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

by

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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.

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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 is complete and I have nothing more to add until/unless I receive comments from the reviewers. Blue indicates a complete, coherent draft, but I still have some thoughts on how to improve it / concrete to-do's. 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

AGB	above ground biomass
AIAA	American Institute of Aeronautics and Astronautics
ALOS	Advanced Land Observation Satellite
APA	Área de Proteção
AVL	American visceral leishmaniasis
CATWOE	Customers, Actors, Transformation process, Worldview, Owners, and Environmental constraints
CBERS	China-Brazil Earth Resources Satellite Program
CEOS	Committee on Earth Observation Satellites
CTEx	Centro Tecnológico do Exército
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
ESVD	Ecosystem Services Valuation Database
ETM+	Enhanced Thematic Mapper Plus
EVDT	Environment, Vulnerability, Decision-Making, Technology
FEMA	Federal Emergency Management Agency
FEWS NET	Famine Early Warning Systems Network
GCVI	Green chlorophyll Vegetation Index
GEE	Google Earth Engine
GEO	Group of Earth Observations
GEOSS	Global Earth Observation System of Systems
GIS	geographic information system
GISc	geographic information science
GLAS	Geoscience Laser Altimeter System

GMW	Global Mangrove Watch
GPM	Global Precipitation Measurement
GKA	Green Keeper Africa
ibase	Instituto Brasileiro de Análises Sociais e Econômicas
IBGE	Brazilian Institute of Geography and Statistics
ICESat	Ice, Cloud, and land Elevation Satellite
ICESat-2	Ice, Cloud, and land Elevation Satellite 2
ICMBio	Instituto Chico Mendes de Conservação da Biodiversidade
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ILUTE	Integrated Land Use, Transportation, Environment
INCOSE	International Council on Systems Engineering
INEA	Instituto Estadual do Ambiente
IPCC	Intergovernmental Panel on Climate Change
IPM	Multidimensional Poverty Index
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
MCMV	Minha Casa Minha Vida
MBSE	Model-Based Systems Engineering
MIT	Massachusetts Institute of Technology
MDG	Millenium Development Goal
MNDWI	Modified Normalized Difference Water Index
MODIS	Moderate Resolution Imaging Spectroradiometer
MSI	Multi-Spectral Instrument
MST	Movimento dos Trabalhadores Rurais Sem Terra
NASA	National Aeronautics and Space Administration
NDMI	Normalized Difference Mangrove Index
NDVI	normalized difference vegetation index
NGO	non-governmental organization
NIR	near infrared
NOAA	National Oceanic and Atmospheric Administration
NYCRI	New York City-RAND Institute
OLI	Operational Land Imager
OPM	Object Process Methodology

OSTP	Office of Science and Technology Policy
OSSE	Observing System Simulation Experiment
OTA	Office of Technology Assessment
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PGIS	participatory geographic information system
PPGIS	public participation geographic information system
PSS	Planning Support System
RA	Regiões Administrativas
RBAG	Reserva Biológica Estadual de Guaratiba
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
SIR	Susceptible-Infected-Recovered
SMAC	Secretaria Municipal de Meio Ambiente
SMU	Secretaria Municipal de Urbanismo
SoS	System of Systems
SPADE	Stakeholders, Problem, Alternatives, Decision-making, Evaluation
SR	Simple Ratio
SRTM	Shuttle Radar Topography Mission
SSM	soft systems methodology
STS	Sociotechnical system
TDRSS	Tracking and Data Relay Satellite System
TM	Thematic Mapper
UFRJ	Federal University of Rio de Janeiro
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNCSD	United Nations Conference on Sustainable Development
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
WHO	World Health Organization

e

Chapter 1

Introduction

1.1 Research Problems, Questions, & Contributions

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]. The diversity of designing, launching, and operating organizations has also expanded. EOSs are no longer the sole province of the militaries and space agencies of a handful of nations. Private companies, universities, and new space nations have all joined the field [cite]. These trends have occurred as part of broader technological and societal trends of increasing data availability, computational power, modeling ability, and technical knowledge.

This is remarkable because, despite some efforts in previous decades [4], 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.

The proliferation of EO (and other) data, and in particular the improvements in spatial and temporal resolution, have opened the door for new kinds of applications. Among these are those at smaller spatial scales and shorter durations. Where historical civilian applications focused on how the environments of nations or continents changed over the course of years or decades, we can increasingly ask questions of on a much more human scale: neighborhoods, towns, and even individual buildings. Obviously new methods must be developed for such applications. Models that work well on a global scale often do not function at the scale of a few blocks. The our understanding of context and our ethical framework must also adapt. No longer are we asking questions about "agriculture in Canada" or "the Brazilian Amazon." We are now asking questions about particular farms, ranches, homes, and communities. The residents of this places should have not just a say, but significant involvement in how this data is used to impact their lives. This moves us from the fields that have traditionally dominated EO (earth science, aerospace engineering, physics, etc.) to those that specialize in operating at such scales (urban planning, anthropology, community organizing, etc.). This poses a problem, as most of those who seek to apply EO data in these new domains come from the former background, not the latter. They may not understand the expertise, history, and ethics needed to operate on these scales and may seek to continue to apply their traditional techniques. This risks not just failing in their own eyes, but also inflicting collateral damage on the communities that they are seeking to help.

Along with this increase in supply of data and analysis capabilities, there has been a corresponding increase in demand, particularly for sustainable development applications. Where previously the fields of environmental conservation and human welfare / economic development were handled largely separately, sustainable development treats this domains as jointly bound in complex systems. As we face such pressures as climate change, natural resource depletion, and the limitations (and sometimes the outright failures) of earlier international development efforts, there is a real need for:

a Developing models that can be used at smaller geographic and temporal scales. This includes making remote observation data not just available but accessible to a broader audience by developing data products that are relevant to everyday individuals.

b Bridging the traditional EO fields with the traditional community planning and social fields. This will enable linking the EO-supported environmental modeling with the societal impact of a changing environment as well as more direct monitoring of human society with EO data.

c Building or adapting frameworks that community participation and collaboration in the use of EO data. This includes putting policy and sensor design decision-making in the hands of a broader population.

This work aims to demonstrate the viability of a particular methodology for advancing towards each of these three goals. 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 Environment, Vulnerability, Decision-Making, Technology (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 lettered **Research 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 avoid the technocratic excesses of the past?
   - *a* A critical analysis of systems engineering, GIS, and the other fields relied upon in this work [Chapter 2]
   - *b* A proposed framework for applying systems engineering for sustainable development in an participatory and social-justice-oriented 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.

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.

1.2 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, as 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 or leader 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, showing that even a statistics-driven urban planner could, *in contradiction to his own statistics*, let his prejudices determine his perspective of the North End of Boston. *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.

By speaking with different members of a community and striving to maintain an open mind about the communities that we work with, we can hope to avoid making a similar mistake.

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. This work focuses primarily on earth observation. By "advance justice in Earth's complex systems," we mean a combination of social justice (e.g. antiracism and anticolonialism) and sustainable development[1]. We typically view these as being closely linked but various projects may focus on one more than the other. This work focuses primarily on sustainable development, though the framework detailed here has been used for social justice-oriented work as well [11].

Fulfilling the mission of Space Enabled is not just an issue of research topics but also of methodology, as "the master's tools will never dismantle the master's house" [12]. 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 2.3), 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] 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 2.2.2.1.

1.4 Methodology Summary & Structure of Thesis

The structure of this thesis, along with the connections of each component to the Research Deliverables (RDs), is summarized in Figure 1-1 below.

Chapter 2 presents the theoretical underpinnings of this work, motivation for its pursuit, and various critical analysis based on literature reviews. The last of these will constitute Research Deliverable 1a and are primarily contained in Section 2.3 but are reliant upon the earlier sections. This will serve to expand upon the research problems introduced in Section 1.1 and justify the novelty of the research contributions in the subsequent chapters.

Chapter 3 provides details on the EVDT Framework, its intended applications, and its novelty. This constitutes Deliverable 1b.

Chapters 4 and 5 contain the primary experimental components of this work in response to Research Question 2. This takes the form of 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 [Chapter 4]; and (2) coronavirus response in six metropolitan areas across Angola, Brazil, Chile, Indonesia, Mexico, and the United States [Chapter 5]. In both cases, the methodology involves the application the Systems Architecture Framework (SAF) [13, 14] an approach that has been previously adapted from the aerospace engineering discipline by Prof. Wood for use in sociotechnical systems [15]. 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.

Chapter 6 contains discussion on both applications and lessons learned. This will serve 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.

Chapter 7 provides a short conclusion summarizing this thesis.

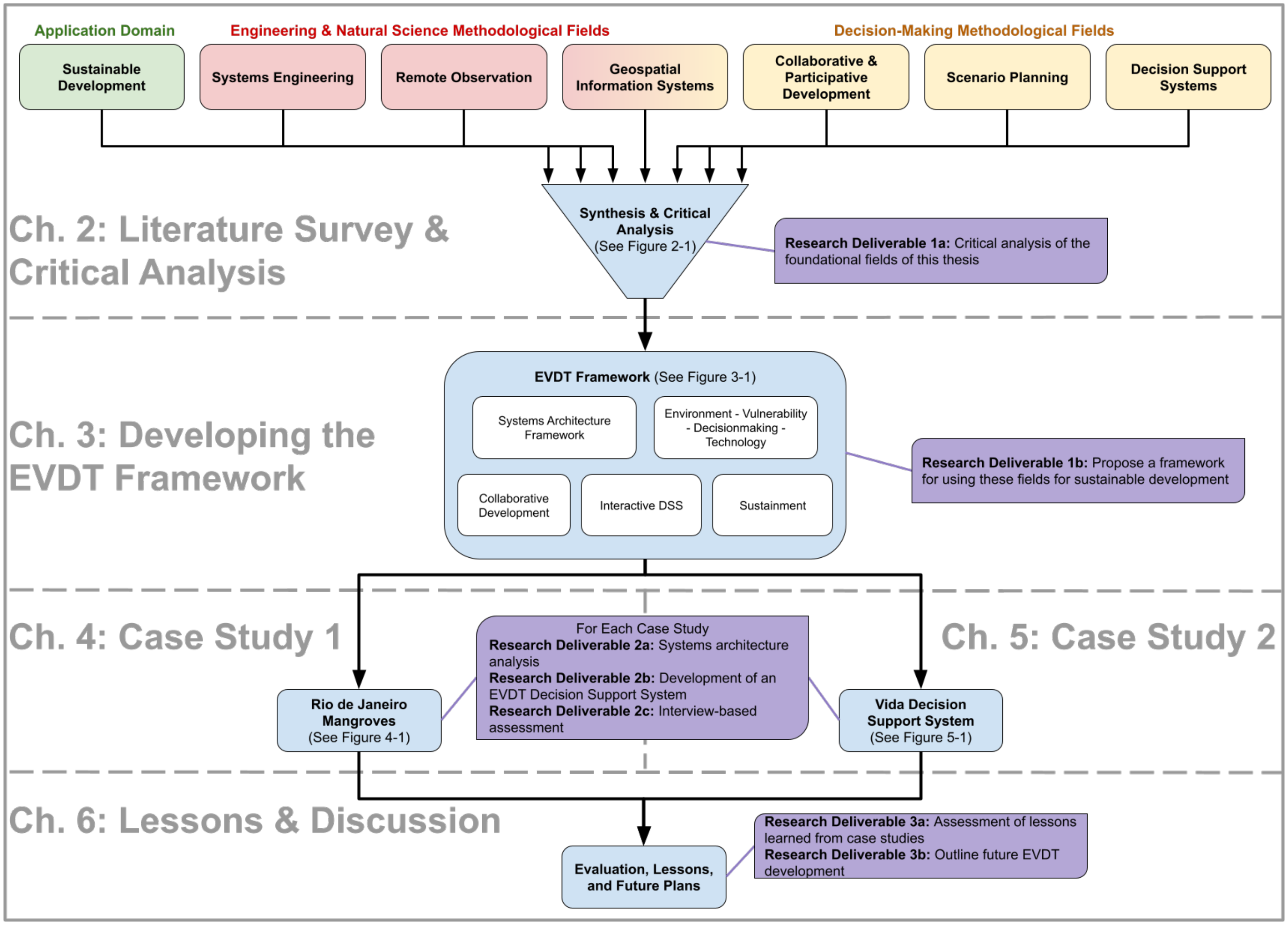


Figure 1-1: Thesis Structure

1.5 How Different Audiences Should Read This Thesis

[** revisit this section once the thesis is mostly complete]

There are several potential audiences for this work, even if the audience is restricted to future Space Enabled students. Some may primarily be interested in how work with a partner community on a sustainable development project. Others may be specifically interested in the analysis of EO data or even some specific type of analysis (such as of mangroves). As was discussed earlier in this chapter, while this thesis is heavily dependent on several different fields, it is primarily interested in explaining and demonstrating the EVDT framework. Those interested in some other topic may find large portions of this work irrelevant. The following paragraphs provide guides to several such potential kinds of readers.

For those primarily interested in sustainable development, I point you to Section 2.2.2 (history and context), Sections 2.3.1.2 and 2.3.2 (critiques of common approaches to sustainable development), and the bulk of Chapters 3 and 4 (which layout of the EVDT framework and demonstrate a sustainable development application). The other case study, Chapter 5, primarily deals with pandemic response and thus may be of less interest.

For those primarily interested in applied modeling or what has sometimes been called "Earth system solutions" [16], I point you to Sections 2.2.5, 2.2.6, 2.2.7 (history); Sections 2.3.1.3 and 2.3.3 (critiques of common methods of applied modeling); and the bulk of Chapters 3, 4, and 5 (for the framework and its applications).

For those primarily interested in the natural environment and the application of earth observation systems, I point you to Sections 2.2.2 and 2.2.4 (history); Sections 4.2.2.1.3, 4.3.1.1, and 4.3.2.1 (mangroves in Brazil); and Sections [** add relevant sections of Chapter 5].

For those primarily interested in systems engineering, I point you Section 2.2.3 (history), Section 2.3.1.3 (critique of systems engineering applied to development and planning), 3.4.2 (the systems engineering core of the EVDT Framework, and [** any other relevant sections in the back half of the thesis].

For those primarily interested in earth observation *systems* in terms of history, design, and deployment, I point you to Sections 2.2.4 and 2.2.5 (history), Sections 2.3.1 and 2.3.1.1 (critique of traditional design process), Section 3.5 and Section 6.2 (relevance of EVDT to EOS design). The last of these in particular discusses how future work could leverage EVDT for the design of EOSs.

