive design of earth observation decision support systems for environmental governance: a case study of Lake Nokoué. *Front Clim*. 2021;3:105.
6. Honoré-Livermore E, Birkeland R, Haskins C. Addressing the sustainable development goals with a system-of-systems for monitoring arctic coastal regions. In: *INCOSE International Symposium*. 2020;30(1):604-619.
7. van Zyl H, Roodt JH. A transdisciplinary design and implementation of sustainable agricultural principles in the Waikato region of New Zealand. In: *INCOSE International Symposium*. 2020;30(1):637-650.
8. Madhavan G, Phelps CE, Rouse WB, Rappuoli R. Vision for a systems architecture to integrate and transform population health. *Proc Nat Acad Sci*. 115;12595–12602.
9. de Weck O, Krob D, Lefei L, Lui PC, Rauzy A, Zhang X. Handling the COVID-19 crisis: Toward an agile model-based systems approach. *Syst Eng*. 2020;23:21557.
10. Gorod A, Sauser B, Boardman J. System-of-systems engineering management: a review of modern history and a path forward. *IEEE Syst J*. 2008;2:484-499.
11. Booton RC, Ramo S. The development of systems engineering. *IEEE Trans Aerosp Electron Syst*. 1984;AES-20:306-310.
12. Hall AD. *Hall's A Methodology for Systems Engineering: 1962 Edition*. 1966th ed. van Nostrand; 1962.
13. Brill JH. Systems engineering? A retrospective view. *Syst Eng*. 1998;1(4):258-266.
14. Honour EC. INCOSE: history of the international council on systems engineering. *Sys Eng*. 1998;1(1):4-13.
15. Talbott M. Why systems fail (viewed from Hindsight). In: *INCOSE International Symposium*. 1993;3(1):721-728.
16. Terry Bahill A, Henderson SJ. Requirements development, verification, and validation exhibited in famous failures. *Sys Eng*. 2005;8(1): 1-14.
17. Petroski H. *To Engineer Is Human: The Role of Failure in Successful Design*. Vintage; 1992.
18. Petroski H. *Design Paradigms: Case Histories of Error and Judgment in Engineering*. Cambridge University Press; 1994.
19. Slegers NJ, Kadish RT, Payton GE, Thomas J, Griffin MD, Dumbacher D. Learning from failure in systems engineering: a panel discussion. *Syst Eng*. 2012;15(1):74-82.
20. Smith RG. The systems approach and the Urban Dilemma. Staff Discussion Paper 181, The George Washington University, United States, July 1968.
21. Light JS. *From Warfare to Welfare: Defense Intellectuals and Urban Problems in Cold War America*. JHUP; 2005.
22. Foster R. *Urban Development Applications Project Quarterly Report*. Contractor report NASA-CR-119025. National Aeronautics and Space Administration; 1970.
23. Karen A, Orrick D, Anuskiewicz T. Technology transfer in New York City—the NASA/NYC applications project. In: 3rd Urban Technology Conference and Technical Display, Boston, MA. American Institute of Aeronautics and Astronautics; 1973.
24. Forrester JW. Systems analysis as a tool for urban planning. *IEEE Trans Syst Sci Cybern*. 1970;6:258-265.
25. Meadows D, Meadows D, Randgers J, Behrens W. *The Limits to Growth*. Potomac Associates; 1972.
26. Jay W. Forrester. System dynamics—a personal view of the first fifty years. *Syst Dyn Rev*. 2007;23(2-3):345-358.
27. Kraemer KL, King JL. A requiem for USAC. *Policy Anal*. 1979;5(3):313-349.
28. Wilson AG. Modelling and systems analysis in urban planning. *Nature*. 1968;220:963-966.
29. Friedmann J. Two centuries of planning: an overview. In: Mandelbaum S, Mazza L, Burchell R, eds. *Explorations in Planning Theory*. Routledge; 2017:10-29.
30. Szanton PL. Analysis and urban government: experience of the New York City-Rand Institute. *Policy Sci*. 1972;3(2):153-161.
31. Rush M, Holguin A. *Remote Sensing Utility in a Disaster Struck Urban Environment*. Technical report NASA-CR-149103. National Aeronautics and Space Administration; 1976.
