Using Integrated Earth Observation-Informed Modeling to Inform Sustainable Development Decision-Making

by

Jack Reid

Submitted to the Program in Media Arts and Sciences
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Abstract

This work aims to demonstrate the viability of a particular methodology for increasing the accessibility and relevance of earth observation data products to a wider audience of local decision-makers through the development of clearer linkages between environmental modeling and societal impact, while laying the groundwork for a more detailed consideration of (c). To that end, this work centers on exploring the efficacy and difficulties of ***collaboratively developing*** a ***systems-architecture-informed***, multidisciplinary ***geographic information system (GIS) Decision Support System (DSS)*** for ***sustainable development*** applications that makes significant use of ***remote observation data***.

This is done through the development and evaluation of DSSs for two primary applications: (1) mangrove forest management and conservation in the state of Rio de Janeiro, Brazil; and (2) coronavirus response in six metropolitan areas across Angola, Brazil, Chile, Indonesia, Mexico, and the United States. In both cases, the methodology involves the application of the system architecture framework, an approach that has been previously adapted from the aerospace engineering discipline by Prof. Wood for use in sociotechnical systems. This includes using stakeholder mapping and network analysis to inform the design of the DSS in question. Other components of the methodology taken in this work are developing the DSS through an iterative and collaborative process with specific stakeholders; pursuing targeted, related analyses, such as on the value of certain ecosystem services, the value of remote sensing information, and human responses to various policies; and evaluating the usefulness of both the DSS and the development process through interviews, workshops, and other feedback mechanisms.

All of this takes place under the umbrella of the Environment, Vulnerability, Decision-Making, Technology (EVDT) Modeling Framework for combining remote observation and other types of data to inform decision-making in complex socio-environmental systems, particularly those pertaining to sustainable development. As the name suggests, EVDT integrates four models into one tool: the Environment (data including Landsat, Sentinel, VIIRs, Planet Lab's PlanetScope, etc.; Human Vulnerability and Societal Impact (data including census and survey-based demographic data, NASA's Socioeconomic Data and Applications Center, etc.); Human Behavior and Decision-Making (data including policy histories, mobility data, and urban nightlight data); and Technology Design for earth observation systems including satellites, airborne platforms and in-situ sensors (data including design parameter vectors for such systems). The data from each of these domains is used by established models in each domain, which are adapted to work in concert to address the needs identified during the stakeholder analysis. This framework is currently being used by several researchers in the Space Enabled Research Group and elsewhere. The capabilities provided by this framework will improve the management of earth observation and socioeconomic data in a format usable by non-experts, while harnessing cloud computing, machine learning, economic analysis, complex systems modeling, and model-based systems engineering.

Thesis Supervisor: Danielle R. Wood
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God, grant me the insight to find and use models to understand the world around me,
The wisdom to acknowledge that they will someday fail,
And the strength to rid myself of them when it is apparent they no longer work.

-inspired by Ze Frank & the Serenity Prayer

To order, to govern,
is to begin naming;
when names proliferate
it's time to stop.
If you know when to stop
you're in no danger.

-*Tao Te Ching* by Laozi, adapted by Ursula K. Le Guin

Acknowledgments

[The colors highlighting section titles are used to indicate their current status. Green indicates a section has been reviewed and is largely finalized. Blue indicates a complete, coherent draft. Yellow] indicates an incomplete draft that contains significant coherent portions. Red indicates a mostly incomplete section consisting primarily of notes, if anything.]

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List of Acronyms

AIAA	American Institute of Aeronautics and Astronautics
AISES	American Indian Science and Engineering Society
CAS	complex adaptive system
CATWOE	Customers, Actors, Transformation process, Worldview, Owners, and Environmental constraints
CBERS	China-Brazil Earth Resources Satellite Program
CEOS	Committee on Earth Observation Satellites
DEM	Digital Elevation Model
DSS	Decision Support System
EO	earth observation
EOC	Earth Observation Center
EOS	earth observation system
EPA	Environmental Protection Agency
ESA	European Space Agency
EVDT	Environment, Vulnerability, Decision-Making, Technology
FEMA	Federal Emergency Management Agency
FEWS NET	Famine Early Warning Systems Network
GEO	Group of Earth Observations
GEOSS	Global Earth Observation System of Systems
GIS	geographic information system
GISc	geographic information science
GPM	Global Precipitation Measurement
ICESat-2	Ice, Cloud, and land Elevation Satellite 2
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ILUTE	Integrated Land Use, Transportation, Environment
INCOSE	International Council on Systems Engineering
IPAC	Indigenous Peoples Advocacy Committee
IPP	the Pereira Passos Municipal Institute of Urbanism

ISO	international standards organization
JAXA	Japan Aerospace Exploration Agency
LIDAR	light detection and ranging
LIS	Land Information System
LUNR	Land Use and Natural Resources Inventory
MBSE	Model-Based Systems Engineering
MIT	Massachusetts Institute of Technology
MDG	Millenium Development Goal
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NGO	non-governmental organization
NYCRI	New York City-RAND Institute
OPM	Object Process Methodology
OSTP	Office of Science and Technology Policy
OSSE	Observing System Simulation Experiment
OTA	Office of Technology Assessment
PGIS	participatory geographic information system
PPGIS	public participation geographic information system
PPBS	Planning-Programming-Budgeting System
PSS	Planning Support System
RFF	Resources for the Future
SAF	Systems Architecture Framework
SAR	synthetic aperture radar
SDG	Sustainable Development Goal
SEBoK	Systems Engineering Body of Knowledge
SERVIR	Sistema Regional De Visualización Y Monitoreo De Mesoamérica
SES	Socio-environmental system
SETS	socio-environmental- technical system
SoS	System of Systems
SPADE	Stakeholders, Problem, Alternatives, Decision-making, Evaluation
SSM	soft systems methodology
STS	Sociotechnical system
TDRSS	Tracking and Data Relay Satellite System
UFRJ	Federal University of Rio de Janeiro
UN	United Nations
USAC	Urban Information Systems Inter-Agency Committee

USAID	United States Agency for International Development
USGS	United States Geological Survey
VALUABLES	Consortium for the Valuation of Applications Benefits Linked with Earth Science
VIIRS	Visible Infrared Imaging Radiometer Suite

Chapter 1

Introduction

Over the past two decades satellite-based remote observation has blossomed. We have seen a rapid increase in the number of earth observation systems (EOSs) in orbit [1], significant improvements in their capabilities [2], and much greater availability of the data that they produce [3]. This trend has occurred as part of greater technological and societal trends of increasing data availability, computational power, and modeling ability. Unfortunately, despite some efforts in previous decades [4], this earth observation (EO) data has been largely used only by governments and academics for military and scientific purposes, with the latter focused on understanding and predicting environmental phenomena. Large corporations and non-governmental organizations (NGOs) have recently been conducting their own analyses (as seen in the growing industry of climate consultants [5]), but these have required significant expertise and resources, and the results have sadly been mostly unavailable to the broader public.

There is a real need for (a) making remote observation data not just available but accessible to a broader audience by developing data products that are relevant to everyday individuals, particularly those involved in local, rather than national or global decision-making; (b) linking the EO-supported environmental modeling with the societal impact of a changing environment; and (c) putting policy and sensor design decision-making in the hands of a broader population.

A quick note on the user of first person pronouns in this piece. The word 'I' will obviously refer to the author, Jack Reid, and will be commonly used when describing work that I have done, arguments that I am asserting, etc. That said, the EVDT Framework and its various implementations, including the Vida DSS, were not solo projects but instead involved multiple contributors, both inside the Space Enabled Research Group and outside of it. Thus when I use 'we' when talking about EVDT

I will be referring to this collection of individuals. Additionally, sometimes I will use 'we' to refer to the Space Enabled Research Group, particularly when discussing our group's set of methodologies and principles. Finally, on occasion, I may use 'we' in the general humanistic sense. I will strive to make in which sense I am using 'we' clear in context.

1.1 Research Questions

This work aims to demonstrate the viability of a particular methodology for achieving (a) and (b), while laying the groundwork for a more detailed consideration of (c). To that end, this work centers on exploring the efficacy and difficulties of ***collaboratively developing*** a ***systems-architecture-informed***, multidisciplinary ***GIS DSS*** for ***sustainable development*** applications that makes significant use of ***remote observation data***. This involves expanding and codifying the previously proposed EVDT Modeling Framework for combining EO and other types of data to inform decision-making in complex socio-environmental systems, particularly those pertaining to sustainable development [6]. Specifically this work will seek to address the following numbered research questions via the listed letter deliverables. The chapters that primarily address each deliverable are noted.

1. What aspects of systems architecture (and systems engineering in general) are relevant and useful for approaching issues of sustainability in complex socio-environmental- technical system (SETS)? In particular, how can they be adapted using techniques from collaborative planning theory and other critical approaches to enable avoid the technocratic excesses of the past?
    a) A critical analysis of systems engineering, GIS, and the other technical fields relied upon in this work [Chapter 2]
    b) A proposed framework for applying systems engineering for sustainable development in an anticolonialist manner [Chapter 3]
2. What are the sustainability benefits of collaborative development of DSSs using the EVDT Modeling Framework in complex SETS?
    a) System architecture analyses of each of the case studies [Chapters 4 & 5]
    b) Development of an EVDT-based DSS for each of the case studies [Chapters 4 & 5]
    c) An interview-based assessment of the development process and usefulness of each DSS [Chapters 4 & 5]

3. What steps are necessary to establish EVDT as a continually development framework, a community of practice, and a growing code repository?
   a) An assessment of lessons learned from these DSS development processes [Chapter 6]
   b) An outline of potential future EVDT refinement and extension, such as using EVDT to inform the development of future EO systems that are better designed for particular application contexts [Chapter 6]

It should be noted that these questions are the overarching questions for this thesis. Each case study project is done in collaboration with local partners and is aimed at providing practical benefits. As a result, each case study DSS has its own specific objectives.

1.2 Framing

This piece is fundamentally about modeling, in particular, multidisciplinary modeling, and how modeling can inform actual action. Now individual models are inherently simplifications, intentional or otherwise, aimed at accomplishing a goal. They are metaphors for how the world really works, intended to enhance human faculties and focus our intention. Now the problem with such metaphors is that, as Elizabeth Ostrom puts it, "Relying on metaphors as the foundation for policy advice can lead to results substantially different from those presumed to be likely... One can get trapped in one's own intellectual web. When years have been spent in the development of a theory with considerable power and elegance, analysts obviously will want to apply this tool to as many situations as possible... Confusing a model with the theory of which it is one representation can limit applicability still further" [7].

This is of course only compounded when multiple models from different domains are strung together, as will be described later. We must accordingly be focused on maintaining intellectual humility and avoid catching ourself in our own web. Fortunately, such interdisciplinary humility is a key principle of the Space Enabled Research Group of which I am a part. We choose to practice a certain "theoretical pluralism" [8] in our methods, learning from those of different fields and not assuming that, merely because we have chose a certain approach, it is the only or the best possible approach.

In addition to our theoretical pluralism, we must also practice a humility in application. Much of our sustainable development work takes place in communities or even countries to which we are outsiders. There is a real danger that we rush in and prescribe the wrong solution to a problem that the community faces or misidentify the problem altogether. We could even to identify a problem were none, in fact exists, pathologizing the normal and natural, the Victorian England medical profession did to women [9].

As is described further later, we strive to avoid this by allowing actual community members to identify the problem; by speaking with multiple community members to garner different perspectives; and, when possible, spending time in the community ourselves. These latter two components are key, because even the member of a community may be afflicted with significant misapprehensions about aspects of their own community, particularly of those who are seen inferior due to economic class, race, gender, education, or some other marker. Jane Jacob's described such a phenomena vividly in her classic text, *The Death and Life of Great American Cities* [10]:

> Consider, for example the orthodox planning reaction to a district called the North End in Boston. This is an old, low-rent area merging into the heavy industry of the waterfront, and it is officially considered Boston's worst slum and civic shame... When I saw the North End again in 1959, I was amazed at the change. Dozens and dozens of buildings had been rehabilitated... The general street atmosphere of buoyancy, friendliness, and good health was so infectious that I began asking directions of people just for the fun of getting in on some talk. I had seen a lot of Boston in the past couple of days, most of it sorely distressing, and this struck me, with relief, as the healthiest place in the city... I called a Boston planner I know.
>
> "Why in the world are you down in the North End?" he said, "That's a slum!... It has among the lowest delinquency, disease, and infant mortality rates in the city. It has has the lowest ratio of rent to income in the city... the child population is just above average for the city, on the nose. The death rate is low, 8.8 per thousand, against the average city rate of 11.2. The TB death rate is very low, less than 1 per ten thousand, [I] can't understand it, it's lower even than Brookline's. In the old days the North End used to be the city's worst spot for tuberculosis, but all that has changed. Well, they must be strong people. Of course it's a terrible slum."
>
> "You should have more slums like this," I said.

1.3 Space Enabled Principles

The mission of the Space Enabled research group is *to advance justice in Earth's complex systems using designs enabled by space.* By "designs enabled by space," we mean primarily six types of space technology that support societal needs: satellite earth observation, satellite communication, satellite positioning, microgravity research, technology transfer, and the inspiration we derive from space research and education. By "advance justice in Earth's complex systems," we mean a combination of social justice (e.g. antiracism and anticolonialism) and sustainable development[1]. Fulfilling this mission is not just an issue of research topics but also of methodology, as "the master's tools will never dismantle the master's house" [11]. Our methods are thus of necessity multidisciplinary, drawing from at least six disciplines: design thinking, art, social science, complex systems, satellite engineering and data science. Our work, unlike the long, problematic history of systems engineering and development (see Section 2.2), is heavily dependent on local partnerships and collaborations with multilateral organizations, national and local governments, non-profits, entrepreneurial firms, local researchers, and other community leaders, both formal and informal. These collaborators guide the research directions and objectives, as well as participating as fully as they desire in each step of the research process.

It should be noted that pursuing these principles is forever a process of improvement. Large sections of Chapter 2 of this thesis are aimed as such self-critique and improvement.

1.4 Methodology Summary

The first research deliverable, 1a, is based on literature reviews and the development of written arguments. These are primarily contained in Section 2.2 but are reliant upon the earlier sections of Chapter 2. Deliverable 1b, the development of a framework is laid out in Chapter 3 and indirectly through most of the thesis. The primary experimental components of this work, however, are in response to Research Question 2: the development and evaluation of EVDT DSSs for two primary applications: (1) mangrove forest management and conservation in the state of Rio de Janeiro, Brazil; and (2) coronavirus response in six metropolitan areas across Angola, Brazil, Chile, Indonesia, Mexico, and the United States. In both cases, the methodology involves

[1] Space Enabled usually refers to the United Nations (UN) Sustainable Development Goals (SDGs) to explain sustainable development, but a more detailed discussion of that term is provided in Section 2.1.2.1.

the application the Systems Architecture Framework (SAF) [12, 13] an approach that has been previously adapted from the aerospace engineering discipline by Prof. Wood for use in sociotechnical systems [14]. This includes using stakeholder mapping and network analysis to inform the design of the DSS in question as well as fulfilling Deliverable 2a. Other components of the methodology taken in this work are developing the DSS through an iterative and collaborative process with specific stakeholders; pursuing targeted, related analyses, such as on the value of certain ecosystem services, the value of remote sensing information, and human responses to various policies; and evaluating the usefulness of both the DSS and the development process through interviews, workshops, and other feedback mechanisms. Finally, to address Research Question 3, lessons learned will be identified from the two case studies and from other EVDT projects undertaken by fellow students and I. These will be used to lay out a future development path for EVDT will be laid out. These deliverables can be found in Chapter 6.

1.5 Structure of Thesis

Chapter 2 presents the theoretical underpinnings of this work, motivation for its pursuit, and various critical analysis. Chapter 3 provides details on the EVDT Framework, its application, and its novelty. Chapter 4 contains the results from the Rio de Janeiro mangrove application. Chapter 5 contains the results from the coronavirus response application. Chapter 6 contains discussion on both applications and lessons learned. Chapter 7 provides a short conclusion summarizing this thesis.

Chapter 2

Motivation, Theory, & Critical Analysis

This chapter lays out the EVDT framework used through this work along with its theoretical underpinnings, motivation for its pursuit, and various critiques. It can thus be understood as an attempted answer of the simultaneously singular and multifaceted question: "Why?"

2.1 Motivation

The question of motivation includes several elements. Why sustainable development? Why remote observation data? Why systems architecture and engineering? Why these particular case studies? Why me? This section will address these questions as well as lay the groundwork for the discussion of several critiques of the chosen approach that takes place in Section 2.2.

2.1.1 Personal Motivation

My background may make my interest in this work, collaborative modeling for sustainable development, seem a bit odd. Almost all of my prior work was either funded by the military or done directly for the military, from improving weapons testing procedures at Sandia National Labs to defense acquisition policy analysis for my masters degree at MIT to summers spent at the RAND Corporation helping the US military to plan aircraft and air defense acquisitions, to name just a few. My one purely private sector job (an engineering internship at a fossil fuel refinery on the coast of Texas) was hardly emblematic of a great commitment to sustainability.

In another way, however, I am merely following in a well trod, if problematic, pathway. Like Jennifer Light [4], I was exposed to scenario planning and other forms of decision support tools during summers working at the RAND Corporation. And like numerous MIT scholars (Jay Forrester, Norbert Wiener, Joseph Weizenbaum, the list goes on) I have pivoted from, or perhaps built upon, my experience with military engineering to instead tackle societal development problems. The convergence of this two institutions is not something to be passed over. "Support for applying cybernetic principles to research on nonliving systems emerged from organizations... studying management, engineering and control. RAND and MIT stood at the forefront of this trend. With their heritage of mathematical innovation and ties to the armed forces... these and cognate institutions offered ideal laboratories to transform cybernetic principles into management practices." [4]

There is a key difference between me and my predecessors (or so I would like to believe). While some of these (Weizenbaum in particular [4]) came to have doubts about the consequences of applying military-originated technical methods to civilian applications, most of them did not. They resolutely swept aside complications, objections, and planning professionals to solve the problems that they identified in their own way. They built names and careers in this way, but also caused significant harms in their hubris, as I will discuss more later in this chapter.

My background and perspective is somewhat different from them in certain ways, however. My undergraduate mechanical engineering degree was obtained alongside a philosophy degree. My masters aerospace engineering degree was obtained alongside a technology policy degree. And now, over the course of my doctorate, I have invested time in taking development and planning classes, reading foundational texts, and engaging with my antiracist and anticolonialist peers in Space Enabled. My education in matters of urban development and ethics is thus more significant than the one-month seminars that MIT and the University of California provided to aerospace workers in 1971 to prepare them for local government positions [4].

Finally, I have the history, both positive and negative, of my MIT predecessors to inform my actions, in a way that they did not. For these reasons, I often find myself more sympathetic to the contemporary critics of some of these MIT scholars, such as Ida Hoos [15]. This, of course, raises the question of why then am I proceeding with this work anyways.

The answer to that is multifaceted. For one, I believe that the relevant fields have advanced significantly and, to some extent at least, have learned from their prior missteps. This is elaborated on in my detail throughout this chapter. Another aspect is that I (and my advisor evidently) believe that my knowledge and systems engineering in general does still have something to offer humanity beyond building rockets. Additionally, I and my peers, with our particular commitment to the principles outlined earlier, may have an important role to play on influencing the aerospace/systems engineering communities, urging them to curb their worst impulses and learn from their own history. Finally, it is because I want to be of service to humanity. As my aerospace education and career progressed, I found myself increasingly faced with only two options: "pure" scientific work or defense work. Reluctant to choose either, I was being quickly sucked into the gravity of the default: the aerospace defense sector. The Space Enabled Research Group, and the work detailed in this thesis in particular, offered me a third option, to apply my skills and interests to directly help humans on Earth. Now all that is left to is to do it.

2.1.2 Why Sustainable Development?

Before exploring the various methodologies and theoretical frameworks used in this work, it is worth exploring exactly what it is we are hoping to accomplish and why it is important. We need to talk about sustainable development.

2.1.2.1 What is Sustainable Development?

The term *sustainable development* is simultaneously one that invites immediate, intuitive understanding, and yet can remain frustratingly vague. *Sustainable* here means something somewhat more specific than its general definitions of "able to be maintained or kept going" or "capable of being supported or upheld." Instead, it builds upon these and gains some association with the natural environment: "pertaining to a system that maintains its own viability by using techniques that allow for continual reuse" [16]. As to what "system" we are talking about here, the "development" half of sustainable development, we mean generally, human society and wellbeing. This is of course still much too vague, so let us turn to the first official use of the term, which was in the 1987 report by the UN World Commission on Environment and Development, commonly known as the Brundtland Report, after the name of the chair of the commission. This report defined sustainable development as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [17]. We have now helpfully clarified the time scale under which this system needs to "maintain its own viability" but still have done little to clarify what aspects of human society are included within "development."

In 1992, the UN provided more detail in the Rio Declaration on Environment and Development. In this report, they said that "human beings are at the centre of concerns for sustainable development. They are entitled to healthy and productive life in harmony with nature." Furthermore, they state that eradicating poverty is "an indispensable requirement for sustainable development" and environmental protection constitutes "an integral part of the development process" [18]. So we know have several key components, including human health and productivity, the protection of the natural environment, and the elimination of poverty. It is still unclear whether this is a complete list, however, and, if so, what are the connections between these components.

Official clarification would come in 2002, at the UN World Summit on Sustainable Development in Johannesburg. There we get the following [19]:

> These efforts will also promote the integration of the three components of sustainable development — economic development, social development and environmental protection — as interdependent and mutually reinforcing pillars. Poverty eradication, changing unsustainable patterns of production and consumption, and protecting and managing the natural resource base of economic and social development are overarching objectives of and essential requirements for sustainable development.

We now have three linked components along with a set of potential actions for implementation. This is the definition that would stick and become commonplace. From this has been built research fields and massive multi-governmental interventions. Jeffery Sachs describes this further, "As an intellectual pursuit, sustainable development tries to make sense of the interactions of three complex systems: the world economy, the global society, and the Earth's physical environment... Sustainable development is also a normative outlook of the world, meaning that it recommends a set of goals to which the world should aspire... SDGs call for socially inclusive and environmentally sustainable growth." [20]

Questions remain, however. Why all this effort? And what are these SDGs?