Chapter 2

Motivation, Theory, Critical Analysis, & Novelty

2.1 Chapter Purpose & Structure

This chapter aims to advance Research Question 1:

> 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 avoid the technocratic excesses of the past?

It accomplishes this by supplying Research Deliverable 1a: “A critical analysis of systems engineering, geographic information system (GIS), and the other fields relied upon in this work." This chapter thus serves both as a survey of the relevant literature to the construction of the Environment, Vulnerability, Decision-Making, Technology (EVDT) framework (which is itself laid out in Chapter 3) and as a critical analysis of some of that literature.

The first portion of this chapter, Section 2.2, seeks to expand upon the research problems and questions laid out in Section 1.1. It lays out the motivation and theoretical underpinnings of this work. It can thus be understood as an attempted answer of the simultaneously singular and multifaceted question: “Why?" Specific topics are organized in order of application domain (sustainable development) → methodological fields grounded in engineering and the natural sciences (systems engineering and remote observation) $\rightarrow$ methodological fields grounded in planning, development, and activism (collaborative development, scenario planning, and decision support systems (DSSs)). GIS is situated between the latter two categories. Obviously this is a somewhat reductionist categorization (has indicated by the hybrid positioning of GIS and these fields have significantly influenced each other over the course of the past century. These fields were chosen to shore up one another's defects and to amplify each other's strong points. The pressing need for sustainable development. The systems thinking and design tools of systems engineering. The diversity of data from remote observation. The interest in human society and problems from collaborative planning and development. A desire to support decisions rather than make them for other communities.

The second portion of the chapter, Section 2.3, turns towards to critiques of the literature and the concept of this thesis. It is an attempt to recognize and preemptively address potential pitfalls of the approach taken in this thesis. These are primarily fundamental or ethical concerns, as opposed to mere questions of implementation, the latter of which are largely held for Chapter 6. The connections between the particular fields to the particular critiques are shown in Figure 2-1 below.

The final portion of the chapter, Section 2.4, summarizes the lessons and findings of the literature survey and critiques that will be relevant to the development of the EVDT Framework in Chapter 3.

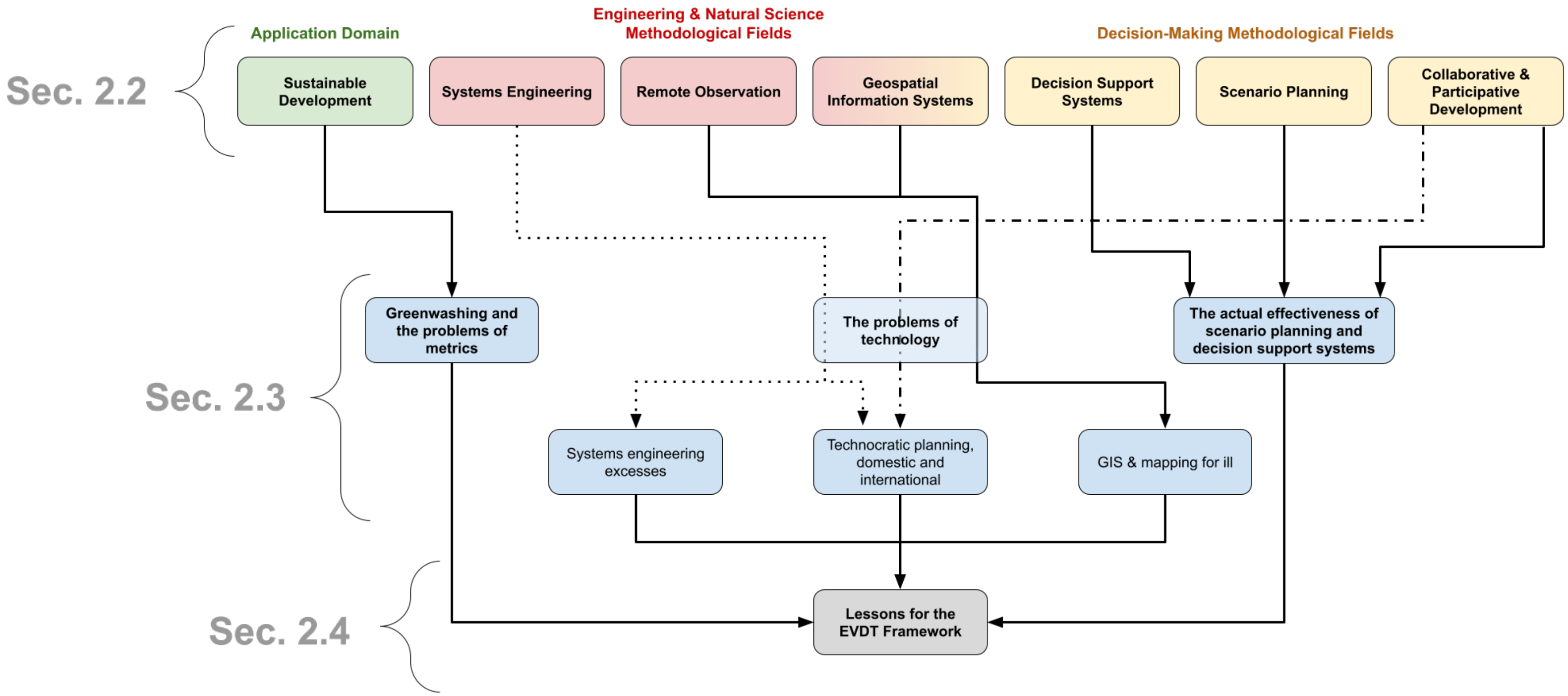


Figure 2-1: Structure of Chapter 2

2.2 Motivation & Literature Survey

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 2.3.

2.2.1 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 Massachusetts Institute of Technology (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 [17]. 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.

2.2.2 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.

2.2.2.1 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" [18]. 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" [19]. 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" [20]. 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 [21]:

> 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." [22]

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

2.2.2.2 Why is Sustainable Development Important?

As former UN Secretary-General Ban Ki-moon put it:"Sustainable development is the central challenge of our times" [22]. 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 2-2.

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 2-3.

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

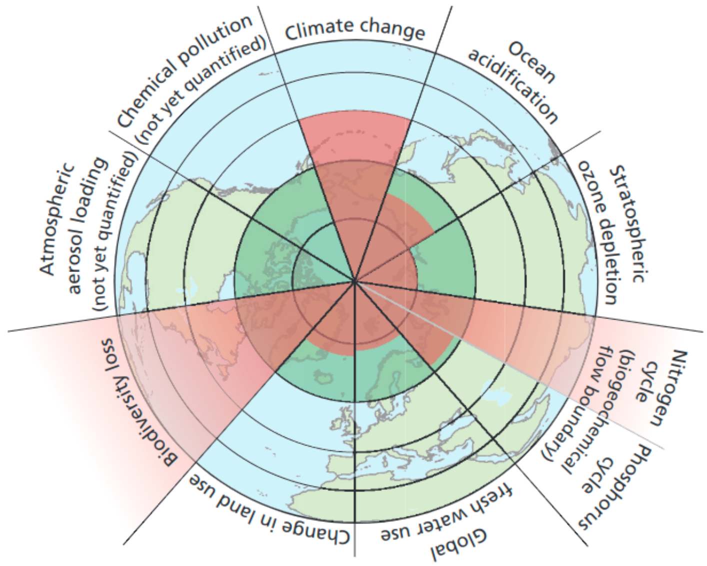


Figure 2-2: Planetary Boundaries. From [23]

motivation for this work and for the methods chosen, as will be seen later.

Table 2.1: Estimated impacts of "business-as-usual" by domain and region. H=High; M=Moderate. Adapted from [25] and [22] [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 correct entry is not known, so I have gone with "M" in yellow here in order to avoid overstatement.

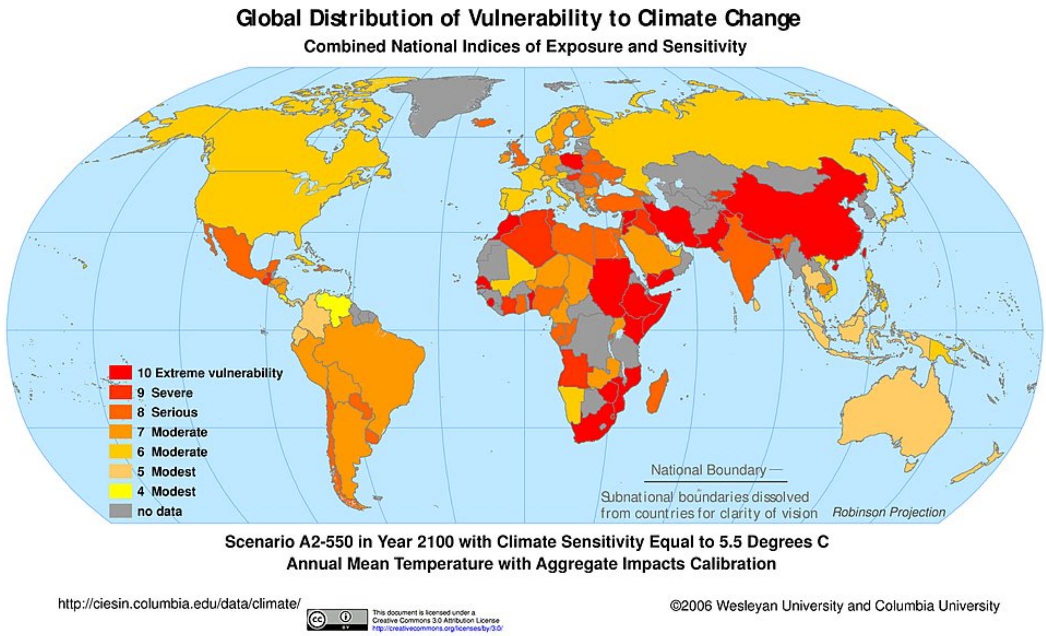


Figure 2-3: Assessment of global distribution of vulnerability to climate change. From [24]

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" [26]. 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.'" ([27–29]as paraphrased in [30]). 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 2-4 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 [31, 32]. 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 [33]. 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.

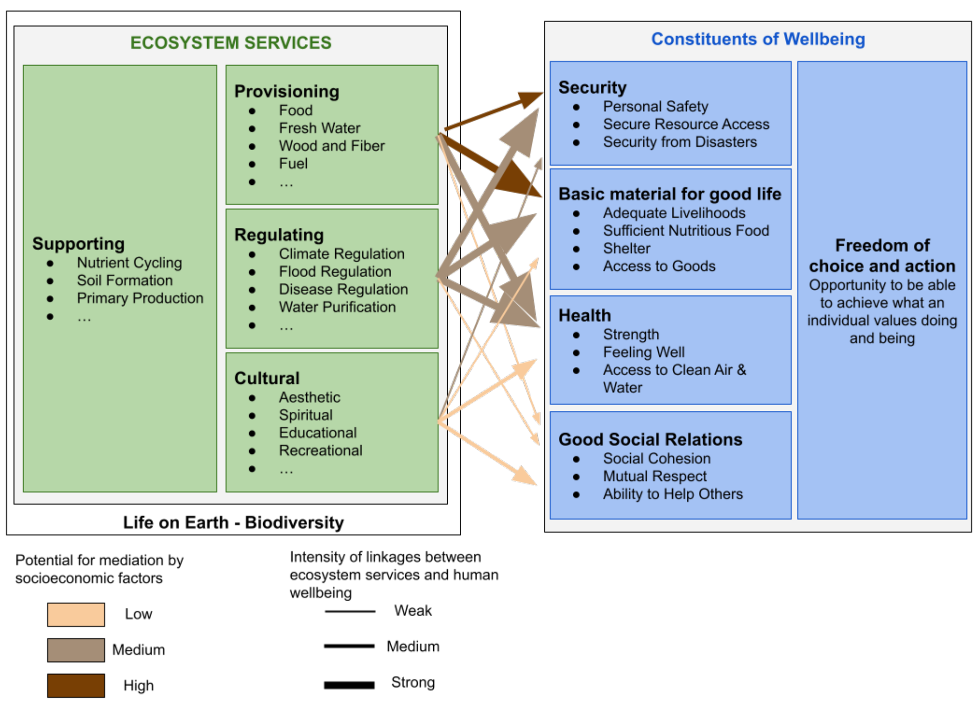


Figure 2-4: Linkages between categories of ecosystem services and components of human wellbeing. Adapted from [34]

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) [35–37] and Socio-environmental system (SES) [38], thereby making sustainable development contexts into socio-environmental- technical system (SETS).

2.2.2.3 What about the Sustainable Development Goals?

At the end of Section 2.2.2.1, 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" [22]. 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 [39]. 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 [40]. 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 2-5.

Figure 2-5: United Nations Sustainable Development Goals

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 [41], 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 goals [42]. 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" [42]. 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.

2.2.3 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*" [13], 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*" [43] . 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" [44]. 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 [45].

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 multistakeholder negotiation and decision-making, which contains numerous lessons on how structure communications to avoid deadlock or domination [46–48]; tradespace visualization and exploration [46, 47, 49–51], 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 [52, 53]. 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 [22]. 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 [54]. This increase in complexity is something that systems engineering is well posed to address.

2.2.4 Why Remote Observation and Earth Observation Data?

Remote observation, often used interchangeably with remote sensing, refers to any form of data collection that takes place at some remote distance from the subject matter [2]. The term is fundamentally about *how* the observation is taking place rather than *what* is being observed, as it includes both astronomical telescopes and aircraft-based surveys of farmland. 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.

Earth observation (EO) meanwhile is, as defined by Group of Earth Observations (GEO), the data and information collected about our planet, whether atmospheric, oceanic or terrestrial. This includes space-based or remotely-sensed data, as well as ground-based or in situ data [55]. As defined by Mather and Koch, the interpretation and understanding of measurements of the Earth's land, ocean, or ice surfaces or within the atmosphere, together with the establishment of relationships between the measurements and the nature and distribution of phenomena on the Earth's surface or within the atmosphere [56]. EO is thus the converse of remote observation, being determined by *what* is being observed (the Earth), rather than *how*.

This thesis is primarily interested in the remote observation of the earth, and secondarily in other forms of EO data. To that end, unless specified otherwise, the reader can assume that "remote observation" and "earth observation" both refer to "remote observation of the earth."