32. Haggerty J. *Spinoff 1980*. Technical report. National Aeronautics and Space Administration; 1980.
33. Medina E. *Cybernetic Revolutionaries: Technology and Politics in Allende's Chile*. MIT Press; 2011.
34. Medina E. Designing freedom, regulating a nation: socialist cybernetics in Allende's Chile. *J Latin Am Stud*. 2006;38:571-606.
35. Robinson IM, ed. *Decision-Making in Urban Planning: An Introduction to New Methodologies*. Sage Publications; 1972.
36. Marcuse P. The three historic currents of city planning. In: Fainstein S, DeFilippis J, eds. *Readings in Planning Theory*. 4th ed. Wiley-Blackwell; 2016.
37. Wren DA. Scientific management in the U.S.S.R., with particular reference to the contribution of Walter N. Polakov. *Acad Manag Rev*. 1980;5:1-11.
38. Quade ES. Some problems associated with systems analysis. In: Electonirc Industries Association Symposium on System Analysis in Decision Making, Washington D.C. 1966:22.
39. Arnold RD, Wade JP. A definition of systems thinking: a systems approach. *Proc Comput Sci*. 2015;44:669-678.
40. International Organization for Standardization, International Electrotechnical Commission, and Institute of Electrical and Electronics Engineers. *Systems and Software Engineering—System and Software Engineering Vocabulary (SEVocab)*. Technical report ISO/IEC/IEEE 24765:2010. 2010.
41. Maier MW. *The Art of Systems Architecting*. 3rd ed. CRC Press; 2009.
42. SEBoK Editorial Board. Systems Engineering (glossary) in *The Guide to the Systems Engineering Body of Knowledge (SEBoK)*, v. 2.6. 2022. R.J. Cloutier (Editor in Chief). Hoboken, NJ: The Trustees of the Stevens Institute of Technology. Accessed February 2, 2022. https://www.sebokwiki.org/wiki/Systems_Engineering_(glossary)
43. The importance of no evidence. *Nat Hum Behav*. 2019;3:197. https://www.nature.com/articles/s41562-022-01443-2
44. Alonso W. The quality of data and the choice and design of predictive models. In: Urban Development Models, Washington D.C. National Academies Press; 1968:178-192. Highway Research Board Special Report.
45. Hoos IR. *Systems Analysis in Social Policy: A Critical Review*. University of California Press; 1972.
46. Lee, Jr DBL. Requiem for large-scale models. *J Am Inst Plann*. 1973;39:163-178.
47. Nelson RR. Intellectualizing about the moon-ghetto metaphor: a study of the current malaise of rational analysis of social problems. *Policy Sci*. 1974;5:375-414.
48. Wilbanks TJ, Lee R. Policy analysis in theory and practice. In: *Large-Scale Energy Projects: Assessment of Regional Consequences*. Vol 12. Elsevier Science Publishing Company, Inc.; 1985:273-304.
49. Scott JC. *Seeing Like a State: How Certain Schemes to Improve the Human Condition Have Failed*. Yale University Press; 2020.
50. Cajot S, Mirakyan A, Koch A, Maréchal F. Multicriteria decisions in urban energy system planning: a review. *Front Energy Res*. 2017;5:10.
51. Pejic Bach M, Tustanovski E, Ip AW, Yung KL, Roblek V. System dynamics models for the simulation of sustainable urban development: a review and analysis and the stakeholder perspective. *Kybernetes*. 2019;49:460-504.
52. Rice R. Failure of the technical role in urban transportation systems planning. In: Proceedings of the 1st Canadian Seminar on Systems

Theory for the Civil Engineer, Calgary, Alberta, Canada. University of Calgary; 1981:153-168.

53. Mao B, Doboku Gakkai IoTE, IC. o. T. a. T. S. Zhong guo ke xue ji shu xie hui, and I. C. o. T. a. T. S. ICTTS 2004, Traffic and Transportation Studies: Proceedings of the Fourth International Conference on Traffic and Transportation Studies, ICTTS 2004, Dalian, China, 2–4 August. Swisshotel, Beijing Science Press; 2004.