2.1.2.2 Why is Sustainable Development Important?

As former UN Secretary-General Ban Ki-moon put it:"Sustainable development is the central challenge of our times" [20]. Despite significant progress in certain domains and certain regions, many individuals and communities are still suffering from severe privations of food, water, healthcare, and more. This is no mere issue of production, but is also connected with issues of allocation (economic inequality is swiftly rising in many parts of the world, including in the author's own country), political mismanagement and oppression, and environmental changes. This work will not detail these numerous concerns (instead I recommend Jeffrey Sach's *The Age of*

Sustainable Development for an accessible survey), but it is worth point out that the last of these issues, that of environmental changes, is particularly important as it shapes how we can seek to rectify the others. Historical means of economic development (such as the extensive use of fossil fuels) is no longer seen as sustainable, due to humanity butting up against and even exceeding certain planetary boundaries or capacity limits, particularly those of climate change, biodiversity loss, ocean acidification, and the nitrogen cycle, as seen in Figure 2-1.

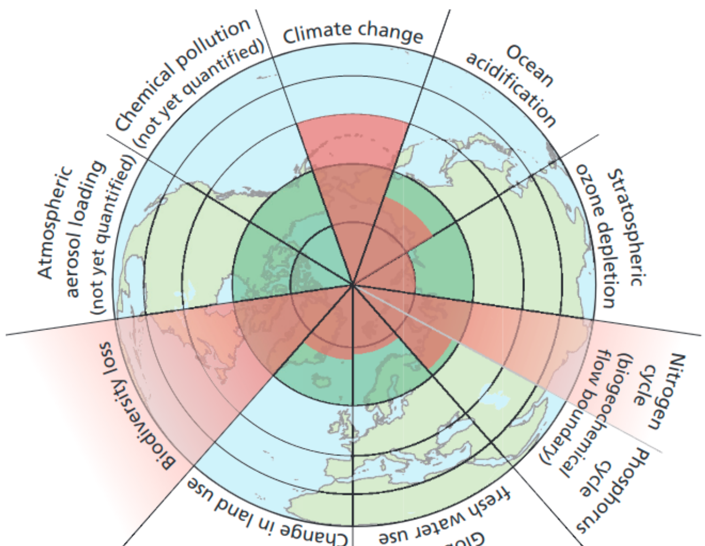


Figure 2-1: Planetary Boundaries. From [21]

While the impacts of these excesses will be felt globally, they will most heavily fall upon some of the poorer and historically oppressed states, harming those with the least capacity of absorb such impacts and thereby potentially exacerbating global inequality. The spatial variation of the estimated impacts of climate change, for instance, can be seen in Figure 2-2.

Furthermore, as was suggested by the Johannesburg definition of sustainable development, the effects of violating these planetary boundaries will not be limited to a particular domain of human life. Table 2.1 estimates such multi-domain impacts on different regions of the world if major, international corrective efforts are not undertaken immediately. The numerous connections between these domains is a key motivation for this work and for the methods chosen, as will be seen later.

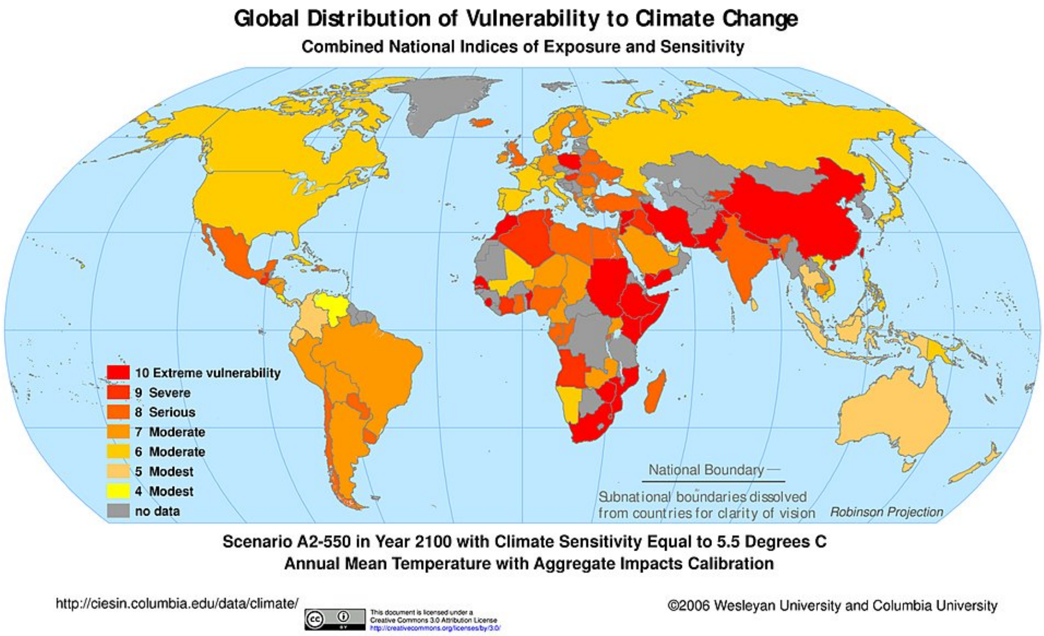


Figure 2-2: Assessment of global distribution of vulnerability to climate change. From [22]

Table 2.1: Estimated impacts of "business-as-usual" by domain and region. H=High; M=Moderate. Adapted from [23] and [20] [1]

	North America	Latin America & Caribbean	Europe	Middle East & North Africa	Sub-Saharan Africa	South & Central Asia	South-east Asia & Pacific	East Asia
Food Insecurity & Malnutrition				H	H	H	M	M
Poverty				M	H	H	M	M
Land Use Change		H			H	M	M	M
Soil Degradation				M	H	H	M	H
Water Shortage	M			H	H	H	M	M
Water & Air Pollution	M		M	M		H	H	H
Biodiversity Loss		H	M	M	M	M	H	H
Sea Level Rise	M	M	H	M	H	H	H	H
Ocean Acidification	M	H	H	M	M	M	H	M

[1]It should be noted that, despite the latter of these two sources citing the former, the two sources differ in noticeable ways, with no explanation provided in either document. Where they are in conflict, I have chosen to use the latter source. In the former source, there is also a error: Ocean Acidification in the Middle East / North Africa is listed as "H" but the cell is in yellow. The

A key reason why these planetary boundaries have been so recklessly exceeded despite the enormous human costs that will result is that these aspects of the environment have historically been both undervalued and poorly understood (at least by those championing economic development). Historically, surveys and quantifications of the natural environment focused primarily, or even entirely, on resources that could be extracted and exploited for economic benefit. In early forest surveys, for instance, "Missing... were all those parts of trees, even revenue-bearing trees, which might have been useful to the population but whose value could not be converted into fiscal receipts" [24]. Just as these factors were missing from accountings of the natural environment, so were they missing form accounts of human society. "Non-human animals are rarely considered within the realms of social theory, and yet... animals can be regarded as a 'marginal social group' that is 'subjected to all manner of socio-spatial inclusions and exclusions.'" ([25–27]as paraphrased in [28]). While these authors were referring primarily to animals, it is also I would argue that this includes plants too, as is particularly evident in the common definition of a weed as a plant growing where it is not wanted.

Fortunately, economists and earth scientists in recent decades have embarked on an effort to better understand and catalog such *ecosystem services*, that is to say, the various benefits that humans are provided by the natural environment and healthy ecosystems in particular. Figure 2-3 illustrates these connections between the environment and human wellbeing, along with the degree to which these connections are mediated by socioeconomic factors. While this kind of accounting can easily veer into a "commodification of nature", the concept of ecosystem services has proven to be a valuable method for analysis trade-offs in environmental and environmental-adjacent policy [29, 30]. This work has progressed to the extent that there is now a regularly updated database of almost 5,000 value observations of ecosystem services in a wide variety of regions and biomes [31]. Cataloging such ecosystem services is only one step, however. We must also present this data in useful ways to decision-makers so that they may act upon it, as well has provide them with the tools for them to identify additional, uncataloged ecosystem services in their own communities.

It is important to note that common to all these perspectives on sustainable development is the interaction of multiple domains that have historically been considered separately. In this way, the pursuit of sustainable development can considered to be a combination of the established fields of Sociotechnical system (STS) [33–35] and Socio-environmental system (SES) [36], thereby making sustainable development contexts into socio-environmental- technical system (SETS).

correct entry is not known, so I have gone with "M" in yellow here in order to avoid overstatement.

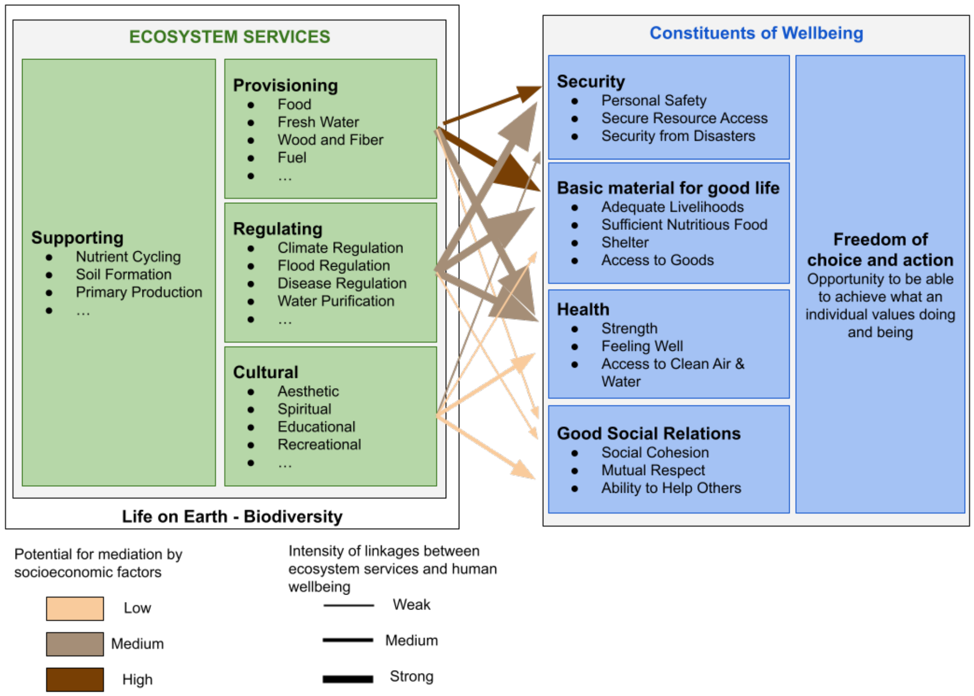


Figure 2-3: Linkages between categories of ecosystem services and components of human wellbeing. Adapted from [32]

2.1.2.3 What about the Sustainable Development Goals?

At the end of Section 2.1.2.1, I quoted a passage that referred to the SDGs, though I did not explain what these were. Now I shall address that deficiency, as the SDGs are a key part of how sustainable development is currently thought about around the world, to the extent that Sachs wrote that, "Our new era will son be described by new global goals, the SDGs" [20]. In order to understand the SDGs, however, we must first go back fifteen years prior to their creation, when the nations of the world sought to proactively face the new millennium. In 2000, the UN established eight Millenium Development Goals (MDGs) that the nations of the world pledged to pursue for the next fifteen years. These were [emphasis added]:

1. To eradicate extreme poverty and hunger
2. To achieve universal primary education
3. To promote gender equality and empower women
4. To reduce child mortality
5. To improve maternal health

6. To combat HIV/AIDS, malaria, and other diseases
7. To ensure environmental **sustainability**
8. To develop a global partnership for development

Within each of these goals were various more specific *targets*, each with a set of quantitative metrics or *indicators*. While significant progress towards the MDGs was made over the course of those fifteen years, significant issues persisted after their conclusion [37]. By the year 2015, numerous changes had occurred. There was an increased interest in recognizing the interdependence of the challenges facing humanity, treating causes rather than symptoms, and in collective action rather than donor-driven action. The MDGs, for instance, often focused exclusively on developing countries and what developed countries could offer them, sometimes explicitly so, such as in Target 8.E: "In cooperation with pharmaceutical companies, provide access to affordable essential drugs in developing countries."

By the year 2015, there was an heightened recognition of disparities and issues within all nations, not just the developing ones. These factors, coupled with the rise in public salience regarding sustainability, resulted in the successors to the MDGs, the SDGs. The SDGs were set in 2015 and are intended to serve as global goals for the international community until 2030. It expanded the number of goals from 8 to 17, each with its own set of indicators and targets [38]. Some of the original MDGs were split into multiple, more specific goals (e.g. #1 became #2 and #3) while other SDGs are wholly novel. The abbreviated forms of these new goals can be seen in Figure 2-4.

The heightened importance of sustainability is evident both in the elevation of the word to the collective title of the SDGs, but also in the increased frequency of its use within the goals. In the original MDGs the word "sustainable" or a variant thereof is used only once in the goals and 6 times among the targets and indicators (and even then it is most commonly in reference to "debt sustainability"). In the SDGs, "sustainable" and its variants is found 13 times in the goals and 68 times among the targets and indicators, referring to a whole host of domains but most commonly referring to "sustainable development" or sustainable use of various resources. While significant gaps in our understanding and recognition of the connections between the environment, human wellbeing, technologies, and decision-making persist [39], the SDGs are a notable step towards acknowledging that our planet is one complex system and that, in many cases, attempts to tackle one domain without considering the others are fated to fail.

Despite their short, clear formulations, actually achieving many of the SDGs involves the significant work by numerous actors in many domains and involving various technologies, as evidenced by the total of 169 targets and 232 indicators within the

Figure 2-4: United Nations Sustainable Development Goals

goals [40]. In short, they require either the creation or the improvement of complex STS. Within SDG #2, for instance, is Target 2.3: "By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment." Associated with this target are indicators 2.3.1, "Volume of production per labour unit by classes of farming/pastoral/forestry enterprise size," and 2.3.2, "Average income of small-scale food producers, by sex and indigenous status" [40]. Clearly, accomplishing this goal will require innovation in agricultural technology, creation of new policy and technological mechanisms for linking financial services to these small-scale food producers, and new methods of collecting information to enable both the evaluation of our progress and the STS created to reach the target.

It is at this need that the research questions of this thesis are addressed.

2.1.3 Why Remote Observation Data?

While many of the initial efforts at remote observation from air and space were done with military objectives in mind, scientific, commercial, and social applications soon became abundant. Since much of space-based remote observation in the past several decades has been primarily driven by large governmental scientific organizations, much of that data has been made publicly accessible. An enormous amount of EO satellite data is freely available to the public through 20+ National Aeronautics and Space Administration (NASA) earth science satellites [41], the European Space Agency (ESA) Copernicus Programme (which includes both the 6 Sentinel satellites and in-situ measurements), the various satellites managed by the Japan Aerospace Exploration Agency (JAXA) Earth Observation Center (EOC), the China-Brazil Earth Resources Satellite Program (CBERS), and the satellites of other space agencies. While this data is largely free currently, this has not consistently been true, nor is it guaranteed to continue in the future [3]. For most of the early history of satellite observation, imagery was kept highly classified and zealously guarded, to the extent that Congressman George Brown Jr., who was integral in the establishment of the US Office of Science and Technology Policy (OSTP), the Environmental Protection Agency (EPA), and the Office of Technology Assessment (OTA), resigned from his post on the House Intelligence Panel in protest over the enforced secrecy in even discussing the topic [42, 43]. Even when the data was available to the public, it was not always freely available, as various countries have made attempts to monetize remote observation data. In the 1970s and early 1980s, for instance, Landsat data was a government-managed operation that provided products at a low-cost, based primarily on the cost of reproduction. In the 1980s, however, the program was transferred to a private entity and prices were increased by more than an order of magnitude and significant copyright restrictions were put in place [44]. Currently the data is once again made free after the monetization efforts met with limited success [45], but this may not remain the case moving forward [46].

The use patterns of remote observation data has varied for reasons beyond cost and military secrecy, however. Social applications were being considered from quite early on. As Jennifer Light recorded, "one proponent [from the last 1940s] explained, photointerpretation data did not directly provide 'social data,' yet they were 'pertinent to social research needs in so far as such 'physical data' have meaningful sociological correlates" [4]. In the succeeding decades, the degree to which humans have altered the surface of our planet has only increased and, as a result, we can now also infer a great deal more about humans from images of that surface. By the early 1970s five rationales for using satellite imagery in city planing had become widespread [4]:

1. It offers a synoptic, total view of the complex system in a given area.
2. Satellites provide repetitive, longitudinal coverage.
3. Satellite inventories were more efficient and up-to-date than ground surveys.
4. Remote sensing was objective.

5. Satellites produced digital imagery that could be easily combined with ground-based data in novel GISs.

Despite these rationales, cities and metropolitan areas largely elected not to use satellite imagery for several decades, choosing instead to rely on aerial imagery and ground-based surveys [4]. The reasons for this are many, but probably include that many of these rationales were overstated for their day. Insufficient resolution and inconsistent coverage limited intra-urban use. While satellite imagery provides a wonderful decades-long longitudinal dataset now, it did not at the time. Satellite imagery was still heavily dependent on human photointerpretation, undermining the argument that the data was "objective" in any meaningful sense. Finally the cost and specialization required to effectively use the data limited its ability to be combined with other datasets. Black-and-white aerial imagery provided sufficient resolution, oblique angles, and immediate interpretability to even the untrained eye. Plus cities were compact enough that the advantages of scale offered by satellites largely did not come into play. Ultimately, while GIS technology (discussed in Section 2.1.4) was readily adopted by cities, satellite imagery was not [4].

Furthermore, despite espousing these five rationales, NASA "did not go a long way toward incorporating remote sensing into day-to-day practices in city planning agencies. This was compounded by the fact that far more academics than local government officials participated in these experiments, providing applications of satellite data that were almost always a step removed from urban mangers' needs" [4]. One of the first use of non-visual imagery for such applications, for example, was unaffiliated with NASA or the space industry in general. In 1970, the city of Los Angeles used aerial infrared imagery to identify unsound housing, and, by 1972, had integrated this imagery with other datasets into a digital decision support system for assessing urban blight [4].

However, much as changed since the 1970s. The rise of multiple EO satellite companies, including the company Planet's 100+ satellites [47], Digital Global's WorldView satellites, and Astro Digital's recent launch of their first two satellites [48], suggests that yet more satellite data is soon to be available for a price. These data sources are likely to be complimentary, with the commercial satellites primarily providing visual imagery and NASA satellites primarily supplying other forms of scientific data, though the Moderate Resolution Imaging Spectroradiometer (MODIS), the Visible Infrared Imaging Radiometer Suite (VIIRS), and the Landsat program all capture visual imagery as well. The launch of Sentinel-1 and other synthetic aperture radar (SAR) satellites has enabled the monitoring of flooding through hurricane cloud cover [49]. While many of these satellites were designed primarily with scientific purposes in mind, this data is increasingly being used by a wide variety of groups around the world to enable sustainable development and other humanitarian applications, such as forest fire tracking [via MODIS and VIIRS [50]], agricultural monitoring [via Global Precipitation Measurement (GPM) for rainfall [51] and GRACE for soil moisture [52]], climate change vulnerability assessments [via Ice, Cloud, and land Elevation Satellite 2 (ICESat-2) for vegetation and ice monitoring [53]], and monitoring military actions [via Sentinel-1 [54]].

Furthermore, over the course of the past two decades, efforts have been made to systematize the application of remote sensing data to inform decision-making on a host of sustainable development areas. Internationally, over 100 countries worked together to form the Group of Earth Observations (GEO)[1] and 60 agencies with active earth observation satellites have formed the Committee on Earth Observation Satellites (CEOS)[2]. In the US, the primary source of government funding for such applications is the NASA Applied Sciences Program, a part of the Earth Science Division, that includes programs focused on disasters, ecological forecasting, health & air quality, water resources, and wildland fires, using data from NASA satellites as well as those of the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) [55–57]. The Applied Sciences Program has clearly learned from NASA past failures of engagement with local decision-makers, and now publish guides on how to ensure that new projects are actually helpful to users [58]. In keeping with this new mentality, the Applied Sciences Program, through their Capacity Building portfolio, frequently partners with other organizations, such as United States Agency for International Development (USAID). For instance, both groups worked together to form the Sistema Regional De Visualización Y Monitoreo De Mesoamérica (SERVIR), which provides geospatial information and predictive models to parts of Africa, Asia, Latin America. In a similar collaborative effort, NASA and USAID have also integrated remote sensing data into the Famine Early Warning Systems Network (FEWS NET).

Such efforts have been quite successful in their goals, but have required significant

[1]GEO, as the name suggests, is dedicated to Earth observation and specifically to the development of a Global Earth Observation System of Systems (GEOSS). In practice this means working together to identify gaps in earth observation and reduce duplication, particularly surrounding sustainable development. In addition to the 100+ national governments, it also includes more than 100 so-called "participating organizations" which include space agencies, NGOs, professional societies, and multiple arms of the UN. For more information see `https://earthobservations.org/`.

[2]CEOS predates GEO and was pivotal in its creation. Regular membership is primarily restricted to space agencies that operate EO satellites (though other organizations can join as associate members) and its activities tend to focus on interoperability and harmonization. Unlike GEO, all associate members are either government agencies or arms of the UN. For more information, see `https://ceos.org/`.

time, expertise, and effort to create and maintain. As overpass frequencies, resolutions, and computational speed have increased, it is increasingly possible to conduct much more rapid, localized, and ad hoc applications of remote sensing data for sustainable development and humanitarian purposes. Within 48 hours and one week respectively, NASA was able to provide maps of damaged areas of Mexico City to Mexican authorities following the 2017 earthquake [59] and maps of damaged areas of Puerto Rico to the Federal Emergency Management Agency (FEMA) following Hurricane Maria [60] (in fact, both of these maps were provided during the same week), through NASA's Disasters Team under the Applied Sciences Program. Such data collection and processing can increasingly be done without the expertise and remote observation systems of governmental space agencies, as demonstrated by a recent effort to conduct near-real-time deforestation monitoring and response [61].