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 available. An enormous amount of EO satellite data is freely available to the public through 20+ National Aeronautics and Space Administration (NASA) earth science satellites [57], 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 [58, 59]. 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 [60]. Currently the data is once again made free after the monetization efforts met with limited success [61], but this may not remain the case moving forward [62].

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 2.2.5) 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 [63], Digital Global's WorldView satellites, and Astro Digital's recent launch of their first two satellites [64], 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 [65]. 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 [66]], agricultural monitoring [via Global Precipitation Measurement (GPM) for rainfall [67] and GRACE for soil moisture [68]], climate change vulnerability assessments [via Ice, Cloud, and land Elevation Satellite 2 (ICESat-2) for vegetation and ice monitoring [69]], and monitoring military actions [via Sentinel-1 [70]].

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 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) [71–73]. 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 [74]. 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).

[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/`.

Such efforts have been quite successful in their goals, but have required significant 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 [75] and maps of damaged areas of Puerto Rico to the Federal Emergency Management Agency (FEMA) following Hurricane Maria [76] (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 [77].

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" ([78] as paraphrased by [79]). 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 [66], aquatic bacterial growths [80], or deforestation [81], with only limited excursions into assessing the connections between such phenomena and human wellbeing. For a survey of such applications see [82].

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 [83]. 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" [82]. 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 [84]. 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 [85], agricultural production [86], and ground water quality [86]. Siddiqi et al. meanwhile have sought to incorporate data uncertainty and quality into estimates of satellites value for decision-making [87, 88]. 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) [89]. 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.

2.2.5 Why GIS?

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 [90]. 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 [91–94]. 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 2-2. 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.) [95, 96]. One important aspect of the acgisc perspective that is not included in Figure 2-2, is that includes "institutional, managerial, and ethical issues [95], something that is naturally core to this work.

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" [97] though arguably Scheiner's 1626 sunspot visualization qualifies as a data map [98], as perhaps do Polynesian knot maps, which long predates either [99]. Graphing data over time, meanwhile dates by to the 14th century [98].

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 [100]. It should be noted that these early instances were primarily application, rather than technology driven [95]. 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" ([101] as paraphrased in [102]).

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 2.2.4. 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 [104]. 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,

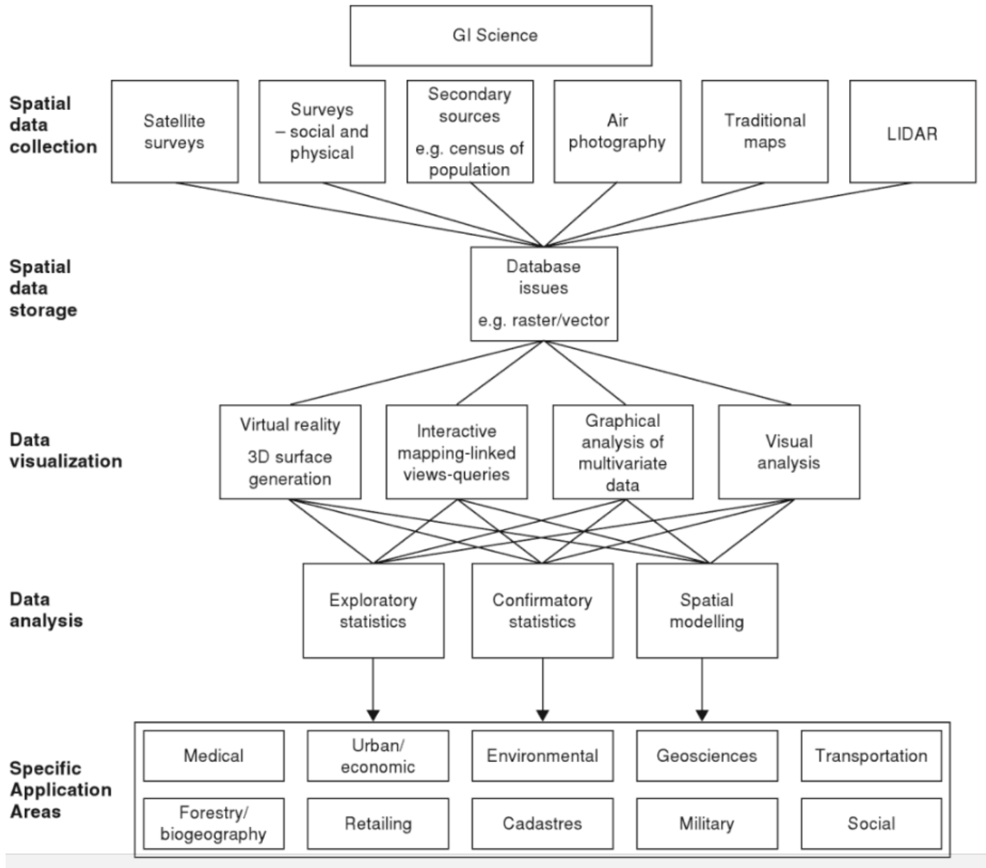


Figure 2-6: Overview of Geographical Information Science. From [103]

data-processing tasks, and data-processing control notation into elementary components that can be recomposed with relative ease and great flexibility" [105]. This theory would come to underlay much of research and development work done with GIS. including that of this thesis.

With the development of GIS and the proliferation of its uses came the realization that no one single type of data field model could serve all needs. In 1991, Goodchild defined six different GIS data field model types and states that "no current GIS gives its users full access to all six" [106]:

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))

The aforementioned ESRI shapefiles are commonly used to store data of types 1 and 4, but is limited in its ability to store the others in an efficient manner. Such limitations are by no means unique to shapefiles. During the mid 90s, Goodchild noted that the field of GIS in general had several shortcomings [100]:

- 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 [96]. Despite this, 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 routine operations" [106]. 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 [107]. 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 [108].

There is now a well established marketplace for geographic data (as shown in 2-7) 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.

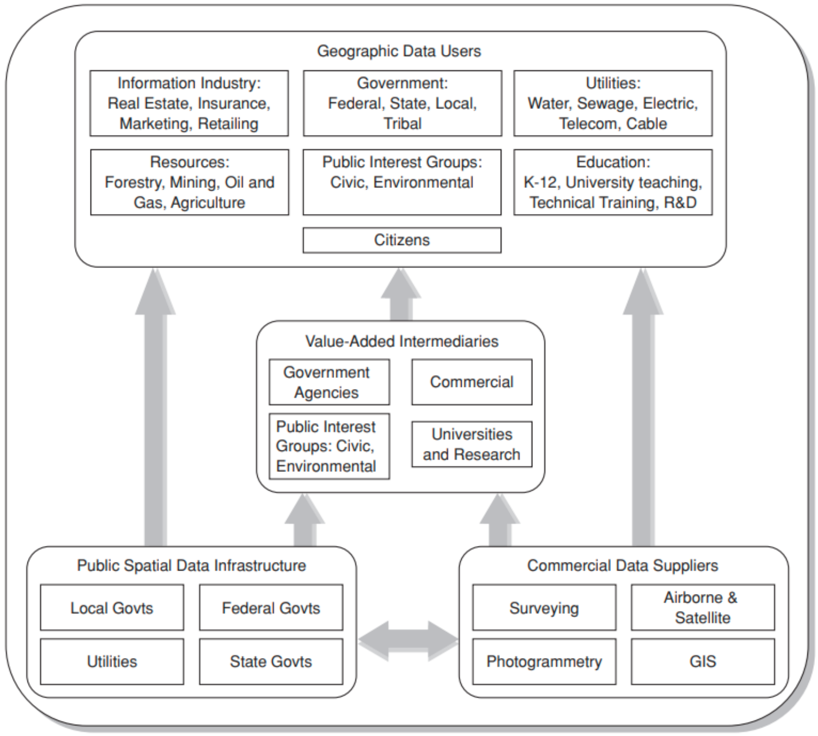


Figure 2-7: The marketplace for geographic data. From [109]

2.2.6 Why Collaborative & Open Source?

As was mentioned in Section 2.2.4, 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 [110]. 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" [100]. 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 [111]. The dynamics at play in such collaborations can be seen in Figure 2-8. This is certainly a more complicated situation than the traditional, straightforward, academic implementation of a GIS project.

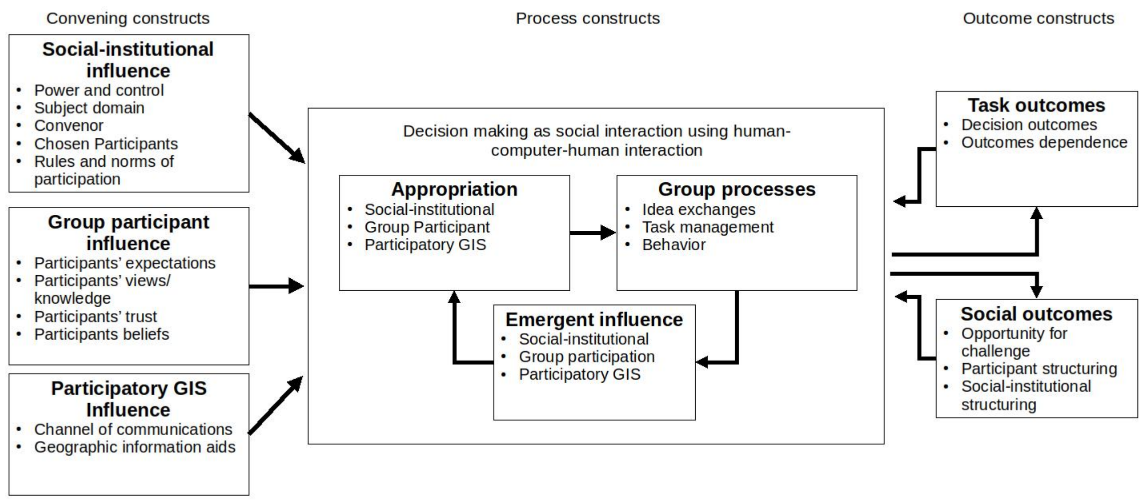


Figure 2-8: Enhanced Adaptive Structuration Theory 2 (EAST2). Adapted from [112]

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 [113]. 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" [114]. 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" ([115] as paraphrased in [116]). 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" [60].

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 [113], critical cartography [117, 118], GIS and Society [119], 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) [119], 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 [120], Data Feminism [121], and Design Justice [122]. 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 [113, 123]. 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" [124]. 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" [125].

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") [126]. 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 [127].

PGIS has thus naturally been strongly advocated and widely adopted over the past three decades [128], with numerous frameworks being proposed for how to implement it [54]. 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 [116]:

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 [107]. That said, some of these implementations have been criticized for being participative in name only, particularly within the research domain [129].

Many PGIS implementations still rely upon closed source, proprietary code for the underlying software [94]. 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 [117]. 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 [130],

> 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" [131].

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 [132]. 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 [133], 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 [134]), suggests that open source is a viable choice for software projects moving forward.

2.2.7 Why Decision Support & Scenario Planning?

2.2.7.1 Decision Support Systems

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" [135]. 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.

One of the chief reasons to use DSSs is that singular optimal solutions to societal problems often either do not exist or are infeasible to calculate. For instance, even in the circumstance where economic welfare is agreed to be the primary or sole objective, in order for cost-benefit analysis to maximize economic welfare, the following conditions must be met [136]:

1. Opportunity costs are borne by beneficiaries in such way 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.

It is not often that all three conditions are met. More detailed 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 [137].

Meanwhile, 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 potential disturbances to the system [138]. 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 [139].

A DSS at least partially circumvents the "lack of a singular solution" problem by not attempting to provide such a singular solution, but instead to facilitate comparison and discussion by community members and/or decision-makers. Instead, according to Jankowski and Nyerges, they accomplish some combination of the following functions [112]:

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 [140]
    (b) Choice models

    (c) Structured group process techniques
3. *Group reasoning support*
    (a) Judgement refinement/amplification techniques
    (b) Analytical reasoning methods

Harris and Batty meanwhile specified two principle requirements of PSSs [135] that are essentially more detailed refinements of function 3 above:

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.

One of the virtues of using modeling and information visualization for decision support, as opposed to presenting a prescriptive solution, is that it allows us to gain the practical benefits of (and moral accord with) collaborative development and participative decision-making as discussed in Section 2.2.6.Harris and Batty noted this as well when they specified additional requirements of a good PSS [135]:

- 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.

The importance of such requirements are discussed further in Section 2.3.1.

There is no definitive typology of DSSs or PSSs, geospatial or otherwise. Goodman describes four primary kinds of models that can serve as the backbone of a PSS [141]:

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 [142].
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 [143].

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.

The framework laid out in Chapter 3 is agnostic with regards to these model types, but it does typically involve at least some geospatial element. As was discussed in Section 2.2.5, decision support was firmly in mind during the creation of GIS several decades ago and decision support continues to be one of the primary uses of GIS to this day. In 2001, Jankowski and Nyerges laid out seven common design requirements for spatial decision support tools worth keeping in mind [112]:

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.

Largely in this discussion is a consideration of what kinds of decisions are DSSs supporting? These vary immensely and while Chapter 3 will provide more detail on the kinds of decisions of interest in this work, it is worth discussing one kind of decision-making process in more detail: scenario planning.

2.2.7.2 Scenario Planning

Scenario planning is a method for planning that centers on considering multiple, plausible futures of the system of interest (scenarios). It typically focuses on the longer term, strategic level, rather than immediate operational decisions [141]. Scenario planning arose in the mid 20th century from two independent sources: (1) Herman Kahn at the RAND Corporation working for the Air Defense System Missile Command and (2) Gaston Berger at the Centre d'Etudes Prospectives [144]. These in turn were further developed in the private sector by Shell and GE, with the former publishing more openly on the topic. Numerous variations 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 and city planners use it primarily for long range business planning [144], or as Goodchild puts it, "vision, framework, comprehensive, system, and redevelopment plans and for those with long time horizons and low or moderate detail" [141]. 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 [145].

As with DSSs there is no single typology of scenario planning or set of steps to follow. Börjeson et al. propose three different kinds of scenario generation: predictive, which focuses on making (usually) quantitative forecasts of the future, sometimes with some probabilistic component; normative, which focuses on identifying some desired target scenario(s) and then works backwards to determine how to reach that target; and exploratory, which focuses on considering the range of possible futures and preparing responses by decision-makers [140]. These roughly correspond with the styles used by Kahn, Berger, and Shell, respectively. Most urban planning applications use the normative type [146].