54. Abersman AI, Haney TP, Wellisch JB. *Emergency Operations Contingency Planning*. Technical report. 1969.
55. Seifert W, Hansen R, *Survey of Technology for High Speed Ground Transport, Part I*. Technical report. Massachusetts Institute of Technology; 1965.
56. Fuka DR, Walter MT, MacAlister C, Degaetano AT, Steenhuis TS, Easton ZM. Using the Climate Forecast System Reanalysis as weather input data for watershed models. *Hydrol Process*. 2014;28(22):5613-5623.
57. Metropolitan Washington Council of Governments. *Model Plumbing Code*. Technical report; 1966.
58. Tonon A, Belluati PL. Digital autopilot design for combat aircraft in Alenia. In: *Advances in Aircraft Flight Control*. Routledge; 1996.
59. Qiu X, Huang GQ. Supply hub in industrial park (SHIP): the value of freight consolidation. *Comput Ind Eng*. 2013;65:16-27.
60. Hua Y, Zhao D, Wang X, Li X. Joint infrastructure planning and fleet management for one-way electric car sharing under time-varying uncertain demand. *Transp Res Part B: Methodol*. 2019;128:185-206.
61. Rider KL. *A Parametric Model for the Allocation of Fire Companies*. Technical report. 1975.
62. Forrester JW. *Urban Dynamics*. Pegasus Communications, Inc.; 1969.
63. Brewer GD. *Systems Analysis in the Urban Complex: Potential and Limitations*. Technical report. RAND Corporation; 1973.
64. Boyce D. Toward a framework for defining and applying urban indicators in plan-making. In: *Decision-Making in Urban Planning: An Introduction to New Methodologies* (I. Robinson, ed.). 1st ed. SAGE Publications, Inc.; 1972:62-84.
65. Clifton K, Ewing R, Knapp GJ. Quantitative analysis of urban form: a multidisciplinary review. *J Urban*. 2008;1(1):17-45.
66. Read A, Takai K, Wolford H, Berman E. *Asset-based economic development: building sustainable small and rural communities*. Technical Report. ICMA's Center for Sustainable Communities. 13-092. 2012.
67. Sawicki DS, Flynn P. Neighborhood indicators: a review of the literature and an assessment of conceptual and methodological issues. *J Am Plan Assoc*. 1996;62:165-183.
68. Val AB. *Regional and Local Economic Analysis for Practitioners: Fourth Edition*. 4th ed. Praeger; 1991.
69. Batty M. *Cities and Complexity*. The MIT Press; 2005.
70. Lauf S, Haase D, Hostert P, Lakes T, Kleinschmit B. Uncovering land-use dynamics driven by human decision-making—a combined model approach using cellular automata and system dynamics. *Enviorn Model Softw*. 2012;27-28:71-82.
71. Goodspeed R. *Scenario Planning for Cities and Regions: Managing and Envisioning Uncertain Futures*. Lincoln Institute of Land Policy; 2020.
72. Zapata MA, Kaza N. Radical uncertainty: scenario planning for futures. *Environ Plan B: Plan Des*. 2015;42:754-770.
73. Miller EJ. Integrated urban modeling: past, present, and future. *J Transp Land Use*. 2018;11(1):387-399.
74. Moeckel R, Garcia CL, Chou ATM, Okrah MB. Trends in integrated land-use/transport modeling: an evaluation of the state of the art. *J Transp Land Use*. 2018;11(1):463-476.
75. Shahumyan H, Moeckel R. Integration of land use, land cover, transportation, and environmental impact models: expanding scenario analysis with multiple modules. *Environ Plan B: Urban Anal City Sci*. 2017;44:531-552.
76. Checkland P. *Systems Thinking, Systems Practice: Includes a 30-Year Retrospective*. 1st ed. Wiley; 1999.
77. Khisty CJ. Soft-systems methodology as learning and management tool. *J Urban Plan Dev*. 1995;121:91-107.
78. Jacobs J. The death and life of great american cities. In: Fainstein S, DeFilippis J, eds. *Readings in Planning Theory*. 4th ed. Wiley-Blackwell; 2016.