These developments have powerful implications for equity. "The geography agenda is distorted by being data-led... The first law of geographical information: the poorer the country, the less and the worse the data" ([62] as paraphrased by [63]). Remote observation has the potential to help upend this, by providing at least some base level of data globally, with no distinctions of borders or wealth. Increasingly, sustainable development applications of remote observation data are not limited by available remote observation platforms, but by lack of knowledge by potential end-users of its value and by the tools to make use of available data. While data is often available (either freely or at some cost), it is not always readily accessible (particularly in real time) or easily interpreted. Those with the knowledge and capabilities to access and transform this data continue to reside primarily in government agencies and universities (though we have certainly seen heartening growth of such users in a much more diverse set of countries over the past couple of decades). The majority of prominent EOSs are still designed primarily with scientific, meteorological, or military purposes in mind, limiting their utility in more applied contexts, regardless of the creativity of users. And many successful applications of EO data, particularly that which is not straightforward visual imagery, remain squarely focused on characterizing specific, usually environmental, phenomena, such as wildfires [50], aquatic bacterial growths [64], or deforestation [65], with only limited excursions into assessing the connections between such phenomena and human wellbeing. For a survey of such applications see [66].

One important exception to generalization is the recent development of critical remote sensing. This field, most clearly laid out by Bennet et al. reconsiders the rationales for the use of satellite data discussed above in a more critical light [67]. In particular, they advocate for a tripartite research agenda of *exposing*, *engaging*, and *empowering*. By exposing, they mean using remote sensing to provide evidence of socioeconomic and environmental injustices, with a particular emphasis on clandestine activities. By engaging, they mean recognizing the very much non-objective perspective of remote sensing and seeking to integrate remote sensing with local knowledge rather than supplant it. By empowering, they mean partnering with groups that remote sensing is collecting data about, particularly marginalized groups, for capacity building and participating in the use of the data.

As stated in the *Common Horizons* report, "space technology provides awareness of how the sustainability of the world is affected and contributes to its improvement" [66]. Due to the potential of such technologies for applications in humanitarian and sustainable development, attempts are starting to be made to quantify the value of various earth observation systems, but many of these have been limited by the inherent difficulties of handling counterfactual scenarios [68]. NASA is well aware of this difficulty, which is why the Applied Sciences Program funded the Consortium for the Valuation of Applications Benefits Linked with Earth Science (VALUABLES) at Resources for the Future (RFF). This consortium is using economic methods to improve estimates of the societal benefits of earth observation. Work by VALUABLES and others has quantified the value of remote observation systems for carbon emission tracking [69], agricultural production [70], and ground water quality [70]. Siddiqi et al. meanwhile have sought to incorporate data uncertainty and quality into estimates of satellites value for decision-making [71, 72]. The recent advances in this field are cataloged in the recent publication of a book on the socioeconomic value of geospatial information (which includes more than remote observation) [73]. Integrating econometric models with remote observation system models is useful for both assessing the impact of past missions and for predicting the impact of future ones. Such results can be used to help justify the field as a whole and specific remote observation systems in particular. Many applications, however, require more detailed models that integrate more domains. This is particularly true if the intent is to provide remote observation data to inform operational decision-making.

More is needed to enable the use of EO data for human decision-making in such a way that acknowledges the linkages between the environment and humans. This is major aim of this work.

2.1.4 Why GIS & Decision Support?

The term GIS refers to any digital system for storing, visualizing, and analyzing geospatial data, that is data that has some geographic component. It can be used to discuss specific systems, a method that uses such systems, a field of studying focusing on or involving such systems, or even the set of institutions and social practices that make use of such a system [74]. This may seem vague, but due to the diversity of its use, it is difficulty to hammer out a more specific definition without excluding important aspects [75–78]. One perspective, however, is to view GIS to the underlying computer systems enabling the middle three components of the broader geographic information science (GISc) methodology, as shown in Figure 2-1. In that sense, the work related in this thesis can be seen as an exercise in GISc spanning all five components, while the specific software produced for this work are instances of GIS. It should be noted that this distinction is not commonly made outside of academia, with GIS commonly being used generically to encompass both GISc and GIS. Along these lines, there being some debate about whether GIS is best viewed as a scientific field in its own right, or as a mere tool for use in various other fields of science (such as environmental science, economics, etc.) [79, 80]. One important aspect of the acgisc perspective that is not included in Figure 2-1, is that includes "institutional, managerial, and ethical issues [79], something that is naturally core to this work.

The term GIS and the associated field of study originated in the 1960s and 70s with experimental efforts of the Canada Geographic Information System and the US Bureau of the Census to digitize their demographic and land cover data [81]. It should be noted that these early instances were primarily application, rather than technology driven [79]. The key value of GIS is that it "allows geographers to integrate diverse types of data over different spatial scales from the regional to the global, while the advanced capabilities of GIS for organizing and displaying these data transform the geographer's view of the world" ([82] as paraphrased in [83]).

Even with the relatively limited computing capabilities of the era, interest in GIS grew quickly with local governments quickly adopting it for planning purposes, as was mentioned in Section 2.1.3. One key moment in the development of GIS as we know it, was ESRI's creation of the shapefile format (which links geometries with data in a standardized, if somewhat limited, fashion) in the late 1980s, and, more importantly, their open publishing of the format, allowing others to create and manipulate such files [85]. In 1990, Tomlin defined the sub-discipline of GIS known as cartographic modeling, which attempts to generalize and standardize the analytic and synthetic capabilities of geographical information systems. It does so by decomposing data, data-processing tasks, and data-processing control notation into elementary components that can be recomposed with relative ease and great flexibility" [86]. This theory would come to underlay much of research and development work done with GIS. including that of this thesis.

By 1991, Maguire et al. felt that "it is not fanciful to suggest that by the end of the century GIS will be used every day by everyone in the developed world for

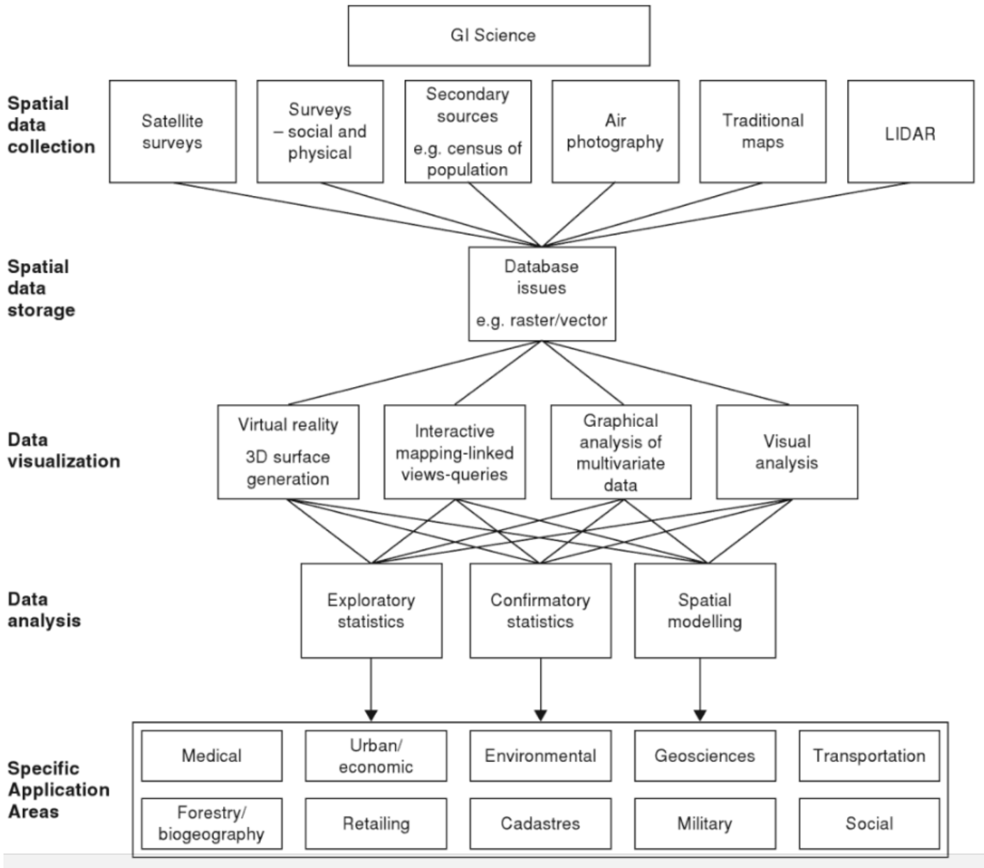


Figure 2-5: Overview of Geographical Information Science. From [84]

routine operations" [87]. This, of course, would turn out to be an understatement, as the world is currently incredibly dependent on GIS. Individuals rely upon the various map applications that we use to search and navigate our world. Governments use maps to visualize their jurisdictions and motivate action, as Chicago has done by visualizing food deserts and mapping where new supermarkets are both needed and economically viable [88]. Since the turn of the millennium, spatial data has become deeply ingrained economics, urban studies, private industry, social networks, environmental science, public health, criminal justice, and more [89].

There is now a well established marketplace for geographic data (as shown in 2-6) and thus for GISs to handle that data. It should be noted that the institution that I am associated with, a university, is classified here as a "value-added intermediary" which serves an important connective role between suppliers, infrastructure, and users. This positioning is crucial to the nature of this work. Whether one is interested in remote observation data or local economics, the question is not whether one should use GIS, but how. To this end, the next two sections will go into more detail about two different veins of GIS: collaborative systems and decision support systems.

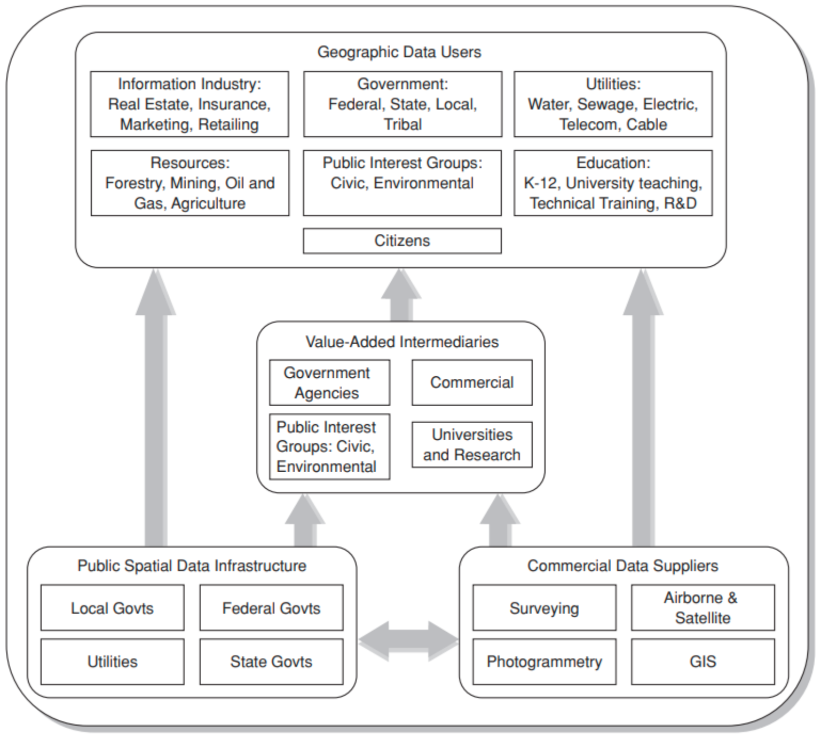


Figure 2-6: The marketplace for geographic data. From [90]

2.1.5 Why Collaborative & Open Source?

As was mentioned in Section 2.1.3, many of the early applications of remote observation data were technology-driven rather than need-driven. So it was with the closely related field of GIS as well, leading to powerful critiques by Pickles and others [91]. These critiques resulted in a reconsideration of the top-down nature of the field and the identification of several potent reasons for broadening the base of participation. First, there was the recognition that the developer of a GIS is not the supreme authority on all fields. "It is the geomorphologist who is best able to choose the data model for representation of terrain in a GIS, not the computer scientist or the statistician, and it is the urban geographer who is best able to advice on how to represent the many facets of the urban environment in a GIS designed for urban planning" [81]. This means that, while collaborations certainly can introduce additional difficulties, such as cultural conflicts, issues of interpersonal trust, effort required to establish rules and norms of participation, they are also immensely rewarding and can improve the results of the work [92]. The dynamics at play in such collaborations can be seen in Figure 2-7. This is certainly a more complicated situation than the traditional, straightforward, academic implementation of a GIS project.

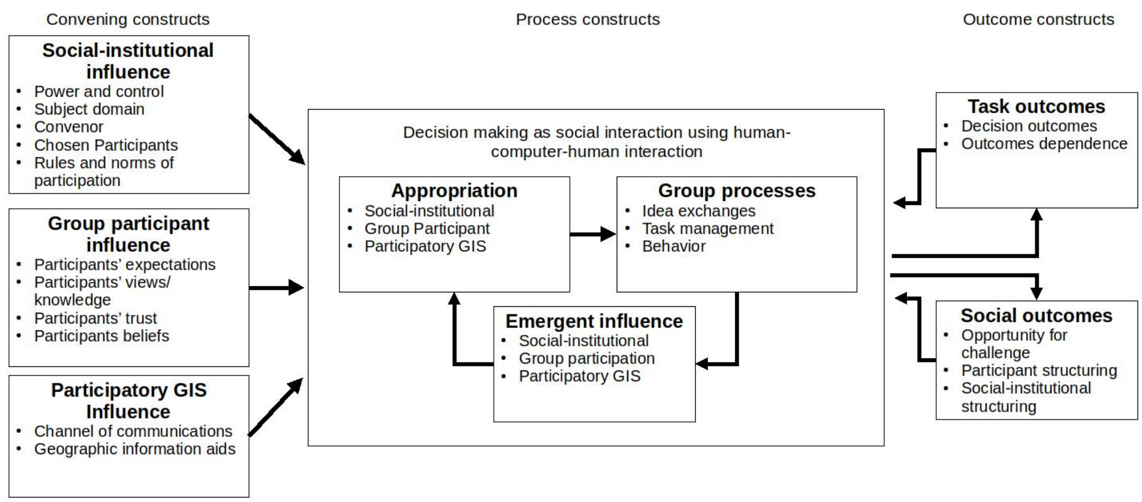


Figure 2-7: Enhanced Adaptive Structuration Theory 2 (EAST2). Adapted from [93]

Second, there was a recognition of the equity concerns at play. Users and disadvantaged communities needed to be involved in the development of GIS data, analysis, and use, if they were going to have a meaningful chance of improving their circumstances [94]. The Canadian International Development Research Centre noted that, "It is impossible to have sustainable and equitable development without free access to reliable and accurate information" [95]. Meanwhile, academic geographer Matthew Edney argued that, "Without equitable access to GIS data and technology, small users, local governments, nonprofit community agencies, and nonmainsream groups are significantly disadvantaged in their capacity to engage in the decision-making process" ([96] as paraphrased in [97]). Williams, in *Data Action*, argues that since "data represents the ideologies of those who control it use," collaboration is essential for creating "trust and co-ownership in the data analysis by allowing the work to be critiqued by those who know the issue the best" and ensuring "that the voices of people represented in the data are neither marginalized nor left unheard."

There was thus reason to seek ways to overcoming the limitations of the technology which, as was common sentiment at the time, meant that "for billions the possibility of accessing the best technology and information made available through digital communications network will always be a luxury. Cartographic information, digital or otherwise, becomes a commodity in its mass production and marketing" [44].

In the early 2000s, this desire motivated the growth in interest towards deconstructing current practices and expanding participation. Several names and frameworks were proposed, including Bottoms Up GIS [94], critical cartography [98, 99], GIS and Society [100], and public participation geographic information system (PPGIS). The last of these, which sought to directly involve the public, would become the most widely used, and would be associated with the broader field of participatory geographic information system (PGIS) [100], which also included other stakeholders, including government officials, NGOs, private corporations, etc. More recently these lesson from GIS have been incorporated with similar lessons from other data science and design fields to form methodologies and approaches such as Data Action [101], Data Feminism [102], and Design Justice [103]. It should be noted that these fields seek involvement in both the production of data and in its application, not merely one or the other [94, 104]. For example, in Washington state in 2002, several American Indian tribes were using GIS technology to "inventory, analyze, map, and make decisions regarding tribal resources... include[ing] timber production, grazing and farm land, water rights, wildlife, native plants, cultural sites, environmental data and hazardous site monitoring, historical preservation, health and human resources" [105]. And in 1999, the 'What If?' Planning Support System (PSS) was created to use "GIS data sets that communities have already developed to support community-based efforts to evaluate the likely implications of alternative public-policy choices" [106].

This dual involvement promotes, as Michael Curry put it, both "knowing *how*" (the "ability to do something") and "knowing *that*" (the "knowledge about how something works") [107]. Having only the former forces the user to rely upon blind trust, instilling a sense of complacency or alienation and preventing creativity. Knowing only the latter, enables discourse about a topic but prevents the user from actually implementing new ideas. It is only with both together that a person becomes a true participant in a field and make their own choices. This is important as expansion of choice is valuable for both intrinsic (for its own sake) and instrumental (to attain preferred positions) reasons [108].

PGIS has thus naturally been strongly advocated and widely adopted over the past three decades [109], with numerous frameworks being proposed for how to implement it [110]. A relatively early project in this vein, for example, sought to try and overcome issues of unequal access and use of GIS technology in South Africa in the early 1990s through the pursuit of five specific objectives [97]:

1. Enhanced community/development planner interaction in a research and policy agenda setting
2. The integration of local knowledge with exogenous technical expertise.
3. The spatial representation of relevant aspects of local knowledge.
4. Genuine community access to, and use of, advanced technology for rural land reform.
5. The education of "expert" rural land use planners about the importance of popular participation in policy formulation and implementation.

Such objectives are common across PGIS projects and the success of this pursuit has come to be recognized even by many entrenched institutionalists. The former vice-mayor of New York City, for instance, argues that digital GIS tools that provide open data (1) free data from bureaucratic constraints, allowing real time combination of data from different sources; (2) construct a loop between government and the community in which cooperation builds respect continuously; (3) enable two-way communication, promoting collaboration [88]. That said, some of these implementations have been criticized for being participative in name only, particularly within the research domain [111].

Many PGIS implementations still rely upon closed source, proprietary code for the underlying software [78]. Participants made have been able to generate new data and perform analyses, but they often could not access the code itself or change the models directly. This was due to a combination of factors: limited diffusion of programming knowledge; a limited selection of software tools, many of which were closed source; limited access to computers and the internet; and limited collaboration tools, particularly for geographically distributed collaborations [98]. Over the past couple decades however, all three of these limitations have been greatly mitigated (though not eliminated), due to the growth of the internet and the related diffusion of programming knowledge and rise of the open source movement. As two leaders of the *theirwork* PPGIS project in 2011 put it [112],

> The open source movement at its core stands for the development of source code... in a completely open and free way. Pragmatically, this

> manifests itself as a methodology of making code freely available to anyone who may wish to access it for any purpose, unconditionally. Concurrently, open source is for many a philosophical approach to software development, and is see as the only truly sustainable approach to software development... In both its execution as a model for making possible new forms of collaborative work, and its philosophical underpinnings of sustainability and openness, it is an essential component in and fluence upon a computer-based mapping solution.

This passionate call for open source software is about more than a philosophical ethical stance. It is also about enabling critique and improvements. “Map studies needs to open the ‘black boxes’ of mapping software, to start to interrogate algorithms and databases, and in particular to investigate the production of ready-made maps that appear almost magically on the interfaces of gadgets and devices we carry and use everyday, often without much overt thought about how they work and whose map they project onto their interface" [113].

It should be noted that some work has placed the responsibility for limited adoption of GIS tools on the planners/users themselves, specifically their lack of will and training with the tools [114]. While this may be the case, this lack of will and training is almost certainly itself due to a lack of outreach on behalf of the tool developers, and thus PGIS is still reasonable strategy to address these barriers. Other challenges around open source tools involve concerns about long-term support. As many (though certainly not all) open source projects are volunteer or academic-driven, changes of interest, financial support, or time availability can have major impacts on the software development and maintenance process. That said, similar concerns can be raised around commercial software products, which can be abruptly canceled, leaving the users with little recourse. It should be acknowledging that the economics, incentives, and decision-theory surrounding open source vs. closed source software is complex [115], but the continued endurance of open source software (or even thriving, as virtually all servers used for cloud computing are running on open source operating systems [116]), suggests that open source is a viable choice for software projects moving forward.

2.1.6 Why Scenario Planning & Decision Support?

One common use of GIS is in DSSs. These are technical systems aimed at facilitating and improving decision-making. Functions can include visualization of data, analysis of past data, simulations of future outcomes, and comparisons of options. Such GIS

DSSs are particularly common in development and planning spheres. Planning here refers to "the premeditation of action, in contrast to management [which is] the direct control of action" [117]. In general, planning tends to concern itself with more long-term affairs that management does. Planning strives for the "avoidance of unintended consequences while pursuing intended goals." Models, and their specific implementations as decision/planning support tools, are one means of achieving this.

There is no definitive typology of DSSs, spatial or otherwise, but in general they accomplish some combination of the following functions [93]:

1. *Basic information handling support*
    (a) Information management
    (b) Visual aids
    (c) Group collaboration support
2. *Decision Analysis Support*
    (a) Option modeling (including scenario planning [118]
    (b) Choice models
    (c) Structured group process techniques
3. *Group reasoning support*
    (a) Judgement refinement/amplification techniques
    (b) Analytical reasoning methods

As late as 1990, many researchers were arguing that GIS was not mature enough to serve as the basis for a DSS [119].

Börjeson et al. propose three different kinds of scenario generation: predictive, exploratory, and normative [118], with most urban planning applications focusing on the normative type [120]. Maier et al. built upon this to provide a framework for how to handle varying degrees of uncertainty in scenario planning [121].