One of the more detailed practical guides to scenario planning was put together by the Oregon Sustainable Transportation Initiative, a multi-agency program of the Oregon state government. The 100+ page *Oregon Scenario Planning Guidelines*, which focuses on scenario planning for land use and transportation, contains a six-step process for scenario planning ([147] as paraphrased by [141]:

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

This is a clear example of the normative form of scenario planning. The framework developed in Chapter 3 is fairly agnostic among the three types, but in practice most projects tend to be of the normative or exploratory variety, as probabilistic models can be difficult to develop for complex socio-environmental- technical system (SETS). That said Maier et al. (not to be confused with the Maier referred to in Section 2.2.3 have put forth some methods of distinguishing at least the most “plausible" scenarios in high uncertainty systems [148].

2.3 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.

- **Section 2.3.1:** 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.
- **Section 2.3.2:** 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.

- **Section 2.3.3:** The effectiveness of most forms of model-based decision support, and scenario planning in particular, is ambiguous at best, despite their long history. Another research project in this vein is thus fundamentally flawed and is not real science.

These are not the only critiques that may be raised against the fields and methods discussed in this thesis. Many others are discussed incidentally throughout the work. Ultimately, however, these were the ones deemed to be most relevant to what is already any overly long work.

2.3.1 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[149], as is currently seen with the proponents of Big Data and machine learning [150]. 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" [151].

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." [152]. John Pickles was one of the more articulate purveyors of such an argument [110]:

> 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" [153]. 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" [154].

For examples of these two types, Hayes suggested the inherently bulky and centralized nuclear power with inherently decentralized solar power [155] (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" [156].

The ideas of Mumford and Winner have become commonplace. Even self-admitted technological optimists like Jeffrey Sachs [157] 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] [22]. 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 [158]).

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

2.3.1.1 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 [60]. 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" [159], 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" [60]. 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 [160].

A more specific, early critique, also by Pickles, was that of privacy and control over one's own information [92]:

> 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 [161], and big data in general [150].

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 [90].

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" [159]. Meanwhile Tulloch argued that GIS is naturally developing through phases, seen in Figure 2-9, 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

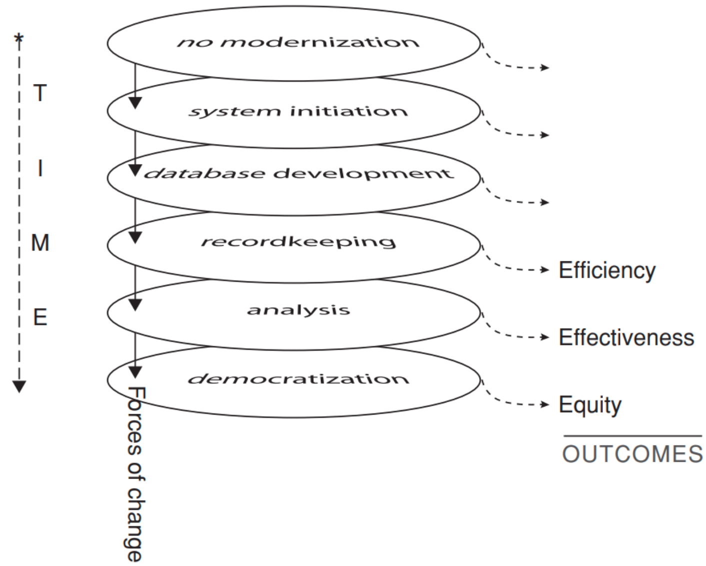


Figure 2-9: Development of GIS development and associated outcomes. From [162] as reprinted in [111]

responsibility is highly problematic. Many designers of digital tools seek to reject the former and commit themselves to a sort of technological determinism [90]. 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) [107]. 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," [141] thereby aligning it with the democratic, human-centered type of technology. As Monmonier noted, "A single map is but one of an indefinitely large number of maps that might be produced for the same situation or from the same data." [163] We must therefore thoughtfully consider how that single map is selected.

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" [164]. 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" ([165] as paraphrased in [166]).

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 [167]. 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 [168]. 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 [167]. Florence Nightingale's famous rose diagrams famously shifted policy on the handling of sanitation in war zones [98], 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" ([169] as paraphrased in [102]). 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 [170].

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

[159].

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 2.2.6. 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," [166] 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" [171].

2.3.1.2 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 [172]), 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" [26]. 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 [26]:

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 [173]. The Planners, meanwhile, fashion themselves into benevolent dictators (though they would eschew being called as such) focused on implementing their solution [174]. 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 [175].

James Scott argued that four elements were necessary to precipitate the most tragic of social engineering disasters [26]:

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." [176]
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" [26]. 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" [79].

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" [26]. 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." [170] 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" [170] (something that we are currently seeing repeated with discussions about Big Data and machine learning [177]).

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." [26] 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' [178], 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" [26].

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) [26].

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) [26]. The egregiously racist influence that Robert Moses had the design of New York City [156] 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" [179]. 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 2.2.3 and 2.3.1.3. 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 [22]. 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 [173], were specifically aimed at Sach's efforts, with some arguing that many of his projects left people worse off than before [180].

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 2.2.6. 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" [181]. Even if participation is quite extensive and includes actual political power, "democracies rarely end up expropriating and redistributing capital" [182]. 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'" [175].

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 [183]. This can occur even unintentionally, as "an inappropriate level of participation may disempower individuals... and it also can distract groups from a desired outcome" [119]. In fact, increased community involvement can result in more restrictive, unambitious goals that are not in the interests of certain minorities [184]. 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" ([185] as paraphrased by [141]). Similarly, merely connecting individuals and enabling the sharing of information does not necessarily promote engaged political deliberation [186].

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 [141]. I discuss further evidence to this effect in Section 2.3.3.

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 2-10 [187]. 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 [188].

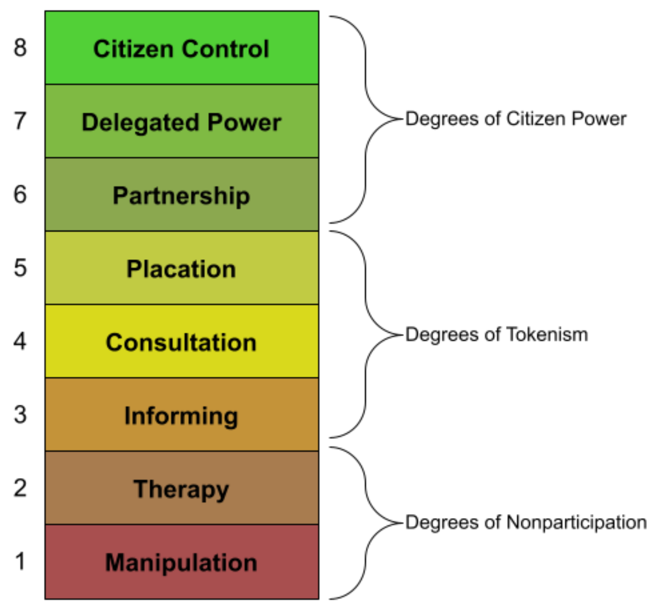


Figure 2-10: Arnstein's ladder of civic participation. Adapted from [187].

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 [186].

In line with some of Easterly's arguments, Virginia Eubanks proposers two gut check questions to ensure that a planning tool avoids harmful consequences [170]:

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 ([189] as paraphrased by [166]):

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.

2.3.1.3 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 [190]. 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 [191], followed by a New York City Applications Project in 1972, and an NSF Urban Technology System Experiment in 1973 [192]. Also in 1970, Jay Forrester published his seminal paper "Systems Analysis as a Tool for Urban Planning" [193] which in 1972 would be expanded upon with the World3 model used in the (in)famous book *The Limits to Growth* [194]. System dynamics, the modeling approach underlying both of these, would go on to have major impacts on business management, urban development, and environmentalism [195]. 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 [196]. 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 [197]. 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" [198]. 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" [199]) 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." [199] The USAC was shutdown in 1977 after significant criticism for spending large amounts of money on projects that failed to deliver [196]. NASA's efforts lasted somewhat longer, continuing to encourage the use of remote observation data by urban planners as late as 1980 [200, 201] 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 [202]. 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) [203].

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. [204]
>
> 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 2-11 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" [198]. 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." [181]. 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.

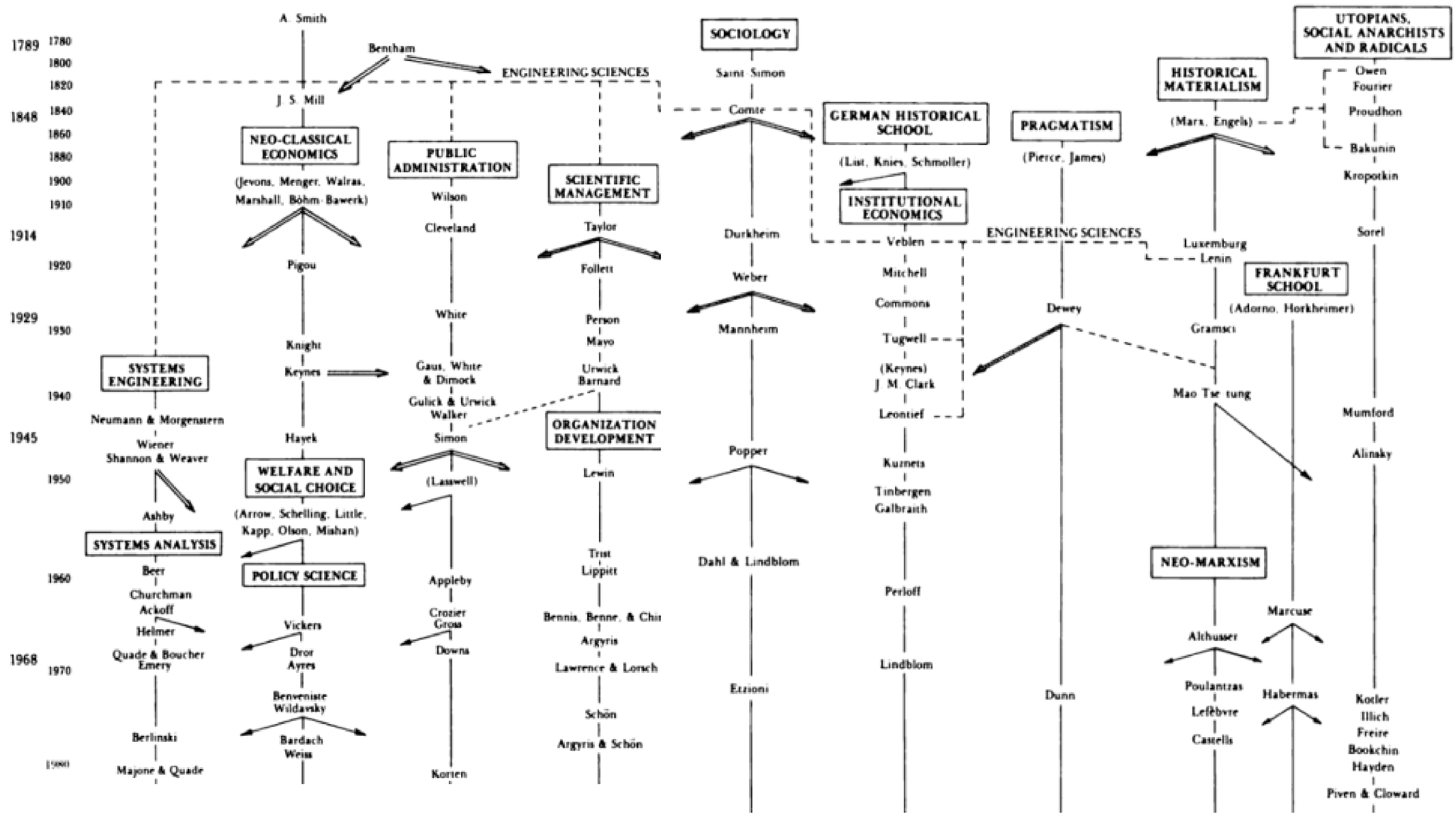


Figure 2-11: Timeline of intellectual influences on American planning theory. From [198]

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 [205–208]. The official formation of a professional society, the INCOSE, would follow much later in the early 90s [209]. 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) [210]. 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 [211]. 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 [212, 213]. A 2011 panel of senior practitioners in the field examined multiple aerospace failures from a systems engineering perspective [214].

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 [215]. 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 2.2. 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 2.2: Identified Themes and Pitfalls from reviews, including the proportion of systematic and integrative review publications that contained each pitfall. From [215].

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 Considera-tion	**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 [181, 198]. 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" [216]. **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?'" [190] 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" [217].

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 [218] 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" [216]. 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." [219] 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 [26]. 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 [216]. 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 [220–224] 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 [225, 226]. Digital models underlie the popular subdiscipline of scenario planning [141, 227]. Interdisciplinary, integrated models have even started to re-emerge [228–230].

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 [231]. 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]. Complex systems, emergence, "ilities", systems-of-systems, and complex adaptive systems have all become popular fields of study within systems engineering [232–242], with numerous frameworks being proposed for how to classify and handle such systems [243–248]. 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 [52, 53] (which has many similarities to the aforementioned urban planning method called scenario planning) and fuzzy probabilistic programming [249, 250]. 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 [251].

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 [252], Stakeholder Value Network Analysis [253], 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 [254], Industry 5.0 [255], MBSE [256], and other fields [257].

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 [46–48] tradespace visualization and exploration [46, 47, 49–51], 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 [258]. 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" [170]. Systems engineering thus has potentially useful tools and perspectives to contribute to the such endeavors as collaborative planning theory [259] and participatory development [260].

With regards to **P6: Cost & Time**, significant infrastructure has been put in place to support the urban planning profession. Interactive DSSs abound [143, 261]. The use of GIS has become the norm [105, 112, 262], including more participatory variants [119]. Systems engineering likewise has seen a heightened emphasis on re-usable tools and infrastructure in the form of both specific modeling languages like Object Process Methodology (OPM) [263] and in general approaches such as MBSE [264]. 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 2.3. 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 [265], as well as in the rise of industrial ecology [266]. 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 [267, 268], metabolism [269], and scaling laws [270]. Some of this work is explicitly picking up avenues of research from the 1970s that were abandoned in the 1980s [269]. 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 2.3: New Developments for the Identified Pitfalls. From [215].