79. McDermid J. Complexity: concept, causes and control. In: *Proceedings of the Sixth IEEE International Conference on Engineering of Complex Computer Systems, 2000*. ICECCS 2000. IEEE; 2000:2-9.
80. Sussman JM. *Collected Views on Complexity in Systems*. Technical Report. 2002.
81. Chen CC, Nagl SB, Clack CD. Complexity and emergence in engineering systems. In: Tolk A, Jain L, eds. *Complex Systems in Knowledge-based Environments: Theory, Models and Applications*. Springer Science & Business Media; 2009:99-127.
82. Deguet J, Demazeau Y, Magnin L. Elements about the emergence issue: a survey of emergence definitions. *Complexus*. 2006;3:24-31.
83. Office of the Director of Systems and Software Engineering. *Systems Engineering Guide for Systems of Systems*. Office of the Director of Systems and Software Engineering; 2008.
84. Glass RJ, Ames AL, Brown TJ, et al. *Complex Adaptive Systems of Systems (CASoS) Engineering: Mapping Aspirations to Problem Solutions*. Technical report. Sandia National Laboratories; 2011.
85. INCOSE Complex Systems Working Group. A complexity primer for systems engineers. 2016.
86. Keating CB, Katina PF. Systems of systems engineering: prospects and challenges for the emerging field. *Int J Sys Sys Eng*. 2011;2(2):234-256.
87. Mittal S, Doyle MJ, Portrey AM. Human in the loop in system of Systems (SoS) modeling and simulation: applications to live, virtual and constructive (LVC) distributed mission operations (DMO) training. In: Rainey LB, Tolk A, eds. *Modeling and Simulation Support for System of Systems Engineering Applications*. John Wiley & Sons; 2015:415-451.
88. Sheard SA. Practical applications of complexity theory for systems engineers. In: *INCOSE International Symposium*. 2005;15(1):923-939.
89. Tolk A, Rainey LB. Toward a research agenda for M&S Support of system of systems engineering. In: Rainey LB, Tolk A, eds. *Modeling and Simulation Support for System of Systems Engineering Applications*. John Wiley & Sons; 2015:583-592.
90. Kurtz CF, Snowden DJ. The new dynamics of strategy: sense-making in a complex-complicated world. *IBM Syst J*. 2003;42(3):462-483.
91. Martin P-AJY. *A Framework for Quantifying Complexity and Understanding Its Sources: Application to Two Large-Scale Systems*. PhD thesis; 2004.
92. Sheard S. A complexity typology for systems engineering. In: INCOSE International Symposium. 2010.
93. Righi AW, Wachs P, Saurin TA. Characterizing complexity in socio-technical systems: a case study of a SAMU Medical Regulation Center. *Work*, 2012;41:1811-1817.
94. Schöttl F, Lindemann U. Quantifying the complexity of socio-technical systems—a generic, interdisciplinary approach. *Procedia Comput Sci*. 2015;44:1-10.
95. Reymondet L. A framework for sense-making of complex sociotechnical systems. Master's thesis. Massachusetts Institute of Technology; 2016.
96. Ross AM, Rhodes DH. Using natural value-centric time scales for conceptualizing system timelines through Epoch-Era Analysis. In: INCOSE International Symposium, Utrecht, The Netherlands. 2008.
97. Vascik P, Ross AM, Rhodes DH. A method for exploring program and portfolio affordability tradeoffs under uncertainty using epoch-era analysis: a case application to carrier strike group design. In: Proceedings of the 12th Annual Acquisition Research Symposium, Fort Belvoir, VA. Defense Technical Information Center; 2015.

98. Zhang X, Huang GH, Nie X. Robust stochastic fuzzy possibilistic programming for environmental decision making under uncertainty. *Sci Total Environ*. 2009;408:192-201.
99. Liu Z, Huang G, Li W. An inexact stochastic– fuzzy jointed chance-constrained programming for regional energy system management under uncertainty. *Eng Optim*. 2015;47:788-804
100. Sillitto H, Martin J, McKinney D, et al. *Systems Engineering and System Definitions*. Technical report INCOSE-TP-2020-002-06. INCOSE; 2019.