Harris and Batty defined two principle requirements of planning support systems [117]:

1. The search for good plans take place through informed trial and error, since system optimization is impossible.
2. The tool must be able to trace out the consequences of alternatives, as this is the primary means of comparing alternatives.

They also define some other relevant requirements to this work [117]:

- The tool should be available to public use, including methods and data.
- The tool should accommodate research and adaptation.
- The tool should be self-teaching, within reason.

- The tool should be adaptable, including to a wide variety of situations, levels of information, etc.
- The tool should be built on models and methods that are understandable to the user.

"Scenario planning is a method of long-term strategic planning that creates representations of multiple, plausible futures of the system of interest." It arose in military and corporate strategies [122]

Scenario Planning arose from two independent sources: Herman Kahn at the RAND Corporation working for the Air Defense System Missile Command and Gaston Berger at the Centre d'Etudes Prospectives [123]. These in turn were further developed in the private sector by Shell and GE, with the former publishing more openly on the topic. Numerous forms of scenario planning exist. For instance, Kahn's original formulation was probabilistic, focusing on the most likely scenarios. Berger's, on the other hand, was normative, focusing on the scenarios to be aimed for. Lastly, Shell's has eschewed both of these, focusing instead on capturing a range of potential future scenarios and using them to explore responses and to educate decision-makers.Regardless of the focus, scenario planning centers around the construction of some number discrete "future worlds" that consist of a set of both quantitative and qualitative parameters. Impact on the organization and potential responses are then explored. While the exact methodology varies and different organizations use scenario planning for different purposes, most private corporations use it primarily for long range business planning [123]. That said, scenarios planning has also been used to construct early warning systems, by identifying the important areas and trends to monitor to inform decision-making [124].

"A scenario-based strategic plan is... appropriate for vision, framework, comprehensive, system, and redevelopment plans and for those with long time horizons and low or moderate detail" [122].

Oregon Scenario Planning Guidelines proposes a six-step process for scenario planning ([125] as paraphrased by [122]:

1. Create a framework for the scenario planning process.
2. Select evaluation criteria.
3. Set up for scenario planning: evaluation tools ,data, and building blocks.
4. Develop and evaluate base-year conditions and reference case.
5. Develop and evaluate alternative scenarios
6. Select the preferred scenario

Zapata and Kaza provide evidence that scenario planning, particularly when incorporating diverse participants, can help planners cope with significant levels of uncertainty about the future (though they also note that few programs actually involve diverse participants) [126].

Goodman describes four primary kinds of planning support models [122]:

1. Generic Systems Models: Developing a typically non-spatial abstract representation of a system and analyzing how it functions. System dynamics is a classic example.
2. Economic and Demographic Models: The set of techniques that focus on changes in employment of particular sectors and in population of different characteristics. Klosterman is the classic text on these methods. [127]
3. Place-Type Development and Analysis: Tools used to simulate future outcomes based on land use, zoning, population density, etc. CommunityViz is an example of this [128].
4. Urban Systems Models: Essentially a combination of generic systems modeling and place-type development and analysis models to accurately represent spatial phenomena over time, such as transportation networks and organic growth. Examples include cellular automata and spatial interaction models.

Jankowski and Nyerges lay out seven common design requirements for spatial decision support tools [93]:

1. A spatial decision support system for collaborative work should offer decisional guidance to users in the form of an agenda.
2. A system should not be restrictive, allowing the users to select tools and procedures in any order.
3. A system should be comprehensive within the realm of spatial decision problems, and thus offer a number of decision space exploration tools and evaluation techniques.
4. The user interface should be both process-oriented and data-oriented to allow an equally easy access to task-solving techniques, as well as maps and data visualization tools.
5. A system should be capable of supporting facilitated meetings and hence, allow for the information exchange to proceed among group members, and between group members and the facilitator. It should also allow space- and time-distributed collaborative work by facilitating information exchange, electronic submission of solution options, and voting through the internet.
6. A system functionality should include extensive multiple criteria evaluation capabilities, sensitivity analysis, specialized maps to support the enumeration of preferences and comparison of alternative performance, voting, and consensus building tools.

7. A system should provide necessary functionality to support needs of an advanced user without overwhelming a novice who needs a user-guiding interface.

PGIS: Refer to macro-micro framework from Table 2.1, pg.17. What parts this thesis covers and what parts we envision EVDT covering in the long term.

Table 2.2: Generic macro-micro, participatory decision strategy. Adapted from [93]

	Macro-phases in a decision strategy		
Micro-activities in a decision strategy	***1. Intelligence*** about values, objectives, and criteria	***2. Design*** of a set of feasible options	***3. Choice*** about recommendations
A. Gather...	issues to develop and refine **value trees** as a basis for objectives	**primary criteria** as a basis for option generation	**values, criteria, and option list scenarios** for an evaluation
B. Organize...	**objectives** as a basis for criteria and constraints	and apply approaches(es) for **option generation**	approaches to **priority and sensitivity analyses**
C. Select...	**criteria** to be used in analysis as a basis for generating options	the **feasible option list**	**recommendation** as a prioritized list of options
D. Review...	criteria, **resources, constraints,** and **standards**	**option set(s)** in line with resources, constraints, and standards	**recommendation(s)** in line with original **value(s), goal(s),** and **objectives**

2.1.7 Why Systems Engineering?

Before answering this section's title question, we must first offer an a definition of systems engineering, as, unlike many other fields of engineering (aerospace, mechanical, electrical, biomedical, etc.) the name is not self-explanatory.

Systems engineering, perhaps due to its inherently interdisciplinary nature coupled with its roots in several different fields (aerospace engineering, civil engineering, mechanical engineering, etc.), has had numerous definitions proposed over the course of the past century. Some of these have been by individual authors, such as

Maier and Rechtin's "*A multidisciplinary engineering discipline in which decisions and designs are based on their effect on the system as a whole*" [12], and some by international standards organizations, such as the international standards organization (ISO)/International Electrotechnical Commission (IEC)/Institute of Electrical and Electronics Engineers (IEEE) definition "*Interdisciplinary approach governing the total technical and managerial effort required to transform a set of customer needs, expectations, and constraints into a solution and to support that solution throughout its life*" [129] . For the purposes of this discussion, the specific definition is not overly important, as we do not seek to create a foundational work of systems engineering, but rather to understand its relations to other fields.

It is worth noting International Council on Systems Engineering (INCOSE) affiliated Systems Engineering Body of Knowledge (SEBoK) definition, however: "Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on holistically and concurrently understanding stakeholder needs; exploring opportunities; documenting requirements; and synthesizing, verifying, validating, and evolving solutions while considering the complete problem, from system concept exploration through system disposal" [130]. Something missing from this definition is that systems engineering refers to a specific intellectual tradition that arose out of mechanical, civil, electrical, and aerospace engineering fields in the early-to-mid 20th century. It thus tends to draw from an engineering mindset and relies upon engineering techniques, rather than those of urban planning, architecture, or program management, all of which also could be considered to fall into the SEBoK definition. This is important because the nature of systems engineering is that it is inherently abstracted from its subject matter to a certain degree. The tools of systems engineering were developed in order to design hydroelectric dams, rockets, global communications systems, and much more. In this way it is similar to control theory, in that is is not deeply tied to the specific thing being designed or controlled, only to an abstract understanding of its mechanics and relationships. This means that systems engineers, like some physicists, can have a tendency to see any problem, any situation as tractable with a systems engineering perspective.

So with some shared understanding of what systems engineering is established, why is it relevant to sustainable development? First and foremost, it is the 'interdisciplinary' and 'holistic' nature of the field, along with the tools and frameworks that have been developed to apply this, that makes it most relevant for EVDT. While sustainable development and engineering historically have not been viewed as closely linked, this is changing. Sustainability first enters engineering literature in the 1970s and its frequency rises in a logarithmic fashion over the course of the subsequent decades [131].

The primary systems engineering tools of interest include the aforementioned multidisciplinary optimization, which provides lessons on integrating models of different fields; systems architecture, which is useful for designing EVDT implementations themselves; and stakeholder analysis, as all EVDT applications inherently involve numerous stakeholders, often with different levels of power.

Other subfields that will be relevant later in the EVDT lifecycle include multi-stakeholder negotiation and decision-making, which contains numerous lessons on how structure communications to avoid deadlock or domination [132–134]; tradespace visualization and exploration [132, 133, 135–137], which contains lessons on how to present complex information to stakeholders and enable them to navigate their options; and epoch-era analysis, which is useful to considering how a system may evolve over time in an high uncertainty domain [138, 139]. Sachs stated that "Sustainable development is also a science of complex systems" and argued that two specific tools are important for implementing the SDGs: backcasting and technology road-mapping [20]. Systems engineering is well equipped to address both of these.

External to the field itself, the rise of sustainable development, with its interconnected social, economic, and environmental development, has also been paralleled by the (rightfully) expanded number of stakeholders involved in decision-making processes and a increased recognition of linkages across differing geographic scales [110]. This increase in complexity is something that systems engineering is well posed to address.

2.2 Critical Analysis

While many of the earlier sections of this chapter have discussed various problems in the history of the fields that this work draws upon. Prior to proceeding to the EVDT Framework and its applications, it is important to more squarely address those problems and understand what must be done to avoid the mistakes of the past. To that end, this section will consider and respond to several critiques that can be raised against a work such as this.

- Technology itself is at best a major contributor, if not the source of most of the problems you seek to address. It is inherently elitist, colonialist, racist, and/or authoritarian. Western-run technocratic planning and international development perpetuates colonialism, typically fails in its own goals, and merely destroys traditional communities. If you truly want to save the Earth and stop oppression, you should abandon technology rather than doubling down on it.

This question will considered both in general and in regard to several specific aspects of this work: GIS, planning, and systems engineering.
- Sustainable development, as it is commonly used, is essentially meaningless and the SDGs are likewise such a potpourri of targets and indicators that they have little influence on what would have happened anyways, serving instead as a form of greenwashing.
- The effectiveness of scenario planning and most other forms of decision support is ambiguous at best, despite their long history. Another research project in this vein is thus fundamentally flawed and is not real science.

2.2.1 Technology is inherently elitist, colonialist, racist, etc.

It may not be clear why I am including this section. After all, most readers and certainly the evaluators of this thesis are certainly not of this opinion, or else they would not be working at the forefront of their respective fields, all of which heavily involve the use of technology. Nonetheless, I am reluctant to discard this argument out of hand, particularly when technology has been so integrally involved with so many of the evils of the past several centuries.

While the opinion of society about technology has gone through cycles of optimism and pessimism since the start of the Industrial Revolution and critiques of technological progress date back to at least Rousseau, the idea that technological, economic, and moral progress are both inevitable and inextricably linked has remained persistent, particularly among the scientists and engineers who were most directly involved with the development of technology[140], as is currently seen with the proponents of Big Data and machine learning [141]. They tend to consider it either as neutral tools, extensions of human will, or as deterministic mechanisms of progress towards a better future. Questions of morality are either shifted to the human users (and thus outside the jurisdiction of the designers) or resolved entirely. For example, John Maynard Keynes, one of the more influential thinkers of the early 20th century, explicitly linked technology to progress, as part of his sketching a utopian future: "This slow [historical] rate of progress, or lack of progress, was due to two reasons - to the remarkable absence of important technical improvements and to the failure of capital to accumulate" [142].

It was only in the late 1980s did scholars of geography, informed primarily by Michel Foucault and Karl Marx, start challenging the idea that "cartography produces maps of truth in an objective, neutral, scientific fashion." [143]. John Pickles was one of the more articulate purveyors of such an argument [91]:

> The Western trope of a public space in which people (usually "men") of

> good faith join in debate about their future, appropriated by industrial and urban forms of modernity as a mythic image of a democratic culture of debate and negotiation predicated on individual autonomy, private property, and state power has more recently been further appropriated by the news and communication media through their claim to be the embodiment of the modern civic arena. This trope of public space is now being reappropriated by the electronic age as its wish image - the promise and possibility of "information." The putative openness of new electronic information media and the rhetoric of "voice," "openness," and "information" - the trope of reasoned, open, uncoerced discourse in a public place - is appropriated to the project of social development and private profit.
>
> But, like all highways, the information highway requires points of access, capital investment, navigation skills, and spatial and cultural proximity for effective use. Like the automobile highway, the information highway fosters new rounds of creative destruction and differentiates among users and between users and nonusers. It brings regions of difference under a common logic and technology, and through differential access and use exacerbates old and crates new patterns of social and economic differentiation. While for some, information means the provision of alternatives and the satisfaction of choice (even if a "choice" signifies a socially constructed yet now naturalized whim of the wealthy consumer), for others this postindustrialism (and its attendant postmodern cultural forms) must still be seen in the context of a political economy of graft, monopolism, and uneven development.
>
> Such processes of territorial colonizations, globalization, and production of new scales of action contrast sharply with a technocultural ideology of enhanced autonomy and self-actualization, and severely complicates the assessment of the relationship between technological innovation and social change.

Amid the dilemma of "the disempowering habit of demonizing technology as a satanic mill of domination" and "the postmodernist celebrations of the technological sublime," however, emerged scholars seeking to provide "a realistic assessment of the politics - the dangers *and* the possibilities - that are currently at stake in those cultural practices touched by advanced technology" [144]. Chief among these were Lewis Mumford and Langdon Winner. The former theorized that technology came in two different essential stripes, neither good or evil, but instead authoritarian and democratic, that "from late neolithic times in the Near East, right down to our own day, two technologies have recurrently existed side by side: one authoritarian, the other democratic, the first system-centered, immensely powerful, but inherently unstable, and the other [hu]man-centered, relatively weak, but resourceful and durable" [145].

For examples of these two types, Hayes suggested the inherently bulky and centralized nuclear power with inherently decentralized solar power [146] (though Hayes neglected the immensely centralized nature of the production of solar panels). Winner extended this theory, arguing that many technologies had politics embedded in them, regardless of the intent of either the creator or use. "It is neither correct nor insightful to say, 'Someone intended to do somebody else harm.' Rather, one must say that the technological deck has been stacked long in advance to favor certain social interests, and that some people were bound to receive a better hand than others" [147].

The ideas of Mumford and Winner have become commonplace. Even self-admitted technological optimists like Jeffrey Sachs [148] feel it necessary to qualify their optimism: "*Choosing the right technologies*, we can achieve continued economic growth and also honor the planetary boundaries" [emphasis mine] [20]. Similarly, the largest developers of new technologies, such as Google, find it necessary to put effort into studying the ethics of their systems (though there is some evidence that this is mere lip-service [149]).

The question then is, which category do the technologies used in this fall into? That is what the following sections will address.

2.2.1.1 GIS & Mapping

It is undeniable that the history of mapping and thus of GIS is one of centralization and authoritarianism. National mapping in the US originated in motives that were explicitly of means for resource exploitation and control [44]. Furthermore, as pointed out by Pickles, historically within the GIS research community and its predecessors, there has been a certain "technocratic myopia" and unwillingness to consider novel, insurgent uses of GIS that has led critics to label it as an "inherently conservative form of analysis" [150], or as McHaffie put more movingly, "Perhaps the 'frightened Africans' who once 'threw spears at an Aero Service aircraft' or the 'suspicious moonshiners in Appalachia' who 'took a few rifle shots' at aerial mappers did so not because the intentions of the mappers were 'not always understood,' but because those intentions, and the powerful forces being them, were understood only too well" [44]. Jackson, meanwhile, relates the results of an ethnographic study that highlighted the almost comically numerous negative consequences (both intentional and unintentional) of the introduction of GIS into local planning in Kansas City [151].

A more specific, early critique, also by Pickles, was that of privacy and control over one's own information [76]:

> But in practice, developers and users of GIS have not paid much attention to the rights of individuals to control information about themselves, to withdraw from databases involving themselves, and to review the information available and the ways in which it is being used. Instead, in cases other than those involving criminal and victim identification (and in some cases even there), the field of GIS (as far as I am aware) has no substantive protocols or methodological principles that govern the use of information about individuals or guarantee the rights of individuals included in databases to remove themselves or to see the results of the analysis.

This concern presaged many contemporary concerns about facial recognition [cite], statistical algorithms for criminal justice bail and sentencing setting [cite], telecommunications data gathering [152], and big data in general [141].

Many of these critiques can be traced to the origin of GIS and the role that it had in splitting the geography community between "techies," who were more interested in the natural sciences and even positivism, and "intellectuals," who felt more at home in the humanist social sciences [74].

That said, even Pickles himself did not feel that this was not necessarily so moving forward. Centralized, authoritarianism was not 'baked into' GIS. "GIS and informatics do open virtual space of 'real' social interaction, new communities of dialogue, and new interactive settings... Systems of informatics provide a potential source of counterhegemonic social action, and GIS... offers a diverse array of practical possibilities... Informatics are seen as a potential liberator of socially and politically marginalized groups, and thus a source of democratizing power for these newly networked groups" [150]. Meanwhile Tulloch argued that GIS is naturally developing through phases, seen in Figure 2-8, while the problematically simplistic outcomes of efficiency and effectiveness were the primary result of earlier stages, future states, including democratization of GIS will instead produce equity.

One of the consequences of the Mumford-Winner view, however, is that it implies that the designers of technology have both agency and responsibility to determine what politics are embedded in their designs. To reject either the agency or the

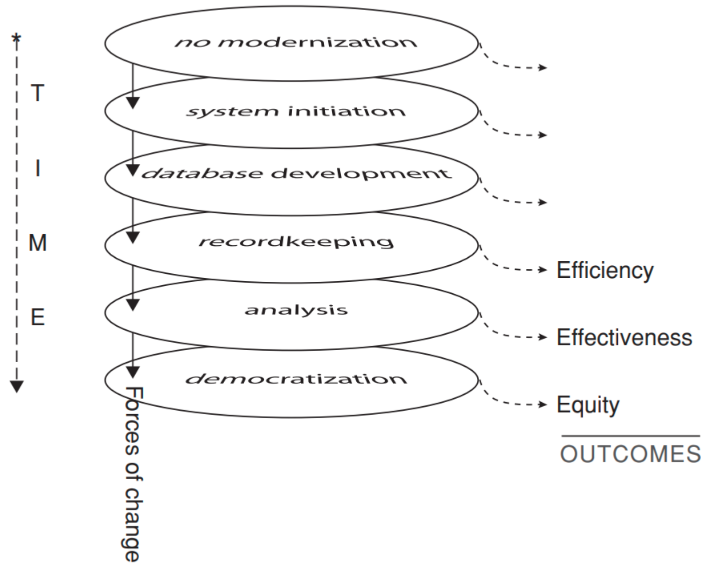


Figure 2-8: Development of GIS development and associated outcomes. From [153] as reprinted in [92]

responsibility is highly problematic. Many designers of digital tools seek to reject the former and commit themselves to a sort of technological determinism [74]. For example, Stephen Goldsmith and Susan Crawford, who did a great deal to implement such technologies in New York City and Indianapolis, wrote that "the process of collection is *not going to stop*. We think, it fact, that it would be shortsighted and *probably impossible to halt this natural evolution*. That is all the more reason, then, to carefully establish policies covering data access, data security, and transparency with respect to its collections" (emphasis mine) [88]. They thus divorce themselves of responsibility for the design of the technology itself and restrict themselves for seeking to govern who uses it.

Meanwhile Goodspeed writes about the opposite problem, "Planning theorists have too often accepted Habermas's view that technology is primarily associated with technical rather than moral rationality, which leads them to overlook technology's potential normative dimension... Even choosing a digital tool requires making value-laden judgments about what issues matter enough to be analyzed. Because digital tools typically inherit the worldviews and assumptions of their creators, even well-meaning applications of them can inhibit potentially valuable new ideas or critical perspectives." He then proposes the term *tool of inquiry* to "describe the ideal in which tools are continually shaped, used, and tested by public users," [122] thereby aligning it with the democratic, human-centered type of technology.

We must recognize that, as Krygier and Wood so playfully illustrated, maps (and all GISs) are, fundamentally, propositions about that world that are asserting a fact and promoting an action. Because of this "you must accept responsibility for the realities you create with maps" [154]. And this is not limited to maps. Design itself is purposeful in that it forges both pathways and boundaries in its instrumental and cultural use" ([155] as paraphrased in [156]).

And there are clear examples of geospatial data being using for positive impact. For instance, there is NASA's famous Blue Marble image, which, while perhaps more iconic than cartographic, is still undeniably a geospatial object, a map even, that has essentially created both "one-world" discourse and "whole-earth" discourse [157]. If that seems to much of a reach or too incidental, we can look at how Laura Kurgan and others used their "Million Dollar Blocks" project to powerful visualize the impact of mass incarceration upon particular, primarily black, American communities, helping to shift public perception and policy discussions [158]. Or how the Sierra Club has made significant use of Google Earth in their efforts to garner support for conservation efforts in the US Arctic National Wildlife Refuge and elsewhere [157]. Florence Nightingale's famous rose diagrams famously shifted policy on the handling of sanitation in war zones [159], even if these diagrams were, in fact, misleading (cite).

Additionally, in some ways, we want to avoid making a seamless tool, as "the most significant impacts of technology tend to occur when the technology becomes indistinguishable from the fabric of every day life" ([160] as paraphrased in [83]). This is not, unfortunately, not sufficient. "We all tend to defer to machines, which can seem more neutral, more objective" even when they are actively warning us of their limitations and fallibility [161].

I do align myself with those who feel that:

> Even though the funding or research and development... of GIS and other imaging systems has come primarily from business, state, and military sources, advocates of the progressive potential information and imaging technologies argue that access is hard to deny, networks are difficult to control, information is readily accessible and used by individuals and groups with limited budgets and expertise, and the ability to use the technology in depth permits groups like environmental organizations to counter claims by polluters about their environmental impacts, by developers about likely local effects of runoff and ground water, and so on... GIS enables communities to make better decisions by providing access to

> more and better information. It offers more powerful tools for local planning agencies; it offers exciting possibilities for data coordination, access, and exchange; and it permits more efficient allocation of resources, and a more open rational decision-making process

[150].