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	[220–224]
	P2	Complex systems, biomimicry, emergence, systems-of-systems, complex adaptive systems, epoch-era analysis, fuzzy probabilistic programming, agent-based modeling	[52, 53, 141, 225–242, 249, 250]
T2: Stakeholder & Contextual Consideration	**P3**	Stakeholder Value Network Analysis, qualitative interviews for use in requirement definition; general expansion of interdisciplinary teams	[253, 271]
	P4	Multi-attribute and multi-objective optimization methods; multi-stakeholder negotiation, tradespace visualization and exploration	[46–51]
	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	[252, 254–257, 259, 260]
	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	[143, 261, 263, 264]
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" [272]. 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 [113, 118, 119, 260, 273]. 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 [83] (as discussed in Section 2.2.4). 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 [274]:

> 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.

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.

2.3.2 Sustainable Development & the SDGs

The concept of sustainable development as espoused by NGOs and UN agencies is not without critique. Nor is the specific substantiation of sustainable development in the SDGs. There are three primary such critiques that this section will address:

1. Sustainable development has become essentially toothless. It is used primarily for greenwashing and providing cover for actions that would have been taken anyways, rather than motivating real change.
2. The reliance on detailed, specific metrics such as the SDG indicators not only distracts from the more important, though harder to quantify, goals of human and environmental wellbeing, but actually works against them.
3. Lack of data and unreliability of data inhibits our ability to meaningfully evaluate our progress towards metrics at all.

All three of these are genuine concern that have some, not insignificant degrees of truth. I will briefly lay out each of this concerns before considering how they jointly impact the manner in which the work envisioned in this thesis should proceed.

The first critique is particularly concerning as the SDGs greatly increased the number of domains of interest compared to the MDGs. Where the MDGs included three issues of human health (child mortality, maternal health, HIV/AIDS, malaria, and and tuberculosis), the acpsdg include at least (child mortality, maternal mortality, tuberculosis, malaria, Hepatitis B, neglected tropical diseases, suicide, various non-communicable diseases, substance abuse, road injuries, reproductive care, hazardous chemical and pollution exposure, tobacco use, and more). While on one hand this is a proper recognition of the long list of items that contribute to a sustainable world, it does run the risk of diluting the importance of any particular issue or allowing organizations to cherry pick the issues that they were already interested in, particularly as the SDGs have no built in mechanism for prioritizing on goal, target, or indicator over another.

As Campbell wrote [274]:

> 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.

Boosters of global goal setting argue that they provide a host of benefits including:

- 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.

Sachs, for example, argues that "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" [22]. Part of this difference of opinion is based on whether one views the individual components of sustainable development mutually reinforcing or as competitive for scant resources. Sachs is certainly in the former camp, as is the concept underlying Figure 2-4 earlier in this thesis. The latter camp can be seen embodied in Figure 2-12, which conceives of sustainable development as a balance of three conflicts. This is a view that Sachs criticized as "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." Despite this, he elsewhere admits the impact of the MDGs was uneven, with public health receiving the most attention, while sanitation and education were largely sidelined. [22]

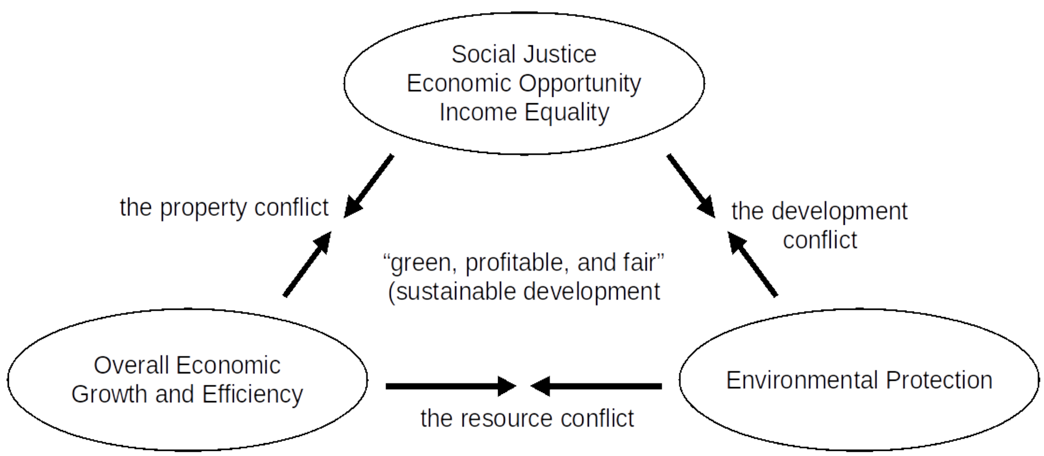


Figure 2-12: The triangle of conflicting goals of sustainable development. Adapted from [274]

Fukuda-Parr et al. advance this concern still further, pointing 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 [275]. We must recognize that ability for global goals to motivate additional action by states and other actors is unclear. It is entirely possible that the creation of the SDGs primarily represents an increased interest by society at large in the idea of sustainability, rather than constituting a motivator for increased action itself. Even if this is the case, however, we can take some solace in the fact that idea of sustainability "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" [274]. The SDGs have become a kind of *linga franca* when it comes to development projects and there is some utility in that. They can enable a certain shortcutting of having to explain why helping mangroves benefits society at large. Instead we can just point to SDG Target 15.1.

Moving onto Critique 2, Fukuda-Parr et al. also pointed out that those issues that did see awareness raised and resources provided due to the MDGs produced "ambiguous impacts on complex social issues," particularly because some of the metrics were chosen for ease of implementation rather than importance. The primary strengths of the MDGs - "simplicity, mensurability, and concreteness - also proved to be sources of distortion" [275]. Section 2.3.1 already partially addressed the more general sense of this problem, the concern that "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" [26]. Here I want to focus in one aspect that applied to the MDGs and SDGs in particular.

One major critique of the MDGs was that they neglected human rights among their metrics, potentially justifying horrendous behavior by state actors and others as long as it made some number go up or go down as needed [276]. This concern was even raised by the UN themselves in a public report towards the end of the MDG lifecycle [277]. One obvious solution to this just incorporate human rights into the next round of goals, which is exactly what happened in SDG 16, which numerous human rights issues from human trafficking to representative decision-making by governments. This likely also explains other, non-human rights additions to the SDGs as well.

This does not wholly address the issue of human rights (or other similarly neglected aspects or a holistic concept of development). Where under the MDGs, a decision-maker could say, "Human rights aren't the list of goals, so they will take a backseat to Goal X," now under the SDGs they could simply say, "We recognize that human rights are an important part of Goal 17, but we believe that Goal Y is more important for our nation (or some other nation in the case of an NGO)." Obviously many of the goods envisioned in the SDGs resist direct comparison or conversion to monetary terms, making it difficult to direct rebut such an argument. Even if you can justify some monetary conversion, Reddy and Heuty point out that any *a priori* means of allocating priorities between goals on a cost-benefit basis is bound to fail due to the lack of data and highly unreliable approaches for estimating said costs and benefits [278].

This leads directly in Critique 3. The uneven availability of data severely hampered international, expert-led development efforts, such as the MDGs. One of the more prominent of MDGs was Goal 6, "Combat HIV/AIDS, malaria, and other diseases," with its associated Target 8: "Have halted by 2015, and begun to reverse the incidence of malaria and other major diseases" [39]. It is difficult to measure progress towards this goal when, in 2005, some researchers indicated that that episodes of malaria globally may have been as much as 50% higher than those reported by the World Health Organization (WHO) [279]. The availability and quality of data (commonly referred to as 'monitoring') was thus a common element of critiques of the MDGs [275, 276, 278]. While many of these critiques used this as an argument for different fundamental models of international development that were not as data-reliant, proponents of the goals instead viewed this as a specific challenge to be overcome. As the MDGs were concluded and their successors, the SDGs, were created, the World Bank labeled the lack of a data a "deprivation" on par with the lack of food, shelter, or healthcare [280]. The United Nations General Assembly, in its commissioning of the SDGs, "called upon the United Nations system, including the Statistics Division of the Department of Economic and Social Affairs of the Secretariat and the regional commissions and international agencies, to support national efforts in building and strengthening national statistical capacity, in particular that of developing countries, and called upon all international agencies to improve the coverage, transparency and reporting on all indicators."

As was discussed in Section 2.2.4, remote EO has been touted as globalizing data collection and addressing the data gap when it comes to the SDGs. Organizations such as GEO have even organized an initiative called EO4SDG to advance such activities [281]. Unfortunately, the historical rule that "the poorer the country, the less and the worse the data" does not just apply to basic demographic and geographical data, such as that collected by standard decennial censuses or by national mapping services, but it also applies to data derived by analysis [282], including global and multi-regional datasets. This is only exacerbated by the fact that such derived datasets are typically created by individuals and organizations based in the wealthier states and thus subject to their particular interests and language limitations. An example of this can be seen in the primary composite dataset of ecosystem services valuations. The Ecosystem Services Valuation Database (ESVD) is maintained by research organizations based in continental Europe and is primarily funded by a UK government agency [33]. The database organizes the studies that it references by the location of the specific ecosystem services being valued. Table 2.4 shows the breakdown of the target continents of these studies, in which a bias can be seen both towards wealthier regions and towards those regions of more interest to the researchers and funding sources.

Table 2.4: Regions studied by publications compiled by ESVD

Region	**Number of Studies**	**Percent of studies**
Africa	309	7.7
Asia	1140	28.4
Europe	1639	40.8
North America	594	14.8
Oceania	223	5.6
South America	109	2.7

This trend tends to be exacerbated in smaller sub-disciplines. Approximately 63% of studies of mangrove-related ecosystem services are focused on parts of Asia despite these regions constituting providing only 38% of the world's mangrove coverage [283].

So how should this work be approached to avoid, or at least mitigate these critiques. First and most obviously, we can be careful about our collection and use of data so as to avoid technical mistakes. This includes such actions as characterizing gaps in the data rather than assuming them to be uniformly random, examining the generation process so as to identify potential errors, and not applying a data-based model out of its domain of calibration. In machine learning of remote observation data, for example, training data should typically be based on in-situ observations that are selected to be representative of the entire application area. These correctives are all important and should certainly be implemented, but they are insufficient on their own to avoid all the harms laid out in the previous section.

Second, we may refuse to do data collection and analysis in areas with authoritarian governments or other unsavory decision-makers and adopting the other conclusions reached in Section 2.3.1. When it comes to data collection and use, this can be done by being critical of the providence, applicability, and original purposes of datasets, and by being willing to take action to fill gaps in the data rather than just relying upon what is available. That said, this is not a trivial undertaking. Furthermore, while you may have avoided working with despots and are not ideologically blinded yourself, data, once collected, has some degree of permanence and it is not always clear who will use it in the future.

Third, we may argue that data collection and analysis methods have developed over time, are now more objective, and are thus no longer vulnerable to historical biases and gaps. This is essentially what proponents of remote observation data advocated as far back as the 1970s, as discussed earlier. While improvements are real and remote observation certainly represents a way of checking claims made by deceptive actors, contemporary methodologies are still vulnerable to intentional exploitation and unintentional misuse, but these issues are inherent in the act of data collection itself, regardless of the methodology.

Fourth, we may change our framework of development. Since data is collected for a purpose and mediated by technology, if we change the purpose, we change both the use and the collection. This is the approach many critics of metrics such as the targets and indicators of the MDGs and SDGs have taken: "The solution cannot therefore be to seek fully to overcome the limitations in our knowledge (which are incapable of being fully overcome), but rather lies in adopting structures for decision-making which address these limitations" [278]. Such altered frameworks include Bayesian cost estimates [278], a focus on human rights [276], qualitative rather than quantitative objectives [275], a focus on freedom of choice [127], and Easterly's "Searchers" (those who seek for bottom-up solution to specific, addressable needs in local areas and thus do not need immense amounts of standardized data collection) [173]. One of the more popular thrusts in this vein are participative and collaborative development activities, as was discussed in Section 2.2.6.

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. [130] We can seek to act similarly, perhaps. The SDGs and the UN's concept of sustainable development are useful for communicating with a broad audience and coordinating action, but they should not be used to overrun more local concepts of sustainability. These are all important lessons to consider during the development of a framework in the following chapter.

2.3.3 Scenario Planning & Decision-Support is unfounded

Skepticism of the usefulness of model-based DSSs are not new. 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 [216]. Similarly, as late as 1990, many researchers were arguing that GIS was not mature enough to serve as the basis for a DSS [284]. And as recently as 2010, existing PSS have 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" [54]" This leads to what some have called the "implementation gap" of PSSs [285]. This argument was explored in more depth in Section 2.3.1.3 with regards to systems engineering, but it also impacts decision support in key ways. If the models underlying a DSS cannot be trusted, neither can the DSS. If you cannot simulate plausible scenarios (as Figure 2-13 would suggest is often the case) you cannot conduct scenario planning.

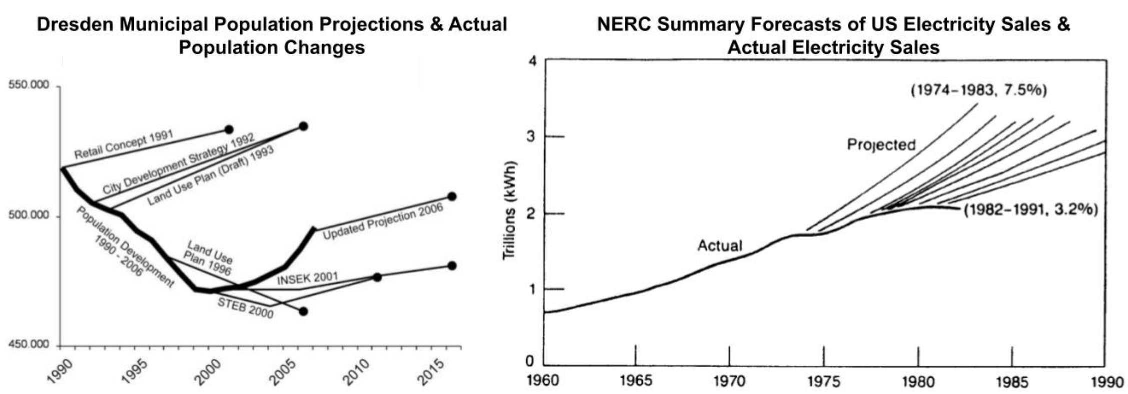


Figure 2-13: Left: Population changes in Dresden compared to various municipal projections. From [286]. Right: US National electricity sales compared with various NERC Summary Forecasts. From [287]

One obvious response to this is, “We just need better models." Miller, for example, argues that, despite the historical difficulties 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 [228]. The potential and the weaknesses of this argument are addressed in Section 2.3.1 (and Section 2.3.1.3

in particular). Another potential response is to avoid pursuing firm predictions and instead seek to gain provide some other benefit with the DSS. Bankes takes this approach, arguing 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 [288]. 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 in the original) [125].