101. INCOSE. *INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*. 4th ed. Wiley; 2015.
102. Feng W, Crawley EF, de Weck OL, Keller R, Robinson B. Dependency structure matrix modelling for stakeholder value networks. In: Proceedings of the 12th International DSM Conference, Cambridge, UK. Design Society; 2010.
103. Samaras GM, Horst RL. A systems engineering perspective on the human-centered design of health information systems. *J Biomed Inf*. 2005;38:61-74.
104. Longo F, Padovano A, Umbrello S. Value-oriented and ethical technology engineering in industry 5.0: a human-centric perspective for the design of the factory of the future. *Appl Sci*. 2020;10:4182.
105. Kim SY, Wagner D, Jimenez A. Challenges in applying model-based systems engineering: Human-centered design perspective. 2019.
106. Ritter FE, Baxter GD, Churchill EF. *Foundations for Designing User-centered Systems*. Springer London; 2014.
107. Fitzgerald ME, Ross AM. Effects of enhanced multi-party tradespace visualization on a two-person negotiation. *Procedia Comput Sci*. 2015;44:466-475.
108. Fitzgerald ME, Ross AM. Recommendations for framing multi-stakeholder tradespace exploration. In: INCOSE International Symposium, Edinburgh, UK. 2016.
109. Weck O. Multi-stakeholder simulation and gaming environment for a future resource economy in space. 2012. /paper/MULTI-STAKEHOLDER-SIMULATION-AND-GAMING-ENVIRONMENT-Weck/8d4c0bf1b644a5fa0e6d8f9ef02e7054d89be124.
110. Grogan PT, De Weck OL, Ross AM, Rhodes DH. Interactive models as a system design tool: applications to system project management. InConference on Systems Engineering Research, Hoboken, NJ. Elsevier; 2015.
111. Ross AM, Hastings DE, Warmkessel JM. Multi-attribute tradespace exploration as front end for effective space system design. *J Spacecr Rockets*. 2004;41(1):20-28.
112. Selva Valero DS. *Rule-Based System Architecting of Earth Observation Satellite Systems*. PhD thesis. Massachusetts Institute of Technology; 2012.
113. Sparrevik M, Barton DN, Oen AM, Sehkar NU, Linkov I. Use of multicriteria involvement processes to enhance transparency and stakeholder participation at Bergen Harbor, Norway. *Integr Environ Assess Manag*. 2011;7(3):414-425.
114. Eubanks V. *Automating Inequality: How High-Tech Tools Profile, Police, and Punish the Poor*. St. Martin's Press; 2018.
115. Goodspeed R. The death and life of collaborative planning theory. *Urban Plan*. 2016;1:1-5.
116. Pert PL, Lieske SN, Hill R. Participatory development of a new interactive tool for capturing social and ecological dynamism in conservation prioritization. *Landsc Urban Plan*. 2013;114:80-91.
117. Waddell P. UrbanSim: Modeling urban development for land use, transportation, and environmental planning. *J Am Plan Assoc*. 2002;68:297-314.
118. Walker D. *The Planners Guide to CommunityViz: The Essential Tool for a New Generation of Planning*. Routledge; 2017.
119. Jankowski P, Nyerges T. *GIS for Group Decision Making*. 1st ed. CRC Press; 2001.
120. Tomlin CD. *GIS and Cartographic Modeling*. Illustrated ed. Esri Press; 2012.
121. Wilson JP, Fotheringham AS, eds. *The Handbook of Geographic Information Science*. 1st ed. Wiley-Blackwell; 2007.
122. Sieber R. Public participation geographic information systems: a literature review and framework. *Ann Assoc Am Geogr*. 2006;96:491-507.
123. Dori D. *Object-Process Methodology: A Holistic Systems Paradigm; with CD-ROM*. Springer Science & Business Media; 2002.
124. Ramos AL, Ferreira JV, Barceló J. Model-based systems engineering: an emerging approach for modern systems. *IEEE Trans Syst Man, Cybern, Part C (Appl Rev)*. 2012;42:101-111.
125. Yamu C, de Roo G, Frankhauser P. Assuming it is all about conditions. Framing a simulation model for complex, adaptive urban space. *Environ Plan B: Plan Des*. 2016;43:1019-1039.