That said, I don't believe that any of this is guaranteed or effortless. It requires intentionality and reflection on the part of the designers, as well as a humble willingness to listen to criticism from anyone, including those who are not 'experts.' This was a key point of the various critical GIS movements discussed in Section 2.1.5. Their work is demonstration that it is possible develop and apply GIS in a collaborative and participatory manner.

As we proceed, we must keep in mind that "the very notion that technologies are neutral must be directly challenged as a misnomer," [156] and that, as Smithsonian curator Lucy Fellowes said, "Every map is someone's way of getting you to look at the world his or her way" [162].

2.2.1.2 Technocratic Planning & International Development

I should start off by noting that this section is not intended to consider all of the arguments for and against planning in general (for that see Klosterman [163]), but instead to focus in on the narrower question of whether *technocratic planning*, particularly in an international context, can be helpful and ethical. This is important because many EVDT applications are international or multinational projects, including both of those focused upon in this work.

By "technocracy" we mean the basic idea that "the human problem of urban design has a unique solution, which an expert can discover and execute. Deciding such technical matters by politics and bargaining would lead to the wrong solution" [24]. It is typical for a believer of this idea to quickly put themselves in the role of the "expert [who] can discover and execute." That said, they quickly find themselves beset by complexity and gapes in the data that frustrate their efforts. For such aspirants "legibility [is] a central problem," one that must be solved prior to addressing urban design itself. To this end, "exceptionally, complex, illegible, and local social practices" must be turned into "a standard grid whereby it [can] be centrally recorded and monitored." This, of course, requires immense simplification. These "state simplifications... have the character of maps. That is, they are designed to summarize precisely those aspects of a complex world that are of immediate interest to the mapmaker and to ignore the rest. To complain that a map lacks nuance and detail makes no sense unless it omits information necessary to its function." And the interest of these would-be-technocrats tends to be their "unique solution." Taken together, there are five specific characteristics of these simplifications [24]:

1. They are interested and utilitarian, aimed at a particular end.
2. They are nearly always written, as opposed to visual or verbal.
3. They are typically static and thus, perpetually out-of-date to at least some extent. "The cadastral map is very much like a still photograph of the current in a river."
4. They are typically aggregate facts, not individual ones.
5. They are standardized, so as to enable comparison and longitudinal analysis.

These individuals are what Easterly calls "Planners," to be distinguished by "Searchers," those who seek for bottom-up solution to specific, addressable needs [164]. The Planners, meanwhile, fashion themselves into benevolent dictators (though they would eschew being called as such) focused on implementing their solution [165]. Beyond outright failure, such endeavors have not infrequently caused immense social harms, including famines, cultural destruction, and environmental collapse. Furthermore, such technocratic planning is bound up in the history of colonialism and, while formal colonialism has ended, its impacts continue and certain mindsets are still embedded within such planning efforts [166].

James Scott argued that four elements were necessary to precipitate the most tragic of social engineering disasters [24]:

1. The "administrative ordering of nature and society." This includes items like cadastral maps, surnames, census records, and a standardized legal system. As Theodore Porter put it, "Society must be remade before it can be the object of quantification." [167]
2. A "high-modernist ideology," which Scott defines as a "strong," "muscle-bound" "self-confidence about scientific and technical progress, the expansion of production, the growing satisfaction of human needs, the master of nature... and the rational design of social order commensurate with the scientific understanding of natural laws."
3. An authoritarian state that is both "willing and able" to wield power to enact the high-modernist ideology.
4. A vulnerable civil society that "lacks the capacity to resist" the plans of that authoritarian state.

In essence what is "truly dangerous to us and our environment... is the *combination* of the universalist pretensions of epistemic knowledge and authoritarian social engineering" [24]. Such a combination often takes the form of undue focus being places on specific metrics, with little interest in underlying causes and dynamics. "Many studies involve ranking places on one or more criteria, and allocating policy benefits accordingly. At its crudest this applied geography merely provides a list of winner and losers with no understanding of why the differences occur" [63].

With regard to the second element a key aspect is that, as Scott notes, high-modernist ideology is not scientific practice exactly. Rather, it is a "faith that borrowed from the legitimacy of science and technology." In fact, it was more an aesthetic predilection than anything scientific. Furthermore, the underlying ideas were in fact quite sympathetic. "Doctors and public-health engineers who did possess new knowledge that could save millions of lives were often thwarted by popular prejudices and entrenched political interests" [24]. The dangers were when an authoritarian state adopted the aesthetic veilings of such ideas to justify actions, in the way that Social Darwinism used evolutionary theory to justify horrid actions. In this way "the classism and racism of elites are mathwashed, neutralized by technological mystification and data-based hocus-pocus." [161] This ideology could also be considered a "dangerous form of magical thinking [that] often accompanies new technological developments, a curious assurance that a revolution in our tools inevitably wipes the slate of the past clean" [161] (something that we are currently seeing repeated with discussions about Big Data and machine learning [168]).

The details lost in the necessary simplifications that the technocrat must make often turn out to not be so negligible after all. In the USSR, "a set of informal practices lying outside of the formal command economy - and often outside Soviet law as well - [arose] to circumvent some of the colossal waste and inefficiencies built into the system. Collectivized agriculture, in other words, never quite operated according to the hierarchical grid of production plans and procurements." [24] The technocratic leaders were often aware of this but so committed to their ideology that they had no alternative but to maintain a sort of pretense, which anthropologist Alexi Yurchak called 'hypernormalization' [169], that served to compound problems until the Soviet Union eventually collapsed. Such a phenomena is particularly visible in strictly planned capital cities that have, "as the inevitable accompaniment of [their] official structures, given rise to another, far more 'disorderly' and complex city *that makes the official city work* - that is virtually a condition of its existence" [24].

Even the 'successful' development projects often came at a high cost and raised the question of "successful for whom?" After all "Haussmann's Paris was, *for those who are not expelled*, a far healthier city" (emphasis mine) [24].

So, with all of this said, do we think that the field of planning still has a positive role to play in society? I will propose three arguments in favor of such an idea, none of which are wholly satisfactory, but together may amount to something credible.

First, we may attempt to avoid fulfilling the conditions proposed by Scott above. We may, for instance, refuse to do work in areas with authoritarian governments, though this would certainly neglect many in dire need. We may also reject the high modernist ideology in our planning. This is certainly easier, as I have been doing exactly that, but it should not be taken as trivial either. In many ways such an ideology is the default of the technologist, and it requires active self-reflection to avoid falling into that trap.

And the unfortunate matter is, even if we assume that Scott is correct in that his conditions are the necessary and sufficient conditions, what are they conditions for? "The *most tragic* episodes of state-initiated engineering" (emphasis mine) [24]. The egregiously racist influence that Robert Moses had the design of New York City [147] happened in at least somewhat democratic society, not an authoritarian one. While it did not directly lead to mass famine and death, it is hardly something that we would want to replicate. I daresay that we want to do more than avoid the most tragic outcomes and instead want to do active good. We must therefore look beyond merely avoiding Scott's conditions.

Second, we may argue that planning has simply "come a long way from focusing on single page map and a timescale of 20-30 years" [170]. It is certainly true that many of the tools have changed over the past few decades. Systems engineering, for instance, is a substantially different field than it was in the middle of the 20th century, as is discussed in Sections 2.1.7 and 2.2.1.3. Sachs meanwhile proposes that prescriptive economics should be modeled on clinical medicine and should not seek to attribute all negative outcomes to the same cause nor to prescribe the same solution to all problems, but instead to "make a differential diagnosis for the economic case at hand." He lays out several different conditions of poverty, for example, and proposes different solutions to each. Foreign aid is effective at treating the "poverty trap" condition (wherein "the country is too poor to make the basic investments it needs to escape from extreme material deprivation and get on the ladder of economic growth"), but less so for other conditions [20]. In this way, he seeks to distance himself from the high modernist ideology, with its affinity for singular, simple solutions, while still doubling down on the technocratic approach in general.

It should be noted, however, that Sachs has been a senior advisor to numerous states and the UN dating back to the mid 1980s and thus has had ample time to demonstrate his ideas. Nonetheless, many of the critiques referred to already were addressing this time period and some, such as Easterly [164], were specifically aimed at Sach's efforts, with some arguing that many of his projects left people worse off than before [171].

I do think that many of the methodological and technological changes over the past several decades are meaningful, but it also seems undeniable that these changes seem insufficient to ensure good outcomes. So we must look elsewhere for means of shoring up the deficiencies.

The third argument we may make that planning still has a positive role to play involves collaborative and participatory forms of planning, similarly to what was done for GIS DSSs in Section 2.1.5. After all even one of the proponents of high modernist ideology recognized that "rational, hierarchical, closed-door decision strategies" had negative consequences and that "more democratic process might produces worse results, but it would respond to the increasing sense of alienation among the nation's urban population" [4]. This avenue is not without its flaws, unfortunately. By providing tools for more participation, we are not necessarily changing anything fundamental. "Participation is not power; its reform is not radical" [172]. Even if participation is quite extensive and includes actual political power, "democracies rarely end up expropriating and redistributing capital" [173]. Thus even "inclusive planning practices cannot 'shift the effects of (post)colonial structures and relations of power on indigenous nations without a fundamental recognition of rights'" [166].

Not only is participation evidently insufficient on its own, but some argue that neoliberalism in factor prefers to use participation as a means of undermining resistance, rather than violence, though this has the risk of providing a structure for coalition building and radicalization [174]. This can occur even unintentionally, as "an inappropriate level of participation may disempower individuals... and it also can distract groups from a desired outcome" [100]. In fact, increased community involvement can result in more restrictive, unambitious goals that are not in the interests of certain minorities [175]. A key aspect of participatory planning is that mere participation does not magically eliminate power hierarchies. Such pre-existing hierarchies can wield their power in planning discussions in three primary ways: "by promoting formal decisions, setting the agenda, and influencing the broader ideological context of the debate" ([176] as paraphrased by [122]). Similarly, merely connecting individuals and enabling the sharing of information does not necessarily promote engaged political deliberation [177].

Despite this, there is evidence that, with proper creation of the structures of participation or in the wholesale rejection of the state-led participatory structures, that planning can be used to promote equity and development. Goodspeed points out several examples of how participatory and even insurgent scenario-based planning helped address injustices such as racism in urban development [122]. I discuss further evidence to this effect in Section 2.2.3.

To resolve this confusion, Arnstein rejects a the binary model of authoritarian vs participative and proposes an eight-step "ladder of civic participation," as seen in Figure 2-9 [178]. In this model, there are different degrees of participation, with direct citizen control at the top to manipulation of the public by central authorities through means only nominally "participative" at the bottom (and the omitted zeroth step of direct central authority with no pretense of participation). In this vein, Bekkers and Moody provide some examples of visualization and GIS use that, while presented as efforts to inform and enfranchise the public, made the citizenry feel manipulated [179].

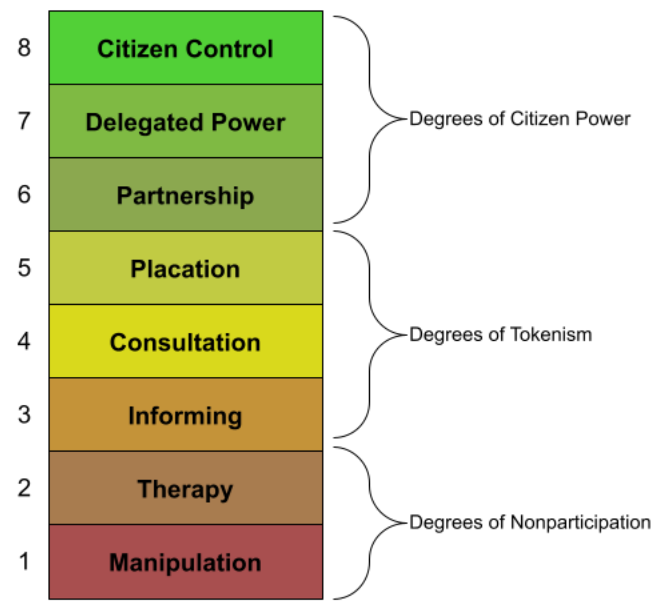


Figure 2-9: Arnstein's ladder of civic participation. Adapted from [178].

This suggests that, while technology-based collaborative or participatory planning efforts are unlikely to effect radical change, they can, *if done well*, still affect positive change. Gordon and Manosevitch, building upon Gastil, argue that two components are needed to have truly participative planning: an 'analytic process' for sharing and analyzing information and a 'social process' for providing for deliberative discussion [177].

In line with some of Easterly's arguments, Virginia Eubanks proposers two gut check questions to ensure that a planning tool avoids harmful consequences [161]:

1. Does the tool increase the self-determination and agency of the poor?
2. Would the tool be tolerated if it was targeted at non-poor people?

Jonathan Furner, meanwhile, proposes three strategies for developing such tools ([180] as paraphrased by [156]):

1. Admission on the part of designers that bias in classification schemes exists, and indeed is an inevitable result of the ways in which they are currently structured.
2. Recognition that adherence to a policy of neutrality will contribute little to eradication of that bias and indeed can only extend its life.
3. Construction, collection, and analysis of narrative expressions of the feelings, thoughts, and beliefs of classification-scheme users who identify with particularly racially-defined populations.

So, while I argue that a combination of new methodologies and technologies, collaborative and participatory design, and a general intellectual humility are sufficient to avoid the more harmful outcomes of the past (and present), Eubank's and Furner's points are worth keeping in mind as we continue.

2.2.1.3 Systems Engineering

So how does systems engineering relate to this discussion of technocratic planning? Well, systems engineering constituted one of the primary fields that technocrats drew upon, particularly in the 1950s-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 [181]. 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" [4]. 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 [4]. In 1970, NASA established the Urban Development Applications Project [182], followed by a New York City Applications Project in 1972, and an NSF Urban Technology System Experiment in 1973 [183]. Also in 1970, Jay Forrester published his seminal paper "Systems Analysis as a Tool for Urban Planning" [184] which in 1972 would be expanded upon with the World3 model used in the (in)famous book *The Limits to Growth* [185]. System dynamics, the modeling approach underlying both of these, would go on to have major impacts on business management, urban development, and environmentalism [186]. 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 [187]. Outside of the US, the London-based think-tank, Centre for Environmental Studies, was advocating for the use of multiscale and multidomain urban models as early as 1968 [188]. 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" [189, (p33)]. These applications were justified by several different rationale, chief among them were [4]:

- Computer simulations and related techniques were simply advances on the statistical models already widely used by the urban planning profession.
- 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.
- 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 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 [4]. 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" [190, (p159)]) 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." [190, (p161)] The USAC was shutdown in 1977 after significant criticism for spending large amounts of money on projects that failed to deliver [187]. NASA's efforts lasted somewhat longer, continuing to encourage the use of remote observation data by urban planners as late as 1980 [191, 192] before retreating from the urban development domain in the early 1980s largely due to a lack of interest from municipal governments and planners [4]. Perhaps the most ambitious application of systems engineering methodologies to economic development was the 1971-1973 Project Cybersyn, a distributed decision-support system based on an economic simulator and cybernetics intended to facilitate the management of Chile's national economy [193]. 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) [194].

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. [195]

> 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. [4]

This perception continues to the present day. Figure 2-10 situates systems engineering and analysis among other intellectual schools of urban planning. It is positioned on the far left of the figure, indicating 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" [189]. Marcuse, meanwhile, refers to systems engineering as primary concerned with efficiency and highly deferential to existing relations of power: "the technicist is inherently conservative: it is to serve an economic and social and political order in which its role is to make that order function smoothly." [172]. It is natural that the more authoritarian-minded decision-makers would thus find systems engineering of interest. It was not only in dictatorships that systems engineering found a planning home, however. Many of the examples cited above where within the United States. In keeping with Scott's theory of social engineering disasters, the democratic nature of the US kept these applications from becoming large scale tragedies, but this does not mean they were successes by any means either.

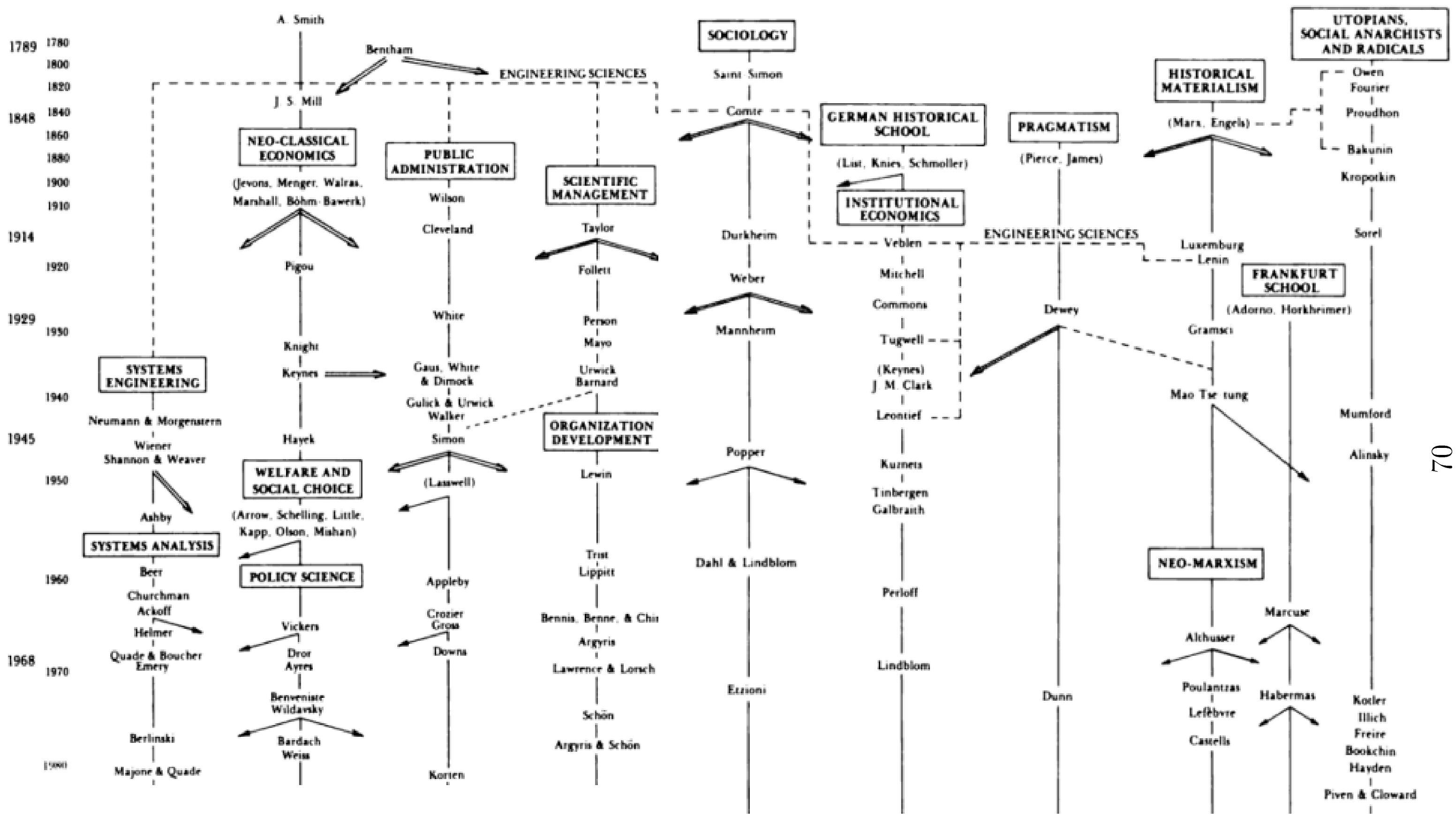


Figure 2-10: Timeline of intellectual influences on American planning theory. From [189]

This part of the history of systems engineering is largely missing in most discussions within the field. Most start in the early 1950s and acknowledge that the field truly hit its stride with the Space Race of the late 50s and 60s [196–199]. The official formation of a professional society, the INCOSE, would follow much later in the early 90s [200]. 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), etc.; 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) [201]. 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 11th, 2001 terrorist attacks [202]. 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 [203, 204]. A 2011 panel of senior practitioners in the field examined multiple aerospace failures from a systems engineering perspective [205].

These histories all omit the flawed use of systems engineering for urban planning during the middle of the 20th century. This gap, particularly striking when compared to the previously discussed histories of GIS and mapping, is highly concerning and lends weight to the critiques of systems engineering quoted above. To better respond to this, I conducted my own pair of reviews of the period, one systematic, focused on the systems engineering literature, and the other integrative, including sources from outside the systems engineering discipline. For full details on the methodology, see [206]. In this section, I present some of the results and discuss its relevance to the critique of technocracy and of systems engineering in particular.

Ultimately, across both the 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 2.3. 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.

Table 2.3: Identified Themes and Pitfalls from reviews, including the proportion of systematic and integrative review publications that contained each pitfall. From [206].

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%

P1: Data & Metrics and **P2: Theory & 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 system to optimize, rather than more critically considering the goals and design of the system as a whole [172, 189]. 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 [4]. 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" [207, (p174)]. **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?'" [181, (p34)] 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" [208, (p146-147)].

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 & 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 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 an 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 [209] 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" [207, (p174)]. 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." [210, (p1-3)] 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 [24]. This is of course closely connected to stakeholder considerations posed by the **T2** pitfalls.

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 [207]. The subsequent decades saw the fields of systems engineering and development planning grow largely independently of one another.

With regard to **P1: Data & Metrics**, numerous quantitative economic and social indices have been developed for the planning field [211–215] 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 [216, 217]. Digital models underlie the popular subdiscipline of scenario planning [122, 126]. Interdisciplinary, integrated models have even started to re-emerge [218–220].

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 [221]. In general, the belief that systems, even human systems, can be made simple, rational, and controllable (**P2: Theory & 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" [10, (p222)]. Complex systems, emergence, "ilities", systems-of-systems, and complex adaptive systems have all become popular fields of study within systems engineering [222–232], with numerous frameworks being proposed for how to classify and handle such systems [233–238]. 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 [138, 139] (which has many similarities to the aforementioned urban planning method called scenario planning) and fuzzy probabilistic programming [239, 240]. 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 [241].