Wack agrees, writing that forecasting can be problematic as it constitutes "someone else's understanding and judgment crystallized in a figure that then becomes a substitute for thinking." He then proposes scenario planning (particularly the exploratory variety) as an alternative, as it 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" [289]. This raises the question if such alternative, non-predictive models and support tools are actually of real use to decision-makers. This is the essence of critique raised at the beginning of Section 2.3. Due to the wide variety of DSSs and planning practices, this is not a trivial question to answer.

To take scenario planning as a specific example, the evidence is decidedly mixed. Goodspeed's review of scenario planning use in urban planning and environmental research found only modest, ambiguous benefits (though use in industry management was more unambiguously positive) [141]. He argued that many the applications in the review were poorly implemented, however. In particular he said that scenario planning was often misapplied to "strategic planning" was 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." His own study of impact of a scenario planning project in Lockhart, Texas, which sought to correct some of the flaws he perceived in many previous studies, confirmed that modest, but real positive changes are the result of scenario planning.

Others have pointed out that adopting a more participative process can improve outcomes. 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) [227]. This extends beyond scenario planning with several sources confirming that higher levels of collaboration improves DSS functionality and usability [54, 259, 273, 290]. Notably, one of the early successes at combining remote observation imagery with socioeconomic data, the 1968 Land Use and Natural Resources Inventory (LUNR), elected to not use the military-developed land use classification schemes, but rather to interview future users about their needs and to use the results from these interviews to develop a classification system tailored to the application. Such benefits, particularly when contrasted with the failures of more technocratic approaches, demonstrate the differences between what philosopher and educator John Dewey “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" ([291] as paraphrased by [141].

Even assuming that participative, model-based decision support has been conclusively been demonstrated to be helpful to decision-makers, there is still the question of whether such a project is the kind of science or engineering worthwhile for a doctoral thesis. 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" [141]. In fact, there are good reasons to avoid practicing “conventional science" in these domains as treating society as a laboratory can lead to significant harms and a “vivisectionist" mentality [292]. This does mean there are certain limitations on this thesis. It cannot directly advance our fundamental understanding of mangroves, as an earth scientist might wish; our understanding of how cities change, as an urban planner might wish; or our ability to design satellites, as an aerospace engineer might wish. Nonetheless there is a certain and necessary purpose to be served by this piece of design science, as it seeks to help provide communities with the tools to decide their future.

2.4 Lessons & Conclusion

This chapter discussed a variety of fields with varying levels of connection, as well as some significant critiques of those fields and how they have been applied in recent centuries. The impetus of this chapter was the question:

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 avoid the technocratic excesses of the past?

Are we now prepared to answer it?

To start with, it is clear there are both major pull and push factors for bringing to bear systems engineering and other ways of making sense of data in complex systems on the issue of sustainability. Pull, in that our concepts of development and human wellness have expanded. They are no longer measured in short-term, purely individual economic of civil rights terms. We are considered with questions of equity, of ecosystem services, of community resilience. With this broadening has also come and increasing sense of urgency as we face various forms of resource depletion, environmental collapse, and climate change. The concept of sustainable development which seeks to capture both this broadness and urgency was discussed in Section 2.2.2. This section made it clear that there is a need for methods that can help with the planning and management of complex systems, particularly ones that involve humans, their technology, and the environment.

The push factors are the increasing supply of such methods. Remote observation (Section 2.2.4) provides data that is new in kind, scale, and temporality. While it has a well developed history of monitoring environmental phenomena at the global scale, it has a much more limited use in local, human-centric applications and there is thus much potential there. Systems engineering (Section 2.2.3) and GIS (Section 2.2.5) represent two approaches for corralling remote observation data along with that of many other sources for use in sustainable development. These two fields have been closely linked since their inception in the mid-20th century and both are based on the idea of using data and models to inform and support decision-making.

These fields are not unalloyed goods, however. Section 2.3.2 explained how common definitions of sustainable development may have been watered down by entrenched powers and serve primarily to distract or co-opt more meaningful change. Section 2.3.1.2 explained exactly what harms international development endeavors, be they ill-willed or good intentioned, can inflict. Sections 2.3.1.1 and 2.3.1.3 showed that GIS and systems engineering have often been key enablers of such harms.

So with these concerns in minds, just how can we “avoid the technocratic excesses of the past?" Several recurrent lessons appear throughout this chapter. First is the importance of involving a wide set of stakeholders in a participative manner. The reasoning and history behind participative approaches is briefly summarized in Section 2.2.6. Often no single, objectives solution exists for a sustainable development problem and, even if it did, our data collection and analysis methods are insufficient to reach it. In absence of such a single solution, consider and selecting a course of action must be made by the community. Such a process helps too with acceptance and implementation of the decision. A wide set of stakeholders also commonly means both a wide concept of human wellness and one that is relevant to the community in questions. This means that the primary role of systems engineering and GIS in such situations is to support decisions rather than to make them, to help communities envision potential future scenarios rather than to dictate one to them. For this reason, decision support systems and scenario planning are presented in Section 2.2.7.

What remains is the question of whether decision support is actually helpful and thus whether the topic is suitable for a doctoral thesis. Section 2.3.3 addresses this. It reinforces the importance of participation in the development of useful DSSs and argues that this thesis approaches it topic in a more responsible, and less technocratic manner.

This chapter has thus supplied Research Deliverable 1a: “A critical analysis of systems engineering, GIS, and the other fields relied upon in this work." The next chapter shall take the lessons learned here and apply them in the development of a framework for sustainable development work.

Chapter 3

EVDT Framework

3.1 Chapter Purpose & Structure

The aim of this chapter is to detail a framework for developing a decision support system (DSS) for a sustainable development application, as is called for by Research Deliverable 1b:

> *A proposed framework for applying systems engineering for sustainable development in an participatory and social-justice-oriented manner.*

This framework, called the Environment, Vulnerability, Decision-Making, Technology (EVDT) Framework, is intended to satisfy the need for a framework for collaboratively developing a systems-architecture-informed, multidisciplinary GIS DSS for sustainable development applications that makes significant use of remote observation data. Compared to most frameworks for applying earth observation (EO) data for sustainable development, the EVDT Framework aims to to create management approaches and toolsets for sustainable development application that the stakeholders find useful; to be applicable to a wider range of spatial and temporal scales than is common in EO applications (particularly on the smaller and shorter end of things); to involve a wider range of stakeholders throughout the development process; and to be attentive to both environmental and human wellness, rather than just one or the other.

This chapter starts with Section 3.2, which builds upon the lessons and priorities identified in Chapter 2 in order to establish that such a need exists. Section 3.3 then considers the extent to which various past and present approaches already satisfy this need in order to justify the creation of a new framework. That new framework is detailed in Section 3.5, which walks through the EVDT Framework element by element. Section 3.5 then presents the intended uses of the framework in more detail. These sections will thus collectively propose an answer to Research Question 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 avoid the technocratic excesses of the past?*

The chapter concludes with Section 3.6. There I will recap the framework and set the stage for the subsequent two chapters, which present applied case studies of the EVDT Framework for those interested in concrete demonstrations. Chapter 6 will finally revisit the EVDT Framework in light of the two case studies and discuss plans for the future.

3.2 The Need for a Framework

Before presenting the EVDT Framework, it is important to establish what motivated the creation of the framework, what the current landscape of approaches looks like, and whether any gap actually exists. This section focuses on the first of these. This motivation is heavily grounded in the lessons from Chapter 2. That chapter surveyed the fields of sustainable development, systems engineering, earth observation, GIS, participatory planning, and decision support. It considered the history and trajectory of these fields, how they overlap and intersect, and both the potential benefits and harms that they can cause. This resulted in several particular conclusions that are important for the EVDT Framework:

- **It is both important and urgent that we, as a society, pursue sustainable development.** As discussed in Section 2.2.2, we face various forms of resource depletion, environmental collapse, and climate change that risk significantly increasing the already unconscionable lack of access to income, health, education and more around the world.
- **Any approach to sustainable development must take a multidisciplinary approach involving the environment, societal impact, human decision-making, and technology.** As discussed in Section 2.2.2, our concepts of development and human wellness have expanded. They are no longer measured in short-term, purely individual economic / civil rights terms. We are

also concerned with questions of equity, of ecosystem services, of community resilience. This broader conception of development as well as the more complicated, interconnected nature of contemporary society means that we must increasingly rely upon models and simulations to better understand the consequences of proposed policies and decisions. We increasingly understand - and appreciate - the complex relationships between these domains, relationships that were previously ignored in analyses [293].

- **The fields of systems engineering, remote observation, and GIS have powerful tools for advancing sustainable development.** Remote observation (Section 2.2.4) provides data that is new in kind, scale (both spatial and temporal). While it has a well developed history of monitoring environmental phenomena at the global scale, it has a much more limited use in local, human-centric applications and there is thus much potential there. Systems engineering (Section 2.2.3) and GIS (Section 2.2.5) represent two approaches for corralling remote observation data along with that of many other sources for use in sustainable development. These two fields have been closely linked since their inception in the mid-20th century and both are based on the idea of using data and models to inform and support decision-making.
- **In order to avoid the technocratic harms of the past, it is important to take a participative, local community approach and focus on decision support, rather than prescriptive solutions.** Often no single, objectives solution exists for a sustainable development problem and, even if it did, our data collection and analysis methods are insufficient to reach it. In absence of such a single solution, consider and selecting a course of action must be made by the community. Such a process helps too with acceptance and implementation of the decision. A wide set of stakeholders also commonly means both a wide concept of human wellness and one that is relevant to the community in questions. This means that the primary role of systems engineering and GIS in such situations is to support decisions rather than to make them, to help communities envision potential future scenarios rather than to dictate one to them.

These lessons establish that there are both push and pull factors motivating the creation and use of a framework for collaboratively developing a systems-architecture-informed, multidisciplinary GIS DSS for sustainable development applications that makes significant use of remote observation data. This leads to the question, do any such approaches or frameworks already exist? And to what extent do they satisfy this need?

3.3 Identifying the Gap

Now that the motivation for *a* framework has been made clear, what are the already available approaches for satisfying that need? This section considers this question and seeks to identify what, if any, gap remains.

First, it is obvious that I am not the first to suggest that sustainable development is an important and urgent issue (see all of Section 2.2.2). Advocating for the use of models is not new either. 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 [194]. As was discussed in Section 2.2.3, 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 there is nothing new in saying that modeling plays an important role in sustainable development.

But what about multidisciplinary model? There have been numerous attempts 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 [261].
- 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 [294].
- The TripEnergy model combines an environmental submodel (transportation systems) and societal impact submodel (energy consumption and emissions of vehicles) [295]. 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" [296].
- 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 [226].
- Pert et al. combined environmental and decision-making in a participatory model to improve conservation outcomes [260].
- Shahumyan and Moeckel linked together existing models in a loose manner using ArcGIS Model Builder to study transportation, land use, mobile emissions, building emissions, and land cover [230].

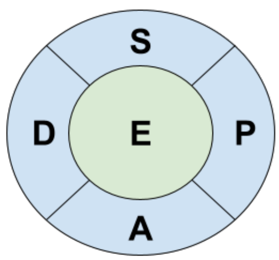
In the field of earth science, integrated models have also become increasingly common. Originally developed for operational weather forecasting, Observing System Simulation Experiments (OSSEs) have found widespread use for designing earth observation systems at NASA and elsewhere [297], by linking models of environmental phenomena with simulations of observing platforms (both hypothetical and real). These models are rigorously validated [298] 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.) [299]. 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.

While most of these only deal with some subset of the environment, societal impact, human decision-making, and technology, they clearly establish that there is interest and active work ongoing in multidisciplinary models. Of all of them, Shahumyan and Moeckel come the closest to addressing the need. They linked together models covering each of the four domains and even included some limited feedbacks between them [230]. However, they lack both an explicit inclusion of systems engineering and a participative aspect, instead relying upon proprietary, closed source code. They also do not provide a generalized framework for applying their approach to other, potentially dissimilar situations.

There are distinct advantages to the development and codification of such 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).

So what dedicated frameworks exist that are focused more directly on sustainable development? First, there are a set intended for use by large governmental (often multi-nation and/or multi-agency) teams and that aim at national or even multinational applications. These include SERVIR, FEWS NET, and various UN-affiliated programs such as the World Food Program). Even to the extent that these fully embrace multidisciplinary modeling (and they often do not), 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.

There are some frameworks operating in this space, some of which include both systems engineering and a participative element. 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 [300]. 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 [301], 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 3-1: The Stakeholders-Problem-Alternatives-Decision-Making-Evaluation (SPADE) Methodology and associated methods. Adapted from Haskins, 2008 [301] as seen in [215].

Van Zyl and Root meanwhile used a transdisciplinary approach involving Wilbur's integral systems theory [302] and the Customers, Actors, Transformation process, Worldview, Owners, and Environmental constraints (CATWOE) framework from SSM [271] to design sustainable agricultural principles in New Zealand [303].

Other recent approaches focus on scenario planning and education for understanding evolution of the urban form [304], sustainable land-use planning that relies upon multilevel stakeholder partnerships [305], a synthesis of participatory planning with systems engineering for sustainable regional planning [306], and leveraging human-centered design to address the SDGs [307]. A survey of sustainable development applications of systems engineering can be found in Yang and Cormican, 2021 [308], which itself was published in a special issue of *Sustainability* dedicated to systems engineering [309].

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. They largely lack the multidisciplinary modeling component, however, and any concrete use of EO data.

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, or for the use of participatory design and decision-making. I am also not the first to recognize that these all are easier said than done [230]. A gap remains however. There is still a need for a generalized framework that puts all of these together. We have multidisciplinary, participatory sustainable development modeling projects that lack a generalized framework. We have frameworks that individually focus on sustainable development, multidisciplinary modeling, participation on a local scale, and remote observation, but not one includes all these aspects. It is this gap that the EVDT Framework, laid out in the following section, seeks to fill.