126. Chertow MR. Industrial ecology in a developing context. In: Clini C, Musu I, Gullino ML, eds. *Sustainable Development and Environmental Management: Experiences and Case Studies*Springer Netherlands; 2008:335-349.
127. Bristow D, Kennedy C. Why do cities grow? Insights from nonequilibrium thermodynamics at the urban and global scales. *J Ind Ecol*. 2015;19(2):211-221.
128. Purvis B, Mao Y, Robinson D. Thermodynamic entropy as an indicator for urban sustainability? *Procedia Eng*. 2017;198:802-812.
129. Kennedy C, Pincetl S, Bunje P. The study of urban metabolism and its applications to urban planning and design. *Environ Pollut*. 2011;159:1965-1973.
130. Lobo J, Bettencourt LMA, Strumsky D, West GB. Urban scaling and the production function for cities. *PLOS ONE*. 2013;8:e58407.
131. Donaldson W. In praise of the "Ologies": a discussion of and framework for using soft skills to sense and influence emergent behaviors in sociotechnical systems. *Syst Eng*. 2017;20(5):467-478.
132. Kim AM. Critical cartography 2.0: From "Participatory mapping" to authored visualizations of power and people. *Landsc Urban Plan*. 2015;142:215-225.
133. Talen E. Bottom-up GIS. *J Am Plan Assoc*. 2000;66:279-294.
134. Ulibarri N. Collaborative model development increases trust in and use of scientific information in environmental decision-making. *Environ Sci Policy*. 2018;82:136-142.
135. Bennett MM, Chen JK, Alvarez León LF, Gleason CJ. The politics of pixels: a review and agenda for critical remote sensing. *Prog Hum Geogr*. 2022;46:729-752.
136. Campbell S. Green cities, growing cities, just cities? Urban planning and the contradictions of sustainable development. In: Fainstein S, DeFilippis J, eds. *Readings in Planning Theory*. 4th ed. Wiley-Blackwell; 2016.
137. de Weck OL, Ross AM, Rhodes DH. *Investigating Relationships and Semantic Sets amongst System Lifecycle Properties (Ilities)*. Working Paper. Engineering Systems Division, Massachusetts Institute of Technology; 2012.
138. De Weck OL, Ross AM, Rhodes DH. *Investigating Relationships and Semantic Sets amongst System Lifecycle Properties (Ilities)*. ESD Working Paper Series. 2012.
139. World Summit on Sustainable Development. *Plan of Implementation of the World Summit on Sustainable Development*. Technical report. United Nations; 2002.
140. Sachs J. *The Age of Sustainable Development*. Columbia University Press; 2015.
141. Inter-Agency and Expert Group on MDG Indicators. *The Millennium Development Goals Report*. Technical report. United Nations; 2015.
142. United Nations. *Transforming our World: The 2030 Agenda for Sustainable Development*. United Nations; 2015.
143. Brömmelstroet MT, Schrijnen PM. From planning support systems to mediated planning support: a structured dialogue to overcome the implementation gap. *Environ Plan B: Plan Des*. 2010;37:3-20.
144. Kirkels A, Evers V, Muller G. Systems engineering for the energy transition: potential contributions and limitations. *Sustainability*. 2021;13:5423.

145. Haskins C. *Systems Engineering Analyzed, Synthesized, and Applied to Sustainable Industrial Park Development*. PhD thesis. Norweigen University of Science and Technology; 2008.
146. Esbjörn-Hargens S. An overview of integral theory. In: *Integral Theory in Action: Applied, Theoretical, and Constructive Perspectives on the AQAL Model*. SUNY Press; 2010.
147. Checkland P. Soft ftems methodology: a thirty year retrospective. *Sys Res Behav Sci*. 2000;17(S1):S11-S58.
148. Crawley E, Weck OD, Magee C, et al. The Influence of Architecture in Engineering Syinfluence of architecture in engineering sy. 2004.
149. Pfotenhauer SM, Wood D, Roos D, Newman D. Architecting complex international science, technology and innovation partnerships (CISTIPs): a study of four global MIT collaborations. *Technol Forecast Social Change*. 2016;104:38-56.