Parallel to this, systems engineers have moved away from narrowly implementing the directives and priorities of an individual client (**P4: Singular Solution** & **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 [242], Stakeholder Value Network Analysis [243], and interviews of representatives from different stakeholder groups. This change in focus can also be seen in the rise of human-centered and user-centered design perspectives, which have spawned numerous specific methodologies and seen application in healthcare [244], Industry 5.0 [245], MBSE [246], and other fields [247].

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 multi-stakeholder negotiation and [132–134] tradespace visualization and exploration [132, 133, 135–137], 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 [248]. 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" [161, (p124)]. Systems engineering thus has potentially useful tools and perspectives to contribute to the such endeavors as collaborative planning theory [249] and participatory development [250].

With regards to **P6: Cost & Time**, significant infrastructure has been put in place to support the urban planning profession. Interactive DSSs abound [128, 251]. The use of GIS has become the norm [86, 93, 252], including more participatory variants [100]. 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) [253] and in general approaches such as MBSE [254]. 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 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 2.4. 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 [255], as well as in the rise of industrial ecology [256]. 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 [257, 258], metabolism [259], and scaling laws [260]. Some of this work is explicitly picking up avenues of research from the 1970s that were abandoned in the 1980s [259]. 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 dialogue 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?

Table 2.4: New Developments for the Identified Pitfalls. From [206].

Theme	Pitfall	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	[211–215]
	P2	Complex systems, biomimicry, emergence, systems-of-systems, complex adaptive systems, epoch-era analysis, fuzzy probabilistic programming, agent-based modeling	[122, 126, 138, 139, 216–232, 239, 240]
T2: Stakeholder & Contextual Consideration	**P3**	Stakeholder Value Network Analysis, qualitative interviews for use in requirement definition; general expansion of interdisciplinary teams	[243, 261]
	P4	Multi-attribute and multi-objective optimization methods; multi-stakeholder negotiation, tradespace visualization and exploration	[132–137]
	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	[242, 244–247, 249, 250]
	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	[128, 251, 253, 254]
T3: Lessons Learned	**P7**	Better histories of the field	
T4: Hype	**P8**		

I 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, fifty 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 multi-stakeholder 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 non-client 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" [262]. 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 [94, 99, 100, 250, 263]. 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 [67] (as discussed in Section 2.1.3). Systems engineering already has many of the tools for this, in the form of multi-stakeholder negotiation methods and tradespace exploration tools. These can be readily adapted to 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. [264, (p230)]

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." As should be obvious at this point, I 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.

2.2.2 Sustainable Development & the SDGs

[Note the unequal distribution of ecosystem services studies, both the full database and those of mangroves. Can cite the paper in progress]

"Substantive goals, the achievement of which are hard to measure, may be supplanted by thin, notional statistics - the number of villages formed, the number of acres plowed." [24]

"The pessimistic thought is that sustainable development has been stripped of its transformative power and reduced to its lowest common denominator. After all, if both the World Bank and radical ecologists now believe in sustainability, the concept can have no teeth: it is so malleable as to mean many things to many people without requiring commitment to any specific policies." [264]

"Yet there is also an optimistic interpretation of the broad embrace given sustainability: the idea has become hegemonic, an accepted meta-narrative, a given. It has shifted from being a variable to being the parameter of the debate, almost certain to be integrated into any future scenario of development." [264]

"To... critics, the prospect of integrating economic, environmental and equity interests will seem forced and artificial. States will require communities to prepare "Sustainable Development Master Plans," which will prove to be glib wish lists of goals and suspiciously vague implementation steps. To achieve consensus for the plan, language will be reduced to the lowest common denominator, and the pleasing plans will gather dust." (written in 1996, pre MDGs and SDGs) [264]

"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. Moreover, the idea of sustainability lends itself nicely to the meeting on common ground of competing value systems." [264]

Williamson and Connolly point out that "the term sustainability exists and operates within a number of governmental hegemonic discourses, i.e. the term itself is continually produced within legislative power structures," and argue that we should not "centre mapmaking praxis on generic or legislative definitions of sustainability, but rather encourages dialogue that supports the re-formation of self, community, and place." Importantly, they do not "seek to overturn generic understandings of sustainability, but rather seek a more complex understanding and proliferation of the term via local 'grounded' definitions. [112]

"That view is much too pessimistic... Investing in fairness may also be investing in efficiency, and... attention to sustainability can be more fair and more efficient at the same time." [20]

"MDG goal setting has energized civil society and helped to orient governments that otherwise might have neglected the challenges of extreme poverty... the MDGs have been important in encouraging governments, experts, and civil society to undertake the 'differential diagnoses' necessary to overcome remaining obstacles." [20]

Goals accomplish several things [20]:

- Global goals are critical for social mobilization and coordinated orientation.
- Global goals provide global peer pressure for adoption, monitoring, and action.
- Global goals mobilizing epistemic communities (experts, researchers, etc. These in turn can help map pathways to achieving the goals, making them seem more manageable and less remote.)
- Global goals mobilize stakeholder networks and thereby leverage capital and other resources.

Even Sachs, a booster of global goals like the MDGs and SDGs, admitted that the impact of the MDGs was uneven, with public health receiving the most attention, while sanitation and education were largely sidelined. [20]

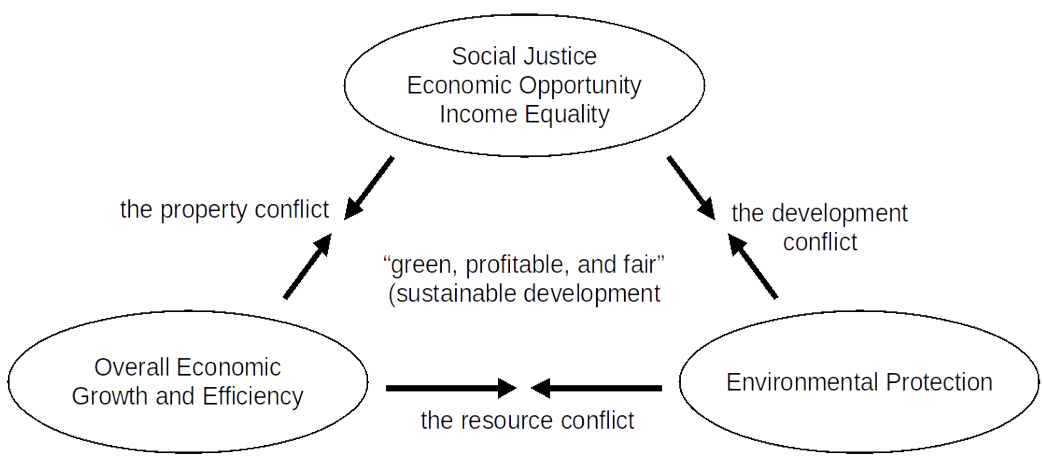


Figure 2-11: The triangle of conflicting goals of sustainable development. Adapted from [264]

Respond to critiques of MDGs/SDGs [265, 266]

Fukuda-Parr et al. argued that the primary strengths of the MDGs - " simplicity, mensurability, and concreteness - also proved to be sources of distortion." They also point to evidence that the MDGs did little to raise awareness and motivate action for neglected priorities, but instead merely provided metrics for already popular initiatives [267]. Those issues that did see awareness raised and resources provided produced "ambiguous impacts on complex social issues," particularly because some of the metrics were chosen for ease of implementation rather than importance.

2.2.3 Scenario Planning & Decision-Support is unfounded

As far back as the 1970s, there have been critiques of the use of complicated, multi-domain models to address multiple concerns at the same time. The models of this era were (rightfully) criticized for failing to provide accurate results, requiring too detailed data while outputting uselessly coarse data, mis-applying theory, being black boxes, and expense [207].

Refer to critique made by [207]

Refer to inaccuracies of the World3 model from the Club of Rome

Many projections have been bad (can also show de Neufville's oil prices projections)

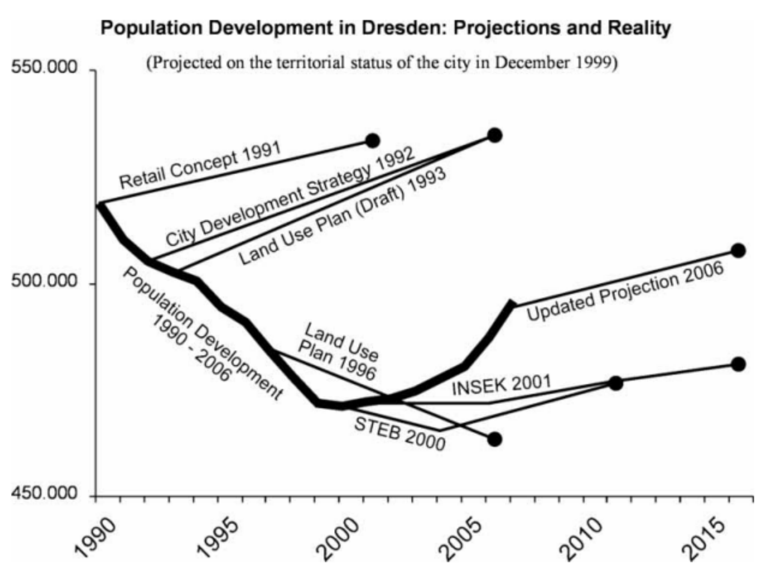


Figure 2-12: Population changes in Dresden compared to various projections. From [268]

Bankes argues that many of these problems can be avoided by clearly differentiating between *consolidative models* that strive to be "a surrogate for the actual system" but are often out of reach, and *exploratory models*, which seek to examine the implications of varying assumptions and hypotheses [269]. Exploratory models are possible to construct more often than consolidative models, as they function in the absence of complete information, but this is only true if they are intentionally constructed as exploratory models with a specific aim. To this end, Bankes defines three categories of purpose for an exploratory model: (1) data-driven, (2) question-driven, (3) model-driven. Most scenario planning, including the many of the historical examples that this work builds upon and the work described in this thesis are question-driven. For example, the 'What If?' tool from the late 1990s, explicitly "does not attempt to predict future conditions exactly. Instead it... can be used to determine *what* would happen *if* clearly defined policy choices are made and assumptions concerning the future prove to be correct" (emphasis original) [106].

Often, however, so-called "strategic planning" is anything but. "A strategic plan might more closely resemble a project plan, with long lists of specific proposals and policies... many have relatively short time frames. Scenario planning may not make sense for these plans." [122]

While forecasting can be problematic as it constitutes "someone else's understanding and judgment crystallized in a figure that then becomes a substitute for thinking," scenario planning instead allows users to "develop their own feel for the nature of the system, the forces at work within it, the uncertainties that underlies the alternative scenarios, and the concepts useful for interpreting key data." [270]

The evidence for such practices as scenario planning is decidedly mixed. Goodspeed's review of scenario planning use in urban planning and environmental research resulted in only modest benefits, with use in management being more unambiguously positive [122]. His own study of impact of a scenario planning project in Lockhart, Texas, which corrected some of the flaws he identified in many previous studies, confirmed that modest, but real positive changes are the result of scenario planning.

I readily acknowledge and embrace the fact that this work is predominantly a piece of design science, which aims to "design propositions, which inform specific practices, artifacts, or tools", rather than 'conventional' science, which "primarily aims to describe, explain, or predict the world but not to change it." [122]

In fact, there are significant reasons to avoid practicing "conventional science" in these domains as treating society as a laboratory can lead to significant harms and a "vivisectionist" mentality [271].

Evidence that collaboration improves DSS functionality and usability [110, 249, 263, 272]

"Dewey famously distinguishes between a *planned* society, which subordinates the present in pursuit of a rigid planned future, and a *planning* society, which is intellectually preoccupied by the future but knows that only the present - and not the future can be controlled." ([273] as paraphrased by [122]

Notably, one of the early successes at combining remote observation imagery with socioeconomic data, Land Use and Natural Resources Inventory (LUNR), elected in 1968 to not use the military-developed land use classification schemes, but instead to interview future users about their needs and to use the results from these interviews to develop a classification system tailored to the application.

Chapter 3

EVDT Framework

Computational models have been closely linked to the pursuit of sustainable development and with its definition, stemming from the World3 system dynamics model underlying the Club of Rome's *The Limits to Growth* report in 1972 [185].

"Sustainable Development involves not just one but four complex interacting systems. It deals with a global economy...; it focuses on social interactions...; it analyzes the changes in complex Earth systems...; and it studies the problems of governance". [20] [Compare this to the EVDT framework]

We are far from the first to argue that such integration is necessary, nor to recognize that it is easier said than done [220].

There have been many land use and transportation models. The open source UrbanSim, for example, combines land use, transportation, and certain environmental factors in a dynamic, area-based simulation system that, similar to EVDT, is a collection multiple models [251].

The agent-based Integrated Land Use, Transportation, Environment (ILUTE) model simulated the urban spatial form, demographics, travel behavior, and environmental impacts for the Toronto area [274].

Existing PSS have often been criticized for being lacking with regard to "visioning, storytelling sketching, and developing strategies," as well as being "too generic, too complex, inflexible, incompatible..., oriented towards technology rather than problems" [110]" This leads to what some have called the "implementation gap" of PSSs [275].

For the past couple of decades, there has been a recognition that DSSs and PSSs must include more than purely spatial analysis components [276].

The closest attempt to what we are proposing is probably that of Shahumyan and Moeckel, though their approach focused on linking together existing models in a loose manner using ArcGIS Model Builder, to avoid having to gain access to proprietary source code. While their example focused on combinging transportation, land use, mobile emissions, building emissions, and land cover, with only limited feedbacks, their approach could be extended to capture the full feedback loops proposed by EVDT. Their example is also proof that the kind of loose integration of library of models that EVDT envisions is possible [220].

Lauf et al. combined cellular automata with systems dynamics to capture both spatial dynamics and macroscale demand-supply dynamics in order to simulate residential development [217]

Pert et al. combined environmental and decision-making in a participatory model to improve conservation outcomes [250].

Miller argues that, despite the historical dificulties that integrated urban models have had, there is reason to be optimistic about the state of the art moving forward, particularly for integrating transportation and land-use models in particular [218]. <—important to discuss at more length

Is not itself a means of planning and implementing projects. It is not a full life-cycle tool such as Planning-Programming-Budgeting System (PPBS) [277]

Clifton et al. breaks down the various ways of modeling the urban form into five categories (though they do not assert that these are comprehensive or mutually exclusive), as seen in Table 3.1 [212]. While EVDT does not focus specifically on urban form, it is interested in these types of models, with the case studies presented in this work focusing on landscape ecology and community design in particular. One downside of examinations of urban form is that they tend to focus on areas and residences, while various forms of social exclusion are better measured by focusing on individuals instead [278].

The motivation for combining so many variables from different disciplines stems from both push and pull factors. The push factors are the simple increase in availability of data, as has already been described, along with the increase in the interoperability of the variables (which the work described in this thesis is trying to help contribute to). The primary pull factor is our increased understanding of - and appreciation for - the complex relationships between these domains, relationships that were previously ignored in analyses [279].

Position EVDT using the different dimensions of models proposed in [280]:

1. descriptive vs. analytic
2. holistic vs. partial
3. macro vs. micro
4. static vs. dynamic
5. deterministic vs. probabilistic

Table 3.1: Five categories of urban form models. Adapted from [212]

Perspective	Principal concern	Disciplinary Orientation	Scale	Nature of Data	Common Metrics
Landscape ecology	Environmental protection	Natural scientists	Regional	Land cover	Land cover change; Contagion
Economic structure	Economic efficiency	Economists	Metropolitan	Employment and population	Density gradient; Land value
Transportation planning	Accessibility	Transportation planners	Submetropolitan	Employment, population and transportation network	Expected travel time; capacity
Community design	Social welfare	Land-use planners	Neighborhood	Local GIS data	Proximity to needs; Zoning; Accessibility
Urban design	Aesthetics and walkability	Urban designers	Block face	Images, surveys, and audits	Lot size; Accessibility

6. simultaneous vs. sequential (directly calculate the output or go through intermediate phases)

Goodchild defines six different GIS data field model types and states that "no current GIS gives its users full access to all six":

1. Sample randomly located points (e.g. weather stations, light detection and ranging (LIDAR) data)
2. Sample randomly from a grid of regularly space points (e.g. many data validation studies
3. Divide the area into a grid in which each rectangular cell records the average, total, or dominant value; i.e. raster data (e.g. satellite imagery)
4. Divide the area into homogenous regions and record the average, total, or dominant value in each area (e.g. census data, soil maps)
5. Record the locations of lines of fixed values (e.g. contour or isopleth maps
6. Divide the area into irregular shaped triangles and assume the field varies linearly within each (e.g. some Digital Elevation Models (DEMs))

In the mid 90s, GIS had several limitations [81]:

- Two-dimensional, with some excursions into three
- Static, with some limited support for time dependence
- Limited capabilities for representing forms of interaction between objects
- A diverse and confusing set of data models
- Dominated by the map metaphor

To some extent, many of these issues, such as the lack of three dimensional systems, persisted well past the 90s [80].

Yamu et al. argue that urban modeling should treat the urban form as a complex adaptive system (CAS) and use fractal metrics to develop scenarios for planning purposes [255].

In order for cost-benefit analysis to maximize economic welfare, the following conditions must be met [281]:

1. Opportunity costs are borne by beneficiaries in such wise as to retain the initial income distribution
2. The initial income distribution is in some sense "best
3. The marginal social rates of transformation between any two commodities are everywhere equal to their corresponding rates of substitution except for the area(s) justifying the intervention in question

More details modeling, as well as breaking down specific costs and benefits (as opposed to converting them to monetary terms and summing them) and attributing them to specific goals, can circumvent these constraints, though at the cost of increased complexity [282].

The Law of requisite variety from the field of cybernetics says that the variety (the number of elements or states) of the control device must be at least equal to that of the disturbances [283]. Any development plan is going to fall far short of the variety expressed by human society and the natural environment. Planning efforts must then make reliance on the natural homeostasis behavior of such systems and of more flexible, ad hoc measures not specified in the plan in order to make up the difference in variety. [284]

3.1 The Framework

The EVDT Framework is process for developing a DSS for a sustainable development application. This processed is characterized by five basic elements:

1. The use of systems architecture & stakeholder analysis to identify needs, design the DSS, and understand the context through the use of the SAF. This requires significant engagement with as many of the stakeholders as is feasible (if not more).

2. Collaborative development of the DSS that continues that stakeholder engagement.

3. A concept of the sustainable development application as a complex SETS, typically involving the Environment, Human Vulnerability and Societal Impact, Human Behavior and Decision-Making, and Technology Design. This concept undergirds the DSS architecture and is critical as it provides the capability both for detailed technical analysis as well as feeding back into the design of data collection systems .

4. An interactive DSS. This can take the form of an in-browser page, a standalone application for a computer or phone, or even a tabletop exercise with paper documents.

5. A consideration towards modularity and re-use in future applications. This includes both technical components of the DSS product and broader capacity building in the community.

Each of these elements span the entire lifecycle of an EVDT project, but can still be usefully considered in the order listed.

3.1.1 System Architecture Framework

The first element of the EVDT Framework builds upon Maier's [12] and Crawley's [285] work to apply systems architecture to international collaborations [14] and sustainable development [286]. As defined by Maier, systems architecture the art and science of creating and building complex systems, and in particular that part of systems development most conerned with scoping, structuring, and certification [12]. This tends to refer to the high level form and function of a system, rather than detailed design. Other's, such as Crawley prefer to characterize it as the mapping of function to form such that the essential features of the system are represented. The intent of architecture is to reduce ambiguity, employ creativity, and manage complexity [13]. Arguably this is a more specific formulation of Maier's definition. In general, Space Enabled and I tend to use Crawley's definition, both due to its clarity, and for the various qualitative and quantitative methods that have been developed

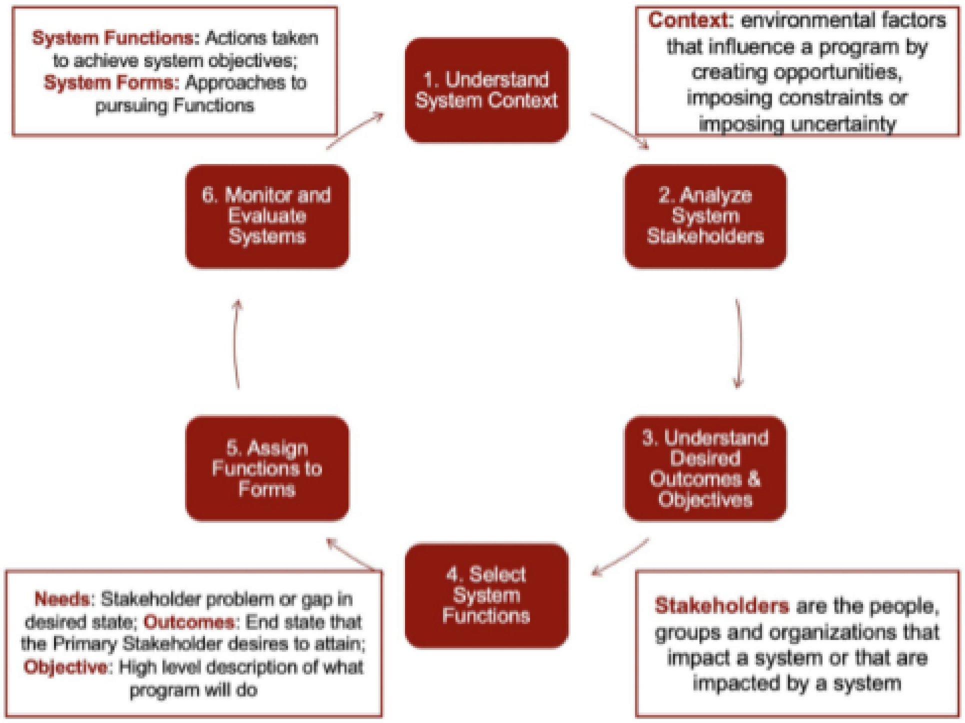


Figure 3-1: Six steps of SAF.

to work well with this formulation. The SAF, as adapted by Space Enabled and previous applied in sustainable development applications [286], involves six steps, shown in Figure 3-1. It seeks to center the full network of stakeholders and invite them into a collaborative development process. By stakeholders, I mean the people, organizations, and communities that either influence the design and operation of the system or are impacted by the system.