3.4 The Framework

The EVDT Framework is process for developing a DSS for a sustainable development application. This process is characterized by five basic elements, shown in Figure 3-2 and enumerated as:

A) The use of systems architecture & stakeholder analysis to identify needs, design the DSS, and understand the context through the use of the Systems Architecture Framework (SAF). This requires significant engagement with as many of the stakeholders as is feasible (if not more). Usually two or more iterations through the SAF cycle are required.

B) 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.

C) 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.

D) 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.

E) Collaborative development of the DSS that continues beyond initial stakeholder engagement.

Each of these elements span the entire lifecycle of an EVDT project, but can still be usefully considered in the order listed. The following subsections walk through each of these elements. A later section in this chapter address in more detail the intended uses and users of the framework.

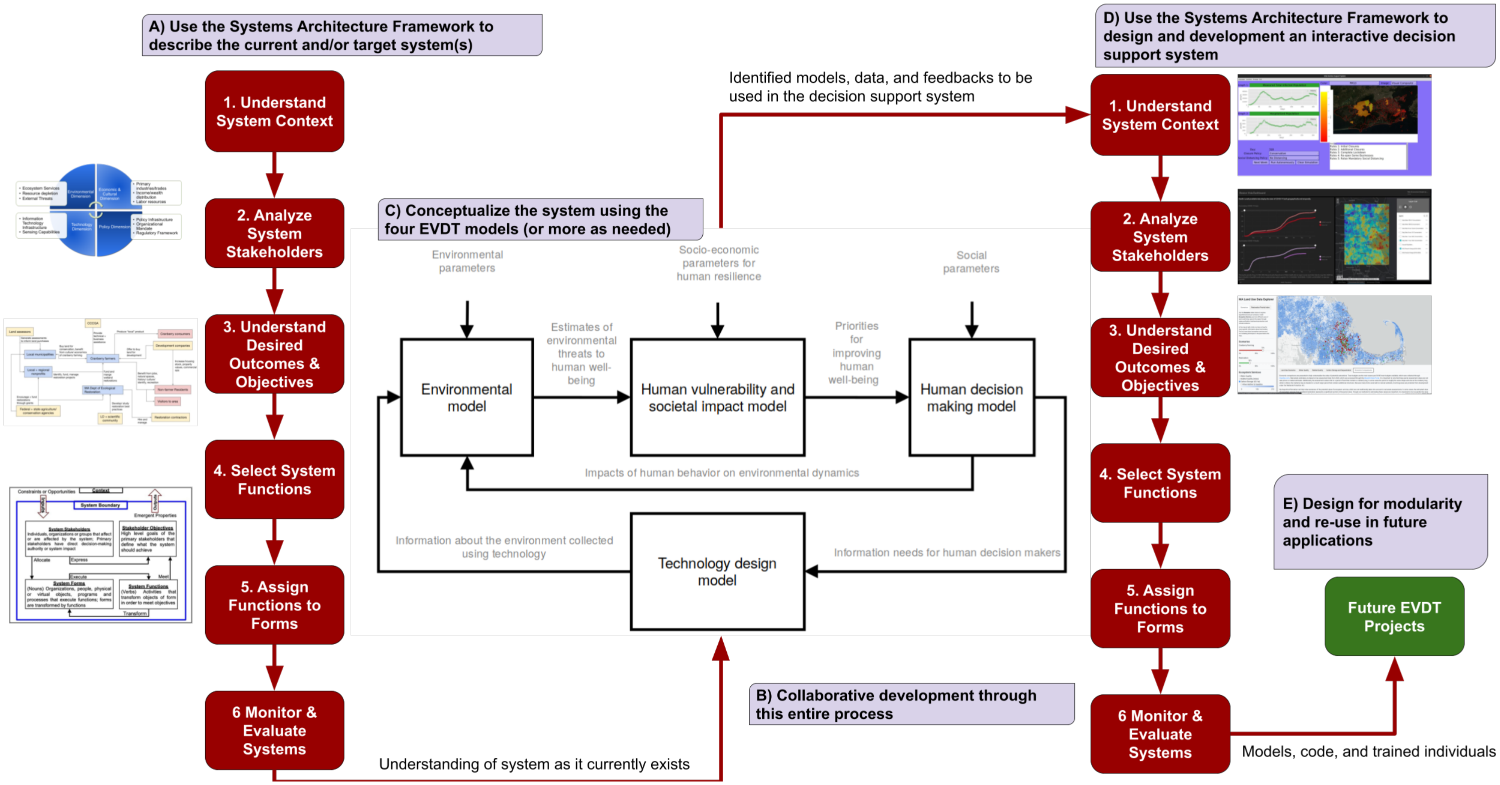


Figure 3-2: Overall EVDT Framework. Lettered circles label the components of the framework. A) The iterations of the Systems Architecture Framework; B) Collaborative development; C) the environment-vulnerability-decisionmaking-technology conceptualization; D) the interactive decision support system output; E) Modularity and re-use

3.4.1 Initiating an EVDT Project

Much of the following sections detail how the EVDT Framework refines a motivating question, understands its context, and determines an approach for answering it. Prior to all of this though is how one realizes there is a question to be asked and that the EVDT Framework is the right approach for addressing it. Here I seek to briefly provide an answer.

Any EVDT project must start with a local stakeholder with a sustainable development problem to solve. This stakeholder, who we refer to as a Local Context Expert (See Section 3.5 for more discussion on this designation), must also be willing to dedicate the time and effort to either lead the EVDT project or heavily collaborate with outside facilitators (such as the Space Enabled Research Group that I am a part of). Maybe the head of a local company wants help dealing with an invasive plant species [310]. Or officials in a municipal planning agency want assistance with improving coastal resiliency [311]. Or a tribal self-governance director wants support in planning natural resource management [312].

In our experience, this initiating Local Context Expert is usually the one who first identifies the problem and pitches the collaboration, with the external facilitator proposing the EVDT Framework as a potential approach. The EVDT Framework does not rule out the idea of an external facilitator identifying a problem and initiating conversation, but caution should be taken in such circumstances to avoid thrusting a malformed question upon a community.

The initiating Local Context Expert should not be assumed to be the sole representative of their community nor should their problem formulation be accepted as written in stone. Much of Section 3.4.2 details how additional stakeholder perspectives are considered and how the motivating question can be refined. As a participative methodology focused on decision-support, the EVDT Framework requires some level of participation from a variety of stakeholders. If not even a single person can be found to be an initial Local Context Expert, or that person is reluctant to participate, this is likely be a sign that this venue is not right for an EVDT project at this time.

Beyond these conditions, there are not any particular restrictions on the kind of problem that the EVDT Framework can be used for. While one of the motivations for its creation was to be able to handle applications at relatively small spatial scales (neighborhoods, small towns, municipalities), the framework is not restricted to such applications. Similarly, while the case studies presented in this thesis focus on informing policy decisions, there are other potential applications of the EVDT Framework (See Section 3.5 for discussion of such uses).

So, with at least one Local Context Expert, at least one EVDT facilitator, and a (perhaps vague) initial sustainable development question, we are ready to move onto the first full element of the EVDT Framework: the SAF.

3.4.2 A: System Architecture Framework

The Systems Architecture Framework (SAF) is the first element of the EVDT Framework. It is used to learn about the system in question, solicit stakeholder perspectives, and identify the necessary features of the DSS to be developed later on. This section will provide an overview of the SAF and its history. The following subsections will then go through each step and then explain why two iterations of the SAF are shown in Figure 3-2.

The SAF as seen in this thesis was developed by Danielle Wood and has gone through several revisions and expansions since its inception [313–315]. It predates the creation of the EVDT Framework. The version here is based on the most recent version, as seen in Ovienmhada et al. [310]. The SAF itself builds upon prior work in systems engineering, particularly the subdiscipline of systems architecture as laid out by Maier, Rechtin, Crawley, Cameron, and Selva [13, 14, 316], with SAF drawing its definitions most directly from Crawley et al. [316]. This prior work tended to be nominally application agnostic, but in practice tended to see application in large aerospace and civil engineering projects. SAF is similarly application agnostic but has seen its primary uses in international collaborations [15] and sustainable development [310].

It should be noted that the SAF includes a variety of technical terms that have similar but not identical definitions to their colloquial use. This terms will typically be indicated with capitalization (e.g. System Boundary). Definitions will be supplied at their first occurrence, but are also listed in the glossary found in Appendix A.

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 concerned with scoping, structuring, and certification [13]. This tends to refer to the high level form and function of a system, rather than detailed design. Others, such as Crawley prefer to characterize systems architecture as the mapping of Function to Form such that the essential features of the system are represented. System Functions here mean the specific actions or processes that the system performs. System Forms meanwhile refers to the approaches and structures used to enable the Functions (i.e. the “stuff" of the system, including tangible objects, software-based objects and organizations). The intent of architecture is to reduce ambiguity, employ creativity, and manage complexity [14]. 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.

The current version of SAF involves six steps, shown in Figure 3-3. It seeks to center the full network of stakeholders and invite them into a collaborative development process. This process can be used to describe an existing system, identify some system modification, or design an entirely new system. 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, or as NASA defines the term: those who are affected by or accountable for an undertaking [317].

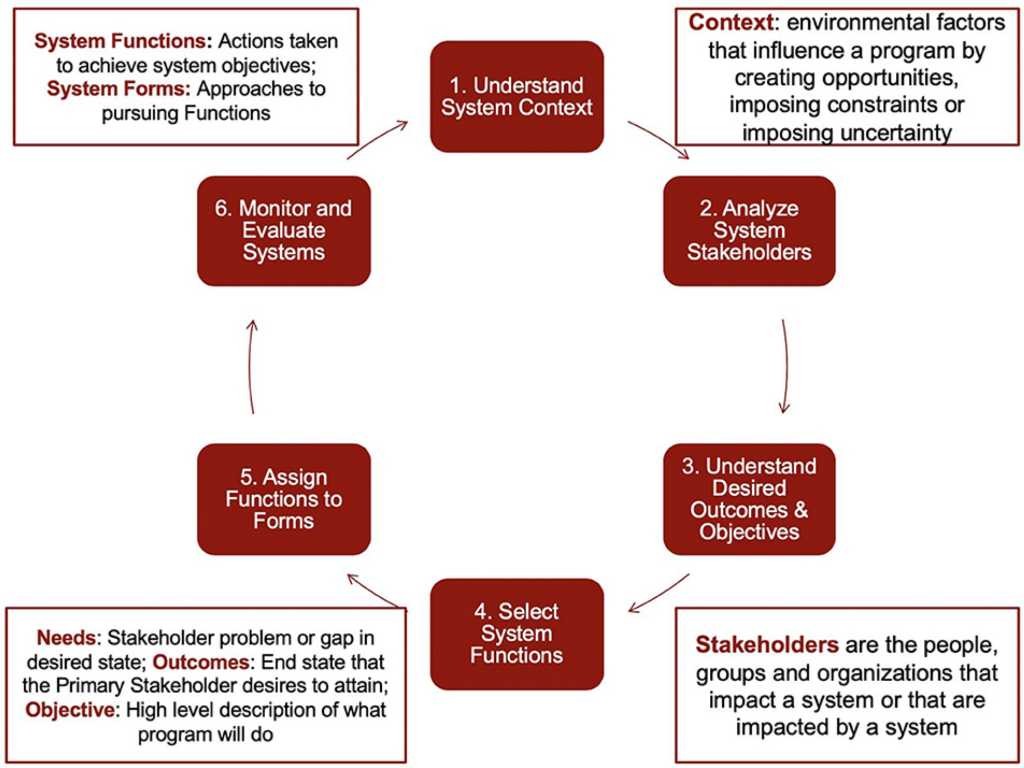


Figure 3-3: Six steps of SAF.

The primary benefit of a systems architecture approach such as SAF is, as Crawley articulates [316]:

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.

As discussed in Sections 2.2.3 and 2.3.1.3, traditionally systems engineering focused on a single stakeholder: the client, with the benefits accruing to that stakeholder primarily. More recent approaches, such as SAF, expand this to considering the perspectives of multiple stakeholders, though still primarily only using stakeholder input to inform system requirements the beginning of the development cycle. Even SAF though only explicitly requires the involvement of a wide set of stakeholders during Steps 1-3. If we desire the benefits of a system to not just accrue to central authorities or technocrats but rather to be held by the community themselves, we must ensure keep stakeholders involved through the full cycle.

The following subsections walk through the SAF steps individually, providing potential methods to achieve each step and discussing continued stakeholder involvement. Section 3.4.6 will expand how to ensure collaboration and participation throughout the process as well.

A summary of useful methods for each step of SAF is available in Table 3.1, along with useful references. Italicized methods are defined in the corresponding following subsection of this chapter. It should be noted that many of these methods are useful in multiple steps but are listed here in the step that they are primarily associated with. Not all methods are recommended for every application.

Table 3.1: Methods for SAF steps. Italicized methods are defined in the corresponding following subsection of this chapter.

SAF Step	**Useful Methods**	
	Data Collection	Analysis/Synthesis
1. Understand System Context	- Academic literature survey - Survey of newspapers, periodicals, popular media, and local museums - Informal conversations with stakeholders - Stakeholder interviews - Stakeholder surveys - Direct observation	- Critical Analysis - *System Scales/Dimensions* - History Narrative
2. Analyze System Stakeholders	- *Primary-Secondary-Tertiary Classification* - Flowchart relational mapping [318] - Stakeholder Value Network Analysis [253] - Agent-based modeling [225]	
3. Understand Desired Outcomes & Objectives	- Unified objective function and constraints [319] - Monetary conversions (e.g. ecosystem services) [33, 320, 321] - Multi-stakeholder negotiations [47]	
4. Select System Functions & Objectives	- Multicriteria negotiations [258] - Pairwise comparisons [322] - Delphi method [323]	
5. Assign Functions to Forms	- *System diagramming* - Scenario planning workshops [141] - Multi-stakeholder tradespace exploration [47] - Collaborative sketch planning [290]	
6. Monitor and Evaluate Systems	- Retrospective evaluations - Stakeholder surveys [318]	

3.4.2.1 Understand System Context

The first step of SAF is to understand the System Context: the external factors that influence and constrain the system. This includes learning about the history of the environments, communities, and organizations that intersect with the system. This information can be of multiple temporal or spatial scales (eg. local, provincial, or international). This step has multiple objectives. The first is to refine the System Boundary: the limit demarcating the system of interest from the rest of the universe. The System Boundary determines what is considered part of the system (and thus subject to the decisions of the designer and stakeholders) and what is not (and is thus considered beyond their control, for the purposes of this project at least). It should be set narrowly enough to provide some level of tractability to both the designer and the major stakeholders, but not so narrowly as to unduly exclude potential interventions from consideration. The designer almost certainly will already have some preconceived System Boundary in mind when starting the project. This step provides a key opportunity to revise that conception, potentially dramatically.