150. Rouse WB, Serban N. Understanding change in complex sociotechnical systems. *Inf Knowl Syst Manag*. 2012;10:25-49.
151. Siddiqi A, Collins RD. Sociotechnical systems and sustainability: current and future perspectives for inclusive development. *Curr Opin Environ Sustain*. 2017;24:7-13.
152. Sussman JM. *Teaching about Complex Sociotechnical Systems*. Technical report. 2010.
153. Elsawah S, Filatova T, Jakeman AJ, et al. Eight grand challenges in socio-environmental systems modeling. *Socio-Environ Syst Model*. 2020;2:16226.
154. Reid JB, Lombardo S, Turner K, Zheng M, Wood DR. Vida decision support system: an international, collaborative project for COVID-19 management with integrated modeling. In: International Astronautical Congress, Dubai, UAE. International Astronautical Federation; 2021.
155. Reida JB, Wood D. Interactive model for assessing mangrove health, ecosystem services, policy consequences, and satellite design in Rio de Janeiro Using earth observation data. In: Jack Re71st International Astronautical Congress (IAC): Cyberspace Editionid. International Astronautical Federation; 2020.
156. Geyer P, Stopper J, Lang W, Thumfart M. A systems engineering ethodology for designing and planning the built environment—results from the urban research laboratory Nuremberg and their integration in education. *Systems*. 2014;2:137-158.
157. Puchol-Salort P, O'Keeffe J, van Reeuwijk M, Mijic A. An urban planning sustainability framework: systems approach to blue green urban design. *Sustain Cities Soc*. 2021;66:102677.
158. Aspen DM, Amundsen A. Developing a participatory planning support system for sustainable regional planning—a problem structuring case study. *Sustainability*. 2021;13:5723.
159. Mueller JL, Dotson ME, Dietzel J, et al. Using human-centered design to connect engineering concepts to sustainable development goals. *Adv Eng Educ*. 2020;8(2):24.
160. Haskins C. Systems engineering for sustainable development goals. *Sustainability*. 2021;13:10293.
161. Yang L, Cormican K. The crossovers and connectivity between systems engineering and the sustainable development goals: a scoping study. *Sustainability*. 2021;13:3176.

AUTHOR BIOGRAPHIES

Jack Reid is a PhD Student working in the Space Enabled Research Group at the Massachusetts Institute of Technology Media Lab in Cambridge, Massachusetts. His research focuses on the use of Earth Observation (EO) technologies for sustainable development. Prior to his PhD program, he completed a dual masters in Aeronautics & Astronautics and Technology Policy from MIT. His undergraduate was at Texas A&M University, where he received a B.S. in Mechanical Engineering and a B.A. in Philosophy. He has worked on technology forecasting and acquisition analysis for the RAND Corporation, as well as shock and vibration testing at Sandia National Laboratories.

Danielle Wood serves as an Assistant Professor in the Program in Media Arts & Sciences and holds a joint appointment in the Department of Aeronautics & Astronautics at the Massachusetts Institute of Technology. Prof. Wood serves at MIT as the Faculty Lead for African and African Diaspora Studies. Within the Media Lab, Prof. Wood leads the Space Enabled Research Group, which seeks to advance justice in Earth's complex systems using designs enabled by space. The research of Space Enabled designs systems that use tools from space to promote sustainability on Earth and designs approaches to support sustainability in Space. Prof. Wood's background includes satellite design, earth science applications, systems engineering, and technology policy. In her research, Prof. Wood applies these skills to design innovative systems that harness space technology to address development challenges around the world. Prior to serving as Faculty at MIT, Prof. Wood held positions at NASA Headquarters, NASA Goddard Space Flight Center, Aerospace Corporation, Johns Hopkins University, and the United Nations Office of Outer Space Affairs. Prof. Wood studied at the Massachusetts Institute of Technology, where she earned a PhD in engineering systems, SM in aeronautics and astronautics, SM in technology policy, and SB in aerospace engineering. She is a Member of the International Academy of Astronautics.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Reid J, Wood D. Systems engineering applied to urban planning and development: A review and research agenda. *Systems Engineering*. 2022;1-16. https://doi.org/10.1002/sys.21642