Each of these steps is amenable to, and arguably requires, collaborative participation from stakeholders, linking this methodology to PGIS. Such an approach means that the primary benefits of systems architecture (listed below) [285] do not just accrue to central authorities or technocrats, but are held by the community themselves.

1. Architecture is a way to understand complex systems.
2. Architecture is a way to design complex systems
3. Architecture is a way to design standards and protocols to guide the evolution of long-lived systems.

4. Architecture is a way to manage complex systems.

The stakeholders are involved in defining the system, understanding the System Context (the external factors that influence and constrain the system), identify System Objectives (the high level description of what the program will do), and develop the System Functions (the specific actions taken to achieve the objectives) and System Forms (the approaches and structures used to pursue the functions).

Notably unlike some forms of stakeholder analysis that primarily use stakeholder input to inform system requirements at the beginning of the development cycle, SAF seeks to involve the stakeholders in ongoing monitoring, evaluation, and participation. Multiple techniques are available for coordinating input and involvement from various stakeholders, with varying levels of detail, time requirements, and balance of quantitative versus qualitative information. Examples include multi-stakeholder tradespace exploration [133], multicriteria negotiations [248], and collaborative sketch planning [272].

3.1.2 Collaborative Development

Involving stakeholders in the development process, in addition to the requirements definition process, is key for ensuring adoption and capacity building. This has been recognized by the PGIS movement, which increasingly emphasizes the importance of open source software [112, 113]. It is also core to the Data Action framework which, responding to the idea that "data is never raw, it's collected," emphasizes the use of participatory and collaborative methods for collecting and using data [101]. Collaborative development is increasingly feasible as barriers have dropped over the past couple of decades. Knowledge and familiarity with computers and programs has expanded, access to sufficient hardware is increasingly common (particularly with the rise of cloud computing platforms), and both synchronous and asynchronous online collaboration tools have proliferated. Obviously such barriers have not been universally eliminated. Furthermore, even in the absence of barriers, not everyone desires to be a computer programmer, earth scientist, EO specialist, or social scientist, even part-time. Collaborative development must therefore take different forms in each project, being as welcome as possible to all while accommodating stakeholder preferences and constraints.

3.1.3 EVDT Questions & Models

The EVDT Framework conceptualizes the application system from two different perspectives. The first is the system boundaries and stakeholders perspective from

SAF shown in Figure 3-1. The second perspective focuses on combining the established fields of sociotechnical systems [33–35] and socio-environmental systems [36] into SETS. To accomplish this, at least four components are considered: the Environment (data including Landsat, Sentinel, VIIRs, in-situ environmental data and knowledge, etc.); Human Vulnerability and Societal Impact (data including census and survey-based demographic data, eocsystem services valuations, NASA's Socioeconomic Data and Applications Center, local knowledge of impacts, etc.); Human Behavior and Decision-Making (data including policy histories, mobility data, urban nightlight data, community input, etc.); and Technology Design for earth observation systems including satellites, airborne platforms and in-situ sensors (data including design parameter vectors for such systems). The data from each of these domains is used by established models in each domain, which are adapted to work in concert to address the needs identified during the stakeholder analysis. These four components, shown in Figure 3-2, seek to encapsulate the major interacting aspects of sustainable development and consider them from a SETS perspective.

We are far from the first to argue that such integration is necessary, nor to recognize that it is easier said than done. The closest attempt to what is proposed here is probably that of Shahumyan and Moeckel, though their approach focused on linking together existing models in a loose manner using ArcGIS Model Builder, to avoid having to gain access to proprietary source code. While their example focused on combining transportation, land use, mobile emissions, building emissions, and land cover, with only limited feedbacks, their approach could be extended to capture the full feedback loops proposed by EVDT. Their example is also proof that the kind of loose integration of library of models that EVDT envisions is possible [220].

The motivation for combining so many variables from different disciplines stems from both push and pull factors. The push factors are the simple increase in availability of data, along with the increase in the interoperability of the variables (which this work itself is trying to contribute to). The primary pull factor is our increased understanding of - and appreciation for - the complex relationships between these domains, relationships that were previously ignored in analyses [279].

This set of four models with the particular linkages shown in Figure 3-2 are not the only form that EVDT can take, merely the most general arrangement. Some applications may involve replacing a model with a human-in-the-loop (e.g. having the user themself substitute for the decision-making model) or omitting a model altogether. For other applications, it may make sense to conceptually break a model into two or more components. In the Vida project, it was considered worthwhile to separate the social impact model into two components, one focusing on public health (the obvious priority when dealing with COVID-19) and one focusing on non-health

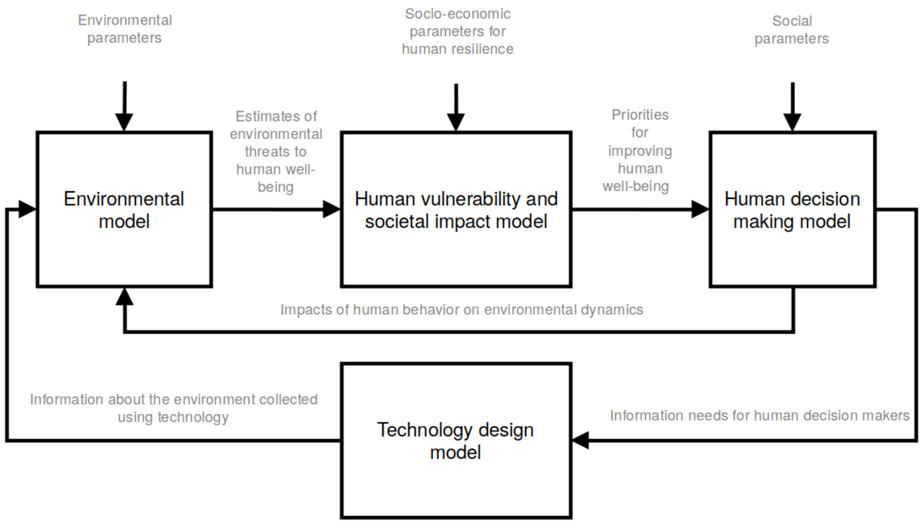


Figure 3-2: Generic version of the Environment - Vulnerability - Decision - Technology Model

metrics (such as income, employment, etc.). Such a separation can be useful if either significantly different modeling methodologies are going to be used or if the linkages with the other EVDT components are different from one another.

One way to determine the optimal arrangment of EVDT components is to consider what questions the user or researcher is seeking to answer with this application of EVDT. For instance, the default EVDT arrangement shown in Figure 3-2 was motivated primarily by the following four questions:

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?

Alternate questions may result in a different configuration or set of components (further discussion of this in Section 3.2). The point of EVDT is not to insist upon a particular set of linkages and feedbacks, but rather to encourage a consideration of such linkages between domains in general, and to consider them through a systems engineering perspective. Of course answering the structuring questions, and even phrasing them in the first place, requires the use of collaborations.

3.1.4 Interactive Decision Support System

A key aspect of the term DSS is the word "support." Crawley et al. state that the goal of a DSS is to "*enhance* the efficiency of decision makers by providing tools to quantitatively and qualitatively explore a space of alternatives for single or multiple decisions" [emphasis added] [13]. This means that the EVDT-developed DSS should not present decisions as a *fait accompli* but instead support stakeholders in developing their own solutions. Ideally this means that individual stakeholders can directly handle and explore any simulations or models used, along with their underlying assumptions and structure. If this is not feasible, an indirect form of interaction can be used, such as when a stakeholder provides verbal instruction to someone who then implements that instruction in the DSS. The latter option can be quite useful when there are barriers of language, familiarity, or technical knowledge, and is commonly used in purposeful gaming [287], wargaming [288–290], and role playing gaming [291, 292]. Additionally, in contrast to Crawley's definition which centers on the "efficiency of decision-makers," we argue that an ideal DSS should cause a decision-maker to consider multiple perspectives (such as the four models of EVDT and those of other stakeholders) and thereby make *better* decisions as well.

3.1.5 Re-use & Community Development

One of the key motivations of participatory, stakeholder-involved processes is capacity building. In the case of the EVDT Framework, this includes both capacity building in a specific application community and in the broader practitioner community of those using EO, GIS, and systems engineering for sustainable development. To that end, the DSS should be designed with re-use and modularity in mind. The ability to track mangrove health in Brazil [293] proved to be useful in a later application in Indonesia [294]. A key aspect of this is making as much of the DSS code available in open source repositories.

The second form of capacity building is pursued by developing a community of practice around EVDT and related endeavors.

3.2 Intended Applications & User Types

EVDT is not intended to be an exclusive project of Space Enabled. It also not intended to be a framework used by isolated individuals. We actively invite involvement from other systems engineers and those from other disciplines. Through this proposed thesis and other related projects, the framework will be refined, initial applications demonstrated, a basis of code built (already available online [295–297]), and a community of collaboration sprouted. These will can be built upon for building a community of practice, where individuals can contribute in a variety of ways, as shown in Figure 3-3.

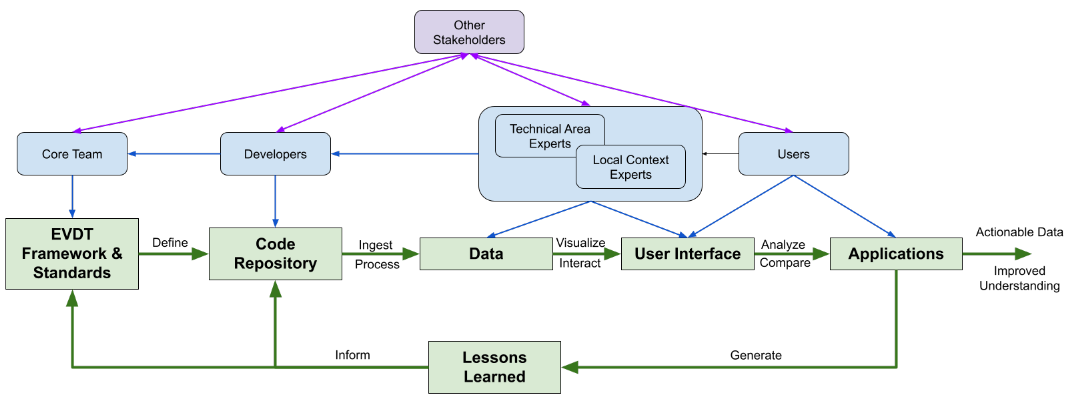


Figure 3-3: The EVDT development pipeline. Note that the different community groups, shown in blue, are not necessarily discrete and one individual could simultaneously participate in multiple.

It is worth further describing some of the categories of EVDT community members shown in the blue boxes of Figure 3-3. What follows will be a generalized discussion of these categories. Specific instances for this thesis are discussed in Chapters 4 and 5.

Moving from left to right, the *Core Team* refers to those directly involved in the development of the EVDT Framework. Right now this is essentially a set of researchers in Space Enabled and some close academic affiliates. This team is likely to remain predominently academic moving forward, though could transition to involving individuals or organizations from NGOs in the future. The members of this team will typically have expertise with sustainable development and DSSs, significant experience with EVDT, and investment in its success. Particularly once EVDT is more developed, this core team is likely to be formally defined.

The *Developers* includes all those who actively develop the models, user interfaces, visualizations, and other associated aspects of the DSS software for the various EVDT projects. These will typically be individuals with expertise in GIS, coding, and/or data processing. Thus they are likely to work in academia or as analysts in a government agency or NGO, though the project will be open source, membership in this category will not be formally defined and participation will be encouraged at any level of expertise or degree of involvement. Currently the Developer team is largely the same as the Core Team, though we have some developer involvement from other collaborators as well.

Technical Area Experts refers to experts in some relevant domain to an EVDT project but are consulted but not directly involved in the ongoing development of the EVDT Framework and code repository. This could include individuals such as ecosystem services economists, human mobility researchers, or fisheries experts. They will typically come from the ranks of academia, though it is not unreasonable to expect some number of government analysts or NGO researchers.

Local Context Experts refers to those who have a high level of knowledge of the SETS and stakeholders of a particular EVDT project. This could include a local community leader, an experienced activist, or a local government official. This category is grouped together with *Technical Area Experts* as the line between the two is oftentimes blurry. A local university researcher who studies the economics of informal housing and who specializes in the city involved with a particular EVDT project is arguably both a Technical Area Expert and a Local Context Expert.

Users refers to those who directly use the DSS software developed through an EVDT project. Exactly who these are will depend on the specific project and thus their level of experience with mapping, earth science, or development may vary significantly. They should be direct stakeholders in the specific EVDT project and have some involvement with the decision-making process (though not necessarily formal involvement).

It should also be emphasized that while Figure 3-3 is fairly linear, the EVDT Framework emphasizes collaborative development. One person may serve multiple roles in the pipeline and, even if not, stakeholders, including users, should be involved throughout the DSS development process.

As the number of applications increase and the code is refined, the various models used in the applications may themselves be the first members of an openly accessible library of models. Potential user groups could adapt and reuse EVDT components in other applications, without having to start from scratch. Initially this would likely still require significant code expertise, but it is entirely possible for functionality to be created to allow for ‘plug-and-play.’ A user may be able to, in browser or on desktop, select a geographic area of interest (e.g. the Sóc Trăng Province of Vietnam), select an environmental model (e.g. coastal forest health), a societal impact model (e.g. cyclone vulnerability), a decision-making model (land use conversion and conservation policy), and a technology model (satellite versus in-situ monitoring), all without writing a line of code (though perhaps being required to import new datasets themselves). Such functionality, along with the recruitment pipeline shown in Figure 3-3, help to expand participation in all aspects of EVDT. In this way the user base will be expanded beyond initially invested experts.

We are cognizant that making EVDT truly participatory is easier said than done, but we do believe it is a worthy goal. In addition to model interoperability standardization, the code moderators will need to specify accessibility norms as well, so as to ensure usability by individuals with a wide range of backgrounds. Existing prototypes have made some steps in this direction, by having multiple language options available. Thus far, this has been accomplished by existing language knowledge of code moderators as well as the occasional volunteer translator, but some more targeted efforts may be required in the future to specifically recruit translators for targeted languages.

Language is not the only accessibility barrier, however. Terminology, presentation, and interactiveness can also be differentiately accessible to different individuals, depending factors such as educational or cultural background. That said, these difficulties can be addressed via some of the same methods that are already core to the EVDT methodology: namely partnerships with local collaborators; stakeholder analysis; and iterative, participative design.

Another consideration in the future of EVDT are the types of applications that it will be used for. Some potential applications include:

1. To inform sustainable development policies. Ex) Comparing the impact of different conservation and zoning policies on the local environment and on economic outcomes.
2. To educate on the connections between the different EVDT domains. Ex) Demonstrating the local ecosystem services value of treecover in an urban environment.
3. To facilitate the comparison of different remote sensing data products for particular applications. Ex) Considering whether to commission periodic aerial surveys of an area or to rely on "free" civil satellite data, such as Landsat and Sentinel. .
4. To facilitate the exploration and evaluation of new sensing technology architectures for particular applications. Ex) Designing a new LIDAR satellite to

assist forest management in a particular region.

5. To facilitate scientific research on ecosystem services and/or the impacts of human behavior on the environment. Ex) Simulating different casual connections and comparing the simulated data with historical data, to assess the strength of those connections.
6. To provide a basis for studies of the effectiveness of different DSS attributes. Ex) Assessing visualization techniques, workshop formats, etc.

These applications are varying levels of interest and importance to different stakeholders, and some could potentially be viewed as competing for development resources and focus. In some cases they may rely upon different configurations of the EVDT components, as shown in Figure 3-4. For instance Items 3 and 4 (best served by configuration B of Figure 3-4) require a functional model of the relationships between different remote observation design parameters and performance parameters, along with a means of visualizing and exploring the tradespace (as has been proposed by Siddiqi et al. [298]). A user who is predominantly interested in Item 1 (configuration A) may find this functionality irrelevant or outright distracting.

On the other hand, some applications are more complementary. While the Item 1 is likely to be a government official or community member while the Item 6 user is likely to be an academic researcher, the findings from Item 6 would result in the design of EVDT being improved, so as better serve the needs of the Item 1 user.

Ideally, EVDT would be open to all these applications and more. In practice, care must be taken so that interests of one user group do not unintentionally dominate those of others or, worse, that the interests of the developers do not send them on a path counter to the interests of the users. This will thus require ongoing discussion and consideration with the EVDT community.

It should also be recognized that not all users will engage with the EVDT DSS software products directly or in the same way. As shown in Figure 3-3, some stakeholders and community members will participate in the SAF process, but may not directly interact with the EVDT software products themselves. This is both due to the fact that many people are unlikely to have the time or inclination to do so (understandably so) and due to various barriers that will doubtlessly remain despite the efforts of EVDT developers. Such barriers include access to the internet, computing power, and electricity. While all of these are becoming available to an increasing number of people globally, they are by no means ubiquitous. Initial prototypes have EVDT have pursued both offline, desktop version and online, browser-based versions to try and accomodate different levels of resource access. Such issues will need to be considered as part of future development decisions as well.

Finally, this envisioned development and expansion process is fundamentally a "snowball model." Existing team members collaborate with new partners and their communities. This results in additional team members who can then collaborate with others. EVDT may (and should aim) to one day be easily accessible even in the absence of connections to existing community members, but that is not in the immediate future.

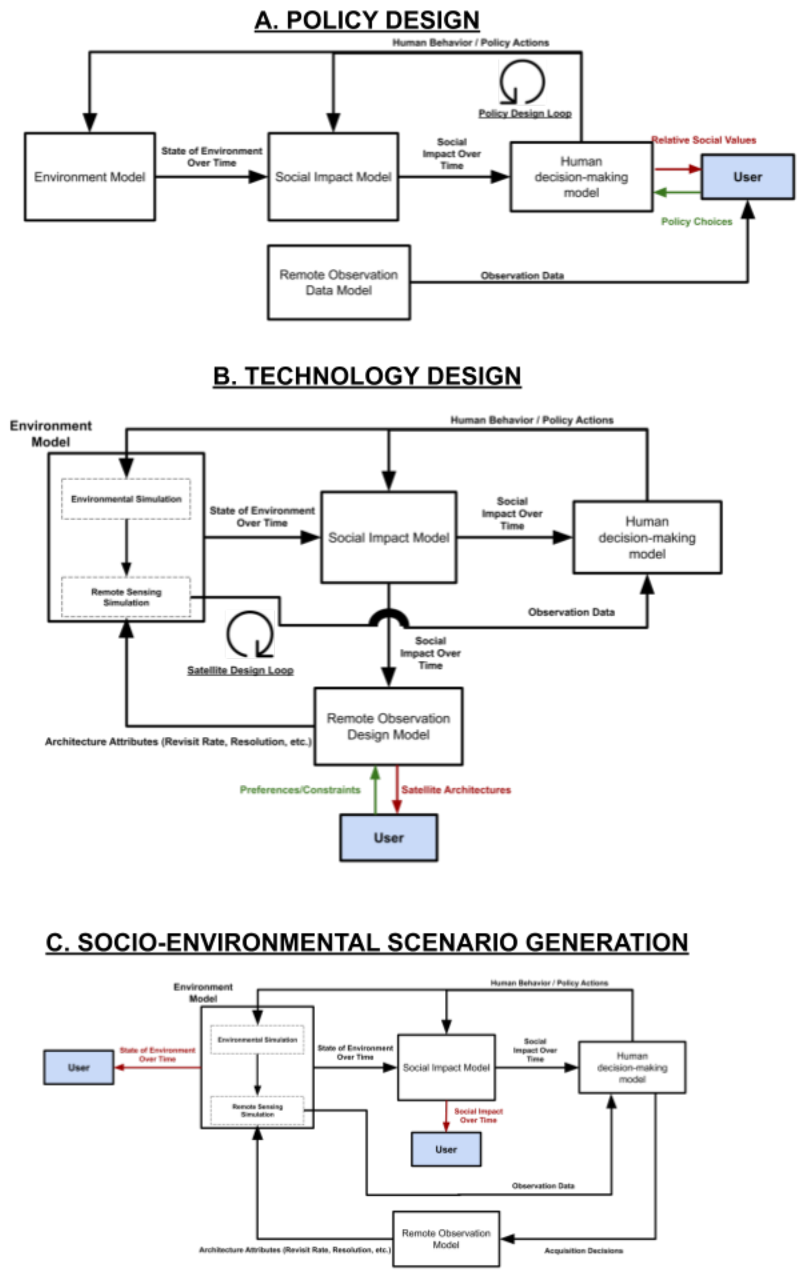


Figure 3-4: Three example EVDT research configurations

3.3 Novelty

It is important to establish what aspects of EVDT are novel and how this framework relates to the current state of practice.

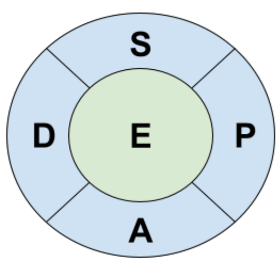
Computational models have long been closely linked to the pursuit of sustainable development and with its definition, stemming from the World3 system dynamics model underlying the Club of Rome's *The Limits to Growth* report in 1972 [185]. As was discussed in Section 2.1.7, the development field would largely come to repudiate such efforts in the mid-to-late 1970s, only to come back around to modeling on their own terms in the subsequent decades. Thus it cannot be said that EVDT is new in saying that modeling plays an important role in sustainable development.