Another objective of this step is to identify the stakeholders in the system of interest. This list need not be definitive or exhaustive, as it will be revisited in the next step. Finally, an understanding of the system Context will also inform the feasibility assessment of various system Forms later in the SAF process.

Methodologies for this step include surveys of literature (including both academic and non-academic literature, including popular media as needed), informal conversations, interviews, surveys, and observation. Once information has been gathered, it needs to be organized into a useful form. For this, it is often useful to consider the system of interest at a variety of System Context Scales and System Context Dimensions. The former refers to how spatially or organizationally "zoomed in/out" one's perspective. Figure 3-4 shows a set of generic such scales, though more or fewer can be used as needed.

Figure 3-4: Generic System Context Scales

Dimensions meanwhile refers to the topical perspective taken within a Scale. There are innumerable potential such perspectives that one can take, but Figure 3-5 shows four basic ones that are commonly relevant in EVDT projects (and that roughly mean the EVDT questions discussed in Section 3.4.3). It also provides examples of the kinds of information that can be summarized with each Dimension.

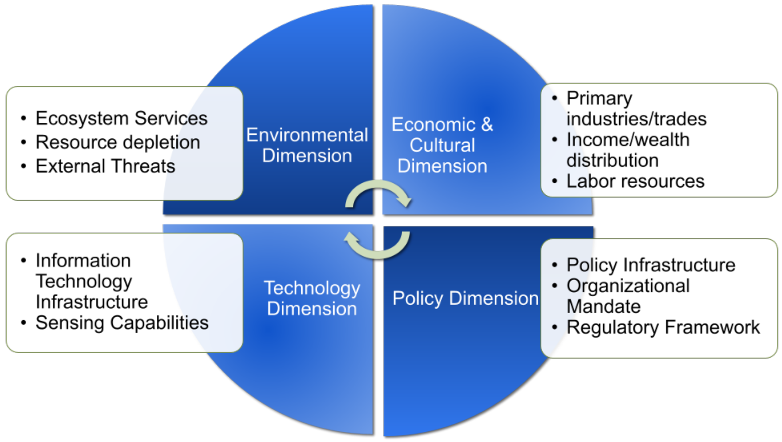


Figure 3-5: Generic System Context Dimensions, including example items.

Note that the most relevant dimensions may change as one progresses through the different Scales. Figure 3-6 provides two examples. Each represents a different project and a different scale. The first is at the local scale for an EVDT project lead by Lombardo [312, 324]. It thus closely mirrors the generic case from above. The latter is at the national scale for a project looking at the creation of a new space agency [325]. The relevant dimensions are thus quite different and even the dimensions that are similar (economic and technical) contain different types of information.

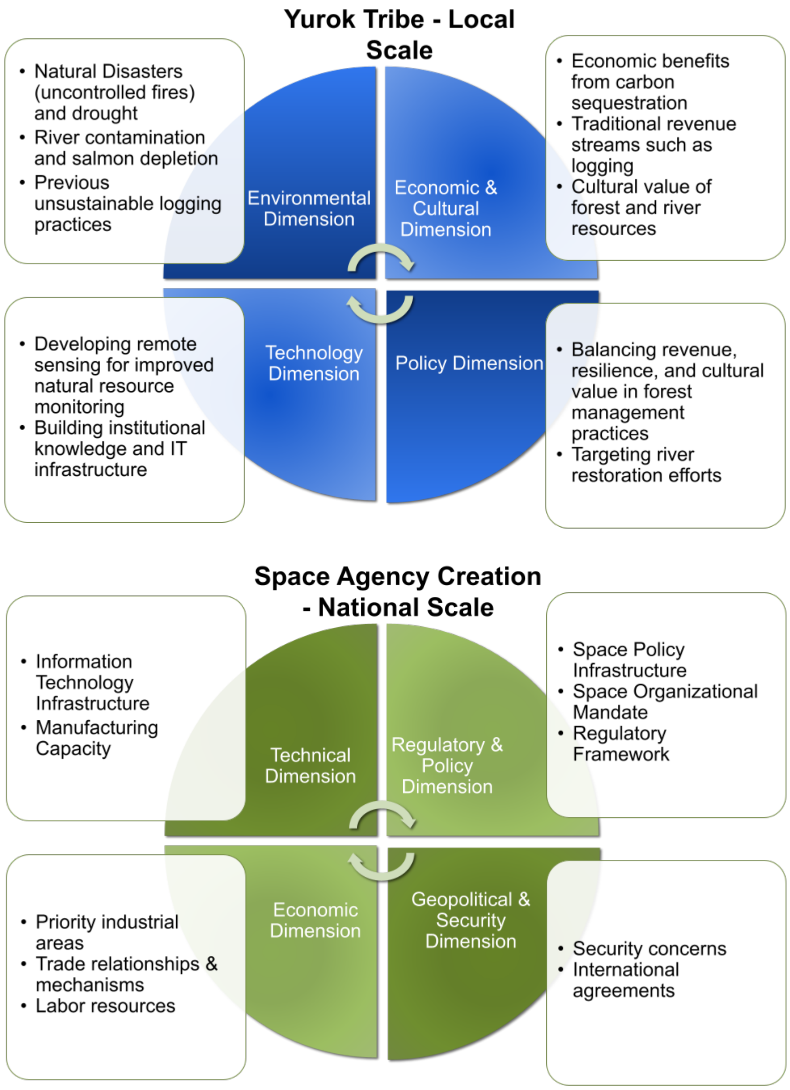


Figure 3-6: Example System Context Dimensions. **Top:** Four dimensions for the local scale Yurok tribe EVDT Project. Adapted from [324]. **Bottom:** Four dimensions for the creation of a space agency at the national scale. Adapted from ???

3.4.2.2 Analyze System Stakeholders

During the second SAF step, the various stakeholders, along with the relationships between them, are analyzed. This process may result in the identification of additional stakeholders or the decision to exclude stakeholders from consideration, though the latter should not be done lightly. The primary objectives of this step are (1) to understand how best to engage the stakeholders throughout the rest of the SAF and EVDT process; and (2) gain an understanding of how the Stakeholder Needs and Desired Outcomes overlap or conflict. The latter will be further examined in the next step.

A common initial approach for this step is to separate stakeholders into three categories: Primary, Secondary, and Tertiary, as shown in Table 3.2. This approach, which draws on Crawley et al. [14] and refined by Wood et al [310], defines Primary Stakeholders as those who make direct decision on the design or operation of the system. Secondary Stakeholders are those who have direct influence on the Primary Stakeholders, typically via authority or funding. Tertiary Stakeholders are those that exert either little control or primarily indirect control on the system, but are impacted by the system. These are somewhat reductive categories and the listing of primary-secondary-tertiary should not be taken to understand a hierarchy of stakeholder worth or importance.

Table 3.2: Primary-Secondary-Tertiary classification of stakeholders, including examples from [326]

	Primary	**Secondary**	**Tertiary**
Description	Those who make direct decision on the design or operation of the system	Those who have direct influence on the Primary Stakeholders, typically via authority or funding	Those that exert either little control or primarily indirect control on the system, but ae impacted by the system
Stakeholders	• Green Keeper Africa (GKA)	• National Institute of Water • GKA investors • Benin government ministries	• People who participate in fishing or acadja practices • GKA harvesters • Lake Nokoue community and surrounding cities

Other methods include both qualitative approaches such as flowchart creation or mapping, and more quantitative approaches such as Stakeholder Value Network Analysis [253] or agent-based modeling. The last of these is more relevant once Stakeholder Needs and Desired Outcomes have been identified. An example of stakeholder relational mapping can be seen in Figure 3-7. In its current form, it provided an excellent qualitative aid to understanding stakeholder relations, but it could also have been extended into a more quantitative Stakeholder Value Network Analysis if that had been considered useful.

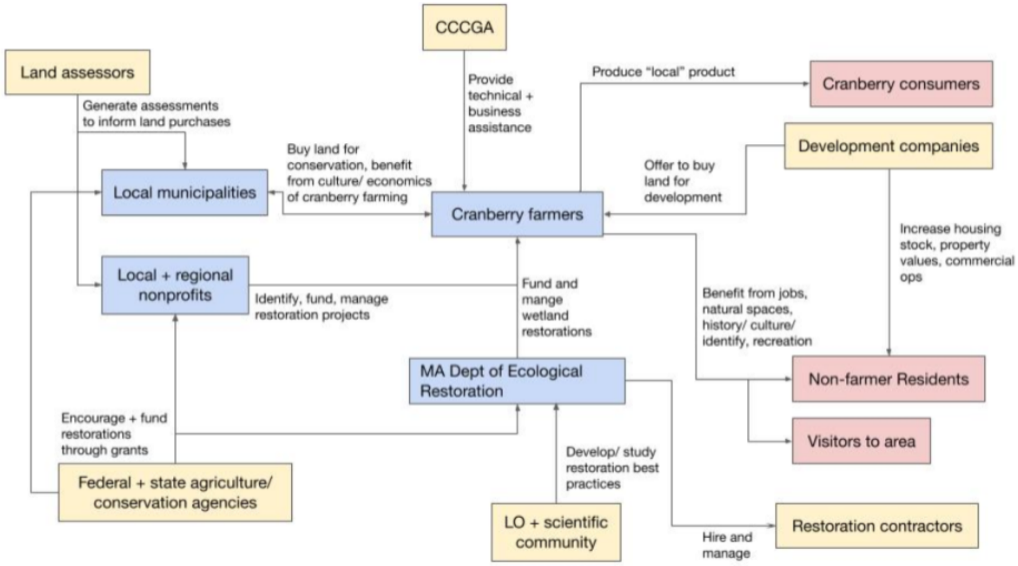


Figure 3-7: Example stakeholder map of the Massachusetts Cranberry Industry. Figure from [318]

3.4.2.3 Understand Desired Outcomes & Objectives

Once both the System Context and the network of stakeholders are understood, we must next identify what the stakeholder Needs, Values, Desired Outcomes, and Objectives are.

System Needs refer to anything that a stakeholder is lacking. These are not necessarily tied to the system of interest. Desired Outcomes meanwhile are the end states that stakeholder would like to attain. Stakeholder Values are things that stakeholders hold as benefit in relation to needs and desired outcomes. It is important to note that Needs, Desired Outcomes, and Values do not exist in the abstract, but only when tied to a particular stakeholder, as shown in the example Table 3.3. This is a critical component of SAF and one of its major distinguishing characteristics compared to earlier applications of systems engineering to urban planning and development, as discussed at length in Sections 2.3.1.2 and 2.3.1.3. They will vary from stakeholder to stakeholder, sometimes aligning in constructive ways and sometimes opposing one another. As a result, no singular, objective "solution" will exist. Tradeoffs will need to be made and the system will serve the interests of some stakeholders more than others. The designer should be aware of this and honest about it.

One way to consider this is with the concept Architectural Alignment. This concept, which can be seen as the systems engineering version of a perspective of critique, asks, “For what stakeholder or set of stakeholders does the system architecture constitute a satisfactory balance of preferences?" A poorly aligned system architecture may be the result of a compromise between some small number of stakeholders who have power over the system's design and operation. A well aligned system has some level of consensus and satisfaction among a wider set of stakeholders.

The goal of this step is to synthesize these Needs, Desired Outcomes, and Values, into (well aligned) System Objectives: the high level description of what the system will do. These can be quantitative or qualitative. Some sources use the term System Goals instead, in order to distinguish them from the optimization term “objective function" [317]

Table 3.3: Example set of Needs, Outcomes, and Objectives. Table from [318]

Stake-holder Group	**Stakeholder Needs**	**Desired Outcomes**	System Objectives
Cranberry farmers	Make a sustainable living, recoup investment in land, provide for family	Improve profitability of farming or sell land for sufficient price, possibly keep land natural/open	Support/justify competitive sale pricing for land
MA Department of Ecological Restoration	Benefit people and the environment through restoration/protection of watersheds and wetlands; improve knowledge of restoration best practices	Widespread restoration/conservation of former cranberry farms; affordable and accessible restoration program	support/justify value of restoration projects; disseminate knowledge on restoration best practices; prototype novel funding models
Local munic-ipalities	Provide clean drinking water, open/recreational space to citizens, address climate threats	Be able to provide high standard of safe, climate-resilient living to all residents	Support investment in projects/properties/programs that support clean water, open space, climate resilience
Local and regional nonprofits	Address risks of climate change and local environmental issues	Effective and affordable interventions to protect drinking water, become more climate resilient	Identify financing mechanisms, develop knowledge and best practices to support projects

The methods described in the previous step for understanding relationships between stakeholders are also useful here to see how their needs, desires, and values overlap.

There are at least two schools of thought about how to approach balancing the needs of multiple stakeholders. One school argues for aggregating needs, values, and constraints into a singular objective function and set of constraints prior to considering any particular system functions or forms [319]. This can be done (a) unilaterally by the designer or a primary stakeholder; (b) through a reduction of all values to a common metric, often monetary [320]; or (c) through a negotiation process among the stakeholders. In general for the kinds of sustainable development applications that EVDT is envisioned to address, I suggest against this approach. Option (a) is essentially a return to the technocratic hubris criticized in Chapter 2. Option (b) is often difficult and morally problematic. It is difficult because many stakeholder values are difficult to reduce to monetary terms, particularly those values around the natural environment [321]. While the field of ecosystem services (discussed further in Section 4.3.1.2) provides some help in this regard, such data is still sparse and unlikely to be comprehensive for a particular application. This option is also morally problematic because reducing values to monetary terms tends to prioritize the needs of wealthy stakeholders (who have more to lose) over economically poorer stakeholders. For example, if a designer is seeking to situate a seawall to reduce damages from cyclones, a purely monetary metric would suggest placing the seawall in front of large vacation homes instead of in front of smaller primary residences. If Option (b) is chosen, I strongly urge the designer to adjust values based on stakeholder wealth to more accurately capture actual impact on the stakeholder. This, of course, adds additional complexity. Option (c) in theory is fine, but many stakeholders will find it difficult to negotiate abstractly, without concrete alternatives available before them. This approach tends to reward those most familiar with fields that deal with the optimization of objective functions, such as systems engineering and economics. By choosing