Nor can it be said that EVDT is the first to advance the concept of multidisciplinary, integrated models in development applications. To refer to just a handful of examples:

- The open source UrbanSim combines land use, transportation, and certain environmental factors in a dynamic, area-based simulation system that, similar to EVDT, is a collection of multiple models [251].
- The agent-based ILUTE model simulated the urban spatial form, demographics, travel behavior, and environmental impacts for the Toronto area [274].
- The TripEnergy model combines an environmental submodel (transportation systems) and societal impact submodel (energy consumption and emissions of vehicles) [299]. It is then combined with a model of human decision-making to create Tripod, "a smartphone-based system to influence individual real-time travel decisions by offering information and incentives to optimize system-wide energy performance" [300].
- The closest attempt to what we are proposing here is probably that of Shahumyan and Moeckel, though their approach focused on linking together existing models in a loose manner using ArcGIS Model Builder, to avoid having to gain access to proprietary source code. While their example focused on combinging transportation, land use, mobile emissions, building emissions, and land cover, with only limited feedbacks, their approach could be extended to capture the full feedback loops proposed in EVDT. Their example is also proof that the kind of loose integration of library of models that EVDT envisions is possible [220].

In the field of earth science, integrated models have also become increasingly common. Originally developed for operational weather forecasting, Observing System Simulation Experiments (OSSEs) have found widespread use for designing earth observation systems at NASA and elsewhere [301], by linking models of environmental phenomena with simulations of observing platforms (both hypothetical and real). These models are rigorously validated [302] and are often custom-made for a particular mission. Significant progress has been made however by the Hydrological Sciences Laboratory and Earth Science Technology Office at NASA in developing the Land Information System (LIS), a more reusable and inter-operable modeling tool with numerous earth sciences applications (soil moisture, hydrology, meteorology, etc.) [303]. One of these uses is the easier development of OSSEs, as a means of facilitating technological development. Since the development of the LIS, the Hydrological Sciences Laboratory has worked to make the earth science models more accurate, utilize a broader range of computational methods, and standardize the validation and evaluation processes for OSSEs.

Systems engineering has also recently seen a handful of approaches proposed for use in sustainable development. In 2020, Honoré-Livermore et al. sought to address the SDGs in arctic coastal regions via an approach grounded in SES and the Stakeholders, Problem, Alternatives, Decision-making, Evaluation (SPADE) methodology [304]. The SPADE methodology was developed specifically for sustainable development applications. The five components of its name constitute five non-linear steps, each of which has various specific associated methodologies [305], as shown in Figure 3.



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 3-5: The Stakeholders-Problem-Alternatives-Decision-Making-Evaluation (SPADE) Methodology and associated methods. Adapted from Haskins, 2008 [305] as seen in [206].

Van Zyl and Root meanwhile used a transdisciplinary approach involving Wilbur's integral systems theory [306] and the Customers, Actors, Transformation process, Worldview, Owners, and Environmental constraints (CATWOE) framework from SSM [261] to design sustainable agricultural principles in New Zealand [307].

Other recent approaches focus on scenario planning and education for understanding evolution of the urban form [308], sustainable land-use planning that relies upon multilevel stakeholder partnerships [309], a synthesis of participatory planning with systems engineering for sustainable regional planning [310], and leveraging human-centered design to address the SDGs [311]. A survey of sustainable development applications of systems engineering can be found in Yang and Cormican, 2021 [312], which itself was published in a special issue of *Sustainability* dedicated to systems engineering [313].

Common across all of these methods are a significant consideration of a wide set of stakeholders and an adoption of different systems engineering techniques for integrating these stakeholder needs into the system design and development process.

All of this clearly demonstrates that I am far from the first to argue that such multidisciplinary integration is necessary, for the potential utility for systems engineering in sustainable development, nor to recognize that both are easier said than done [220]. What then, does the EVDT framework specifically have to offer?

First, there is the developmental process and theoretical underpinnings of EVDT: the combination of systems architecture (and other systems engineering techniques), GIS, collaborative planning, and remote observation. As was argued in Chapter 2, these fields each of complementary aspects that can be brought to bear in the development of future DSSs.

Second, there are distinct advantages to the development and codification of a concrete framework for such integrated modeling projects for sustainable development applications. Many of the above examples of integrated models were developed either without such a framework at all (a one off model intended to solve a particular problem or demonstrate a particular technique) or for a different class of applications (the OSSE framework is fundamentally about designing better EOSs for scientific purposes). Those few that have both a dedicated framework and a sustainable development focus (this includes SERVIR, FEWS NET, and various UN-affiliated programs such as the World Food Program) are intended for large governmental (often multi-nation and/or multi-agency) teams and typically are aimed at national or even multinational applications. There is a real need for a framework that is dedicated for sustainable development applications of small scales, accessible to relatively small teams for specific, targeted projects. The EVDT framework has the potential to fill that gap. Research Question 1 is aimed at developing the EVDT Framework in detail and identying these advantages. Research Question 2 is then aimed at demonstrating these advantages.

3.4 Development & Evaluation

3.5 Mapping and Visualization

"A single map is but one of an indefiniteliy large number of maps that might be produced for the same situation or from the same data." [314]

Data maps have a long history. Tufte dates them to the seventeenth century and cites Edmond Halley's 1686 chart of trade winds as "one of the first data maps" [315] though arguably Scheiner's 1626 sunspot visualization qualifies as a data map [159], as perhaps do Polynesian knot maps, which long predates either [CITE]. Graphing data over time, meanwhile dates by to the 14th century [159].

Choropleths are one of the more common types of non-imagery geospatial data that EVDT uses. These are maps that express "quantity in area" (i.e. some statistic tied to a particular geographic area with color, texture, or shading). It should be noted that choropleths have a few well-known limitations, including the ecological fallacy and the modifiable areal unit problem [214, 316]. It is for these reasons that EVDT does not rely entirely on choropleths and why we strive to store data with the finest geospatial resolution available.

Historically, GIS implementations have often struggled to handle temporal data [117].

Historically social indicators tended to be defined for city, province, or national areas, the MDGs and SDGs being the preeminent examples of the latter. Advances in GIS, however did enable the creation of more neighborhood level indicators starting in the late 1990s [214].

Sawicki and Flynn argue that one must specify the goals before specifying what indicators to use. From their list of possible aims, the following are the most relevant to EVDT [214]:

- Developing dynamic models of neighborhood change
- Evaluating the likely impact of existing and/or poposed policies on neighborhoods and/or their residents.
- Measuring inequality over space and time both within and between regions.

Initial versions of EVDT and Vida featured quite large graphics. Tufte argues that graphics in general should be significantle shrunk and that "many data graphics can be reduced in area to half their current published size with virtually not loss in legibility and information." [315] Inaccordance with this Shrink Principle, these graphics were greatly reduced in later versions.

As with most GIS software [78], early verions of EVDT were structured as entirely object-oriented, and later versions remained primarily object-oriented. This has many advantages but also comes at certain costs, the most important of which include (a) difficulty in recording continuous spatial variables and (b) a requirement to pre-identify the different classes (objects) to sort phenomena and relationships into [85].

It is recognized that this desktop version comes with numerous downsides. *theirwork*, an early collaborative, open source GIS platform, specifically "decided at an early stage to make the software Web-based to allow for a process of rapid development and iteration and allow a maximum number of potential participants." [112] It should be noted, however, that *theirwork* was a UK-based project (an area with high internet connectivity penetration) and started in the mid 2000's, a period with significantly diversity of internet browsing methods, which simplified the task of ensuring accessibility. Nonetheless, it is impossible to deny the collaboration and software sustainability benefits of an online platform, particularly in an age when many of the early concerns with the internet (low speeds, lack of knowledge about how to use it, etc.) [317] have been largly alleviated.

the meeting arrangment that EVDT supports, Table 3.2

Does EVDT aimed at *backward visualization*, which is aimed at assisting experts and professoinals, or *forward visualization*, which is aimed at a less informed audience [318].

While three dimensional data exists for both the urban environment [318] and from remote sensing (reference lidar), EVDT focuses primarily on two dimensional symbolic visualizations.

EVDT takes a somewhat Harleian approach to visualization, in which "*presentation* is de-emphasized in favor of *exploration* of data" [319].

Table 3.2: Different types of meeting arrangements. Adapted from [93]

	Same time	*Different time*
Same place	**Conventional Meeting** *Advantage:* • face-to-face expressions • immediate response *Disadvantage:* • scheduling is difficult	**Storyboard meeting** *Advantage:* • scheduling is easy • respond anytime • leave-behind note *Disadvantage:* • meeting takes longer • difficult to maintain in the long run
Different place	**Conference call meeting** *Advantage:* • no need to travel • immediate response *Disadvantage:* • limited personal perspective from participants • meeting protocols are difficult to interpret • difficult to maintain meeting dynamics	**Distributed meeting** *Advantage:* • scheduling is convenient • no need to travel • submit response anytime *Disadvantage:* • meeting takes longer • meeting dynamics are different from normal meeting ("netiquette" instead of face-to-face etiquette)

Chapter 4

Rio de Janeiro Mangroves

4.1 Study Area & Context

Guaratiba is a relatively rural district of Rio de Janeiro situated in the southwestern corner of the municipality. It is home to a mix of land uses, including decorative plant farming, multiple fishing communities, a military base and training center, a state-run biological reserve, some informal settlements, and a growing ecotourism industry. The biological reserve exists to protect the largest remaining mangrove forest within the municipality. These mangroves are vulnerable due to landward urbanization, including a recently opened urban transit line, and rising sea levels [320] They provide a variety of ecosystem services, including serving as a mechanism for highly efficient carbon sequestration, supporting a small-scale industry of fishing and crab catching, preventing coastal erosion, and attracting the aforementioned local ecotourism industry [321]. Government policies to conserve the mangroves can use integrated modeling tools to consider both the benefits of protecting the forests as well as the economic needs of low-income communities. This, coupled with the Rio de Janeiro municipal government's pre-existing interest in generating useful datasets and making them available online through the Data.Rio platform [322], made the Guaratiba mangroves a particularly suitable case study for the EVDT Modeling Framework.

Our primary Local Context Experts and points of contact are at the Pereira Passos Municipal Institute of Urbanism (IPP), which is the municipal data agency, and ESPAÇO, a research group at the Federal University of Rio de Janeiro (UFRJ) who study various coastal ecosystems in Brazil and elsewhere [323, 324] and who are also familiar with examining socioeconomic impacts of environmental phenomena [321]. The latter can also be considered to be Technical Area Experts. Other Local

Context Experts include a member of a local fisher association and government officials at the municipal urban development agency and the municipal environmental agency Additional Technical Area Experts include two ecosystem services economists (one from the University of West Virginia and one from RFF) and arguably the committee members for this thesis. The primary intended users for this case study are government officials at the IPP who have a fair amount of experience with mapping. Future projects in this area would ideally expand that userbase to non-government individuals.

This project began in 2018 and since that time Jack Reid made two multi-week field visits to Rio de Janeiro and Guaratiba in particular.

4.1.1 Stakeholders

a

4.2 Systems Architecture Framework

a

4.2.1 Interviews

a

4.2.2 Needs, Outcomes, and Objectives

a

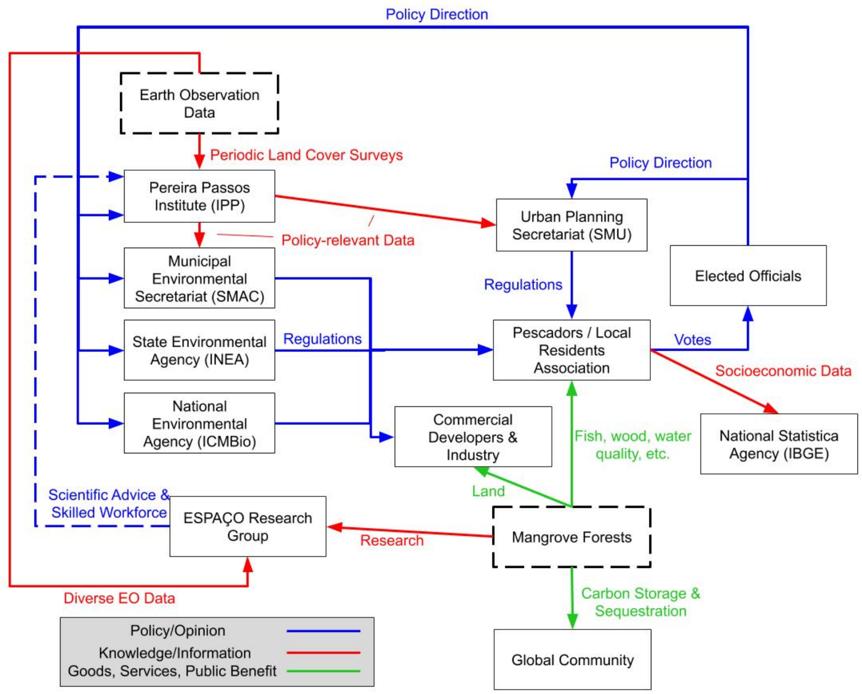


Figure 4-1: Stakeholder Map for the Mangrove Forests of Rio de Janeiro

4.2.3 System Architecture

4.3 EVDT Application

4.3.1 Environment:

4.3.2 Vulnerability

4.3.3 Decision-making

4.3.4 Technology

4.4 Decision Support System

4.5 Evaluation

4.6 Discussion

Chapter 5

Vida Decision Support System

5.1 Study Area & Context

As the coronavirus pandemic swept the globe, many of the local points of contact working with Space Enabled on EVDT and other projects had sudden changes in priorities. Several of them raised the possibility of adapting and expanding the EVDT Modeling Framework to approach coronavirus-related decision-making and impact analysis. This seemed relevant because, as others have noted, coronavirus impacts and response can be characterized as a complex system warranting a multi-domain, model-based approach [325]. The second case study will focus on this project, which ultimately became known as Vida and came to involve six metropolitan areas across Angola, Brazil, Chile, Indonesia, Mexico, and the United States. In each of these areas, Vida was (and is) developed in collaboration with local government officials, university researchers, and general community members.

Whereas the first case study focuses on simulating the changes in mangrove forest over decades, the focus of Vida is examining hourly to weekly air and water quality data alongside daily coronavirus epidemiological data and weekly quarantine policies. Government officials need actionable data to both address the ongoing public health crisis and to cope with the resultant socioeconomic and environmental consequences. Community members need to understand why their government is making the decisions that it is and understand the risks associated with their own actions. The Technical Area Experts on this project include researchers from Harvard Medical School. Meanwhile the Local Area Experts (many of whom are technical experts in their own right) include a mix of government officials and academic researchers, most of whome work in the public health and/or in GIS. The intended Users are those same individuals as well as the various public health agencies / task forces that they are affiliated with. In general, the concept is for our partner organizations to use EVDT to develop analyses and presentations that can inform pandemic response. The exact process by which this takes place varies from location to location.

5.1.1 Stakeholders

5.2 Systems Architecture Framework

5.2.1 Interviews

5.2.2 Needs, Outcomes, and Objectives

5.2.3 System Architecture

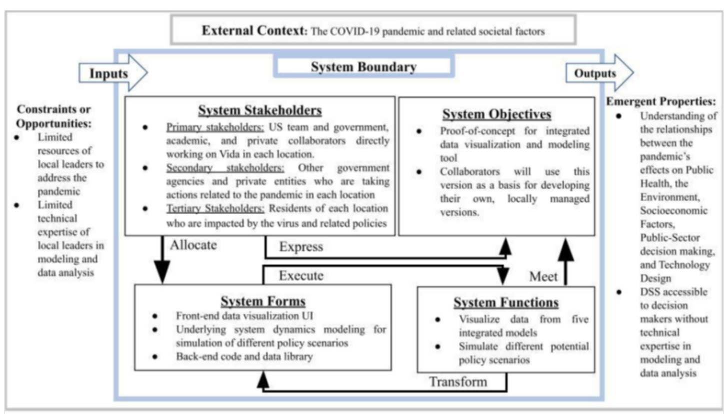


Figure 5-1: The high-level functional systems architecture of the Vida DSS.

5.3 Vida Variant of EVDT

5.3.1 Environment:

5.3.2 Public Health:

5.3.3 Vulnerability

5.3.4 Decision-making

5.3.5 Technology

5.4 Decision Support System

5.5 Evaluation

5.6 Discussion

Chapter 6

Discussion

6.1 Lessons Learned

6.2 The Future of EVDT

Chapter 7

Conclusion

7.1 Research Questions

Appendix A

Glossary

Language in general and technical jargon (of which this glossary qualifies) in particular is intended to communicate. This requires that both the speaker and the listener have some common understanding of the terms used. For this reason, I rarely find it helpful to generate new definitions for commonly used words, except to clarify when there is some significant discrepancies in how the term is commonly used. It is generally preferable to coin a new term if a new meaning is required (see, for instance Myoa Bailey's coining of the term *misogynoir* [326] or the significantly less elegant socio-environmental-technical system in this document).

Availability/Accessibility:

Context:

Critical Remote Sensing:

Decision Support System (DSS): A technical system aimed at facilitating and improving decision-making. Functions can include visualization of data, analysis of past data, simulations of future outcomes, and comparisons of options.

earth observation (EO):

Ecosystem Services:

Environment, Vulnerability, Decision-Making, Technology (EVDT): A four-part modeling framework created by Space Enabled for use in SETSs and sustainable development applications [6]. For more detail, including diagrams, see Chapter 3.

Form:

Function:

geographic information system (GIS): Any digital system for storing, visualizing, and analyzing geospatial data, that is data that has some geographic component. The term can also be used to discuss specific systems, a method that uses such systems, a field of studying focusing on or involving such systems, or even the set of institutions and social practices that make use of such a system [74]. For more discussion of this definition, see Section 2.1.4.

Multidisciplinary Optimization: A methodology for the design of systems in which strong interaction between disciplines motivates designers to simultaneously manipulate variables in several disciplines [327].

Multi-Stakeholder Decision-Making: Any decision-making process in which more than one stakeholder must collaborate to reach a decision [133]. This can take a variety of forms, including cooperation, negotiation, voting, or consultation [328].

Objective:

Observing System Simulation Experiment (OSSE): A method of investigating the potential impacts of prospective observing systems through the generation of simulated observations that are then ingested into a data assimilation system and compared to other real-world data or other simulated data. Most commonly used for remote observation satellite design for purposes of meteorology [301] .

participatory geographic information system (PGIS): A subset of GIS that seeks to directly involve the public and other stakeholders, including government officials, NGOs, private corporations, etc [100]. It should be noted that these means involvement in both the production of data and in its application, not merely one or the other [94, 104]. This is to be contrasted with the older term, PPGIS, which focuses specifically on the involvement of the public and not that of government agencies or other organizations [100]. For more discussion of this and related terms, see Section 2.1.5.

Planning: "the premeditation of action, in contrast to management [which is] the direct control of action" [117]. In general, planning tends to concern itself with more long-term affairs that management does, during which it strives for the "avoidance of unintended consequences while pursuing intended goals." Models, and their specific implementations as decision/planning support tools, are one means of achieving this. The term is often prefaced with 'urban' or 'regional' to indicate the specific spatial scale under consideration.

Planning Support System (PSS): A type of DSS specifically designed to support urban or regional planning efforts. These often involve longer time scales and more general/strategic decisions than most DSSs. In general, this work will use the more general term, DSS, and will only use PSS when referring to the literature.

Remote Observation: Any form of data collection that takes place at some remote distance from the subject matter [2]. While there is no specific distance determining whether a collector is 'remote,' in practice this tends to mean some distance of more than a quarter of a kilometer. Handheld infrared measurement devices are thus usually excluded (and thereby classified as *in-situ* observations. Aerial and satellite imagery are definitively in the remote observation category. Low altitude drone imagery, particularly when the operator is standing in the field of view, is a gray area that is not well categorized at this time.

Remote Sensing: See *remote observation.*

Scenario Planning: A particular form of planning that focuses on long-term strategic decisions through the representation of multiple, plausible futures of a system of interest [122]. These futures are often generated by models such as EVDT.

Sustainable Development: The integration of three separate, previously separate fields: economic development, social development and environmental protection [19]. For a more detailed discussion of the history of this term, see Section 2.1.2.1.

Socio-environmental System: The complex phenomena that occurs due to the interactions of human and natural systems [36].

Sociotechnical System: Technical works involving significant social participation, interests, and concerns [12].

Socio-environmental-technical System: A system in which social, environmental, and technical subsystems are linked together in such a way that none can be neglected without compromising the modeling, planning, or forecasting objectives at hand. This can be seen as the combination of the terms sociotechnical system and socio-environmental system. Note the particular emphasis on the needs of the observer, not the inherent system itself, as virtually all systems on Earth can be viewed as socio-environmental-technical Systems.

Stakeholder:

Stakeholder Analysis: Identifying, mapping, and analyzing the stakeholders in a system and their connections to one another in order to inform the design of the system. This involves both qualitative and quantitative tools, such as the Stakeholder Requirements Definition Process [242] and Stakeholder Value Network Analysis [243]. It should be noted that this term is commonly used by systems engineers but is not clearly defined as some specific list of methods. In a Space Enabled context, it commonly refers to the coding of qualitative interviews with stakeholders to elicit such items as needs, desired outcomes, and objectives. These are then often analyzed in some other method, such as Stakeholder Value Network Analysis.

Systems Architecture/Architeting: As defined by Maier, the art and science of creating and building complex systems. That part of systems development most concerned with scoping, structuring, and certification [12]. This tends to refer to the high level form and function of a system, rather than detailed design. Other's, such as Crawley prefer to characterize it as the mapping of function to form such that the essential features of the system are represented. The intent of architecture is to reduce ambiguity, employ creativity, and manage complexity [13]. Arguably this is a more specific formulation of Maier's definition. In general, Space Enabled and I tend to use Crawley's definition, both due to its clarity, and for the various qualitative and quantitative methods that have been developed to work well with this formulation.

Systems Engineering: An interdisciplinary approach and means to enable the realization of successful systems. It focuses on holistically and concurrently understanding stakeholder needs; exploring opportunities; documenting requirements; and synthesizing, verifying, validating, and evolving solutions while considering the complete problem, from system concept exploration through system disposal [130]. For a more detailed discussion of this definition, including its flaws, see Section 2.1.7.

Tradespace: The space spanned by the completely enumerated design variables, i.e. the set of possible design options [329].

Tradespace Exploration: A process by which various options with a tradespace may be examined and compared in the absence of a single utility function, such as when multiple stakeholders are involved or multiple contexts with no clear priority exist [329].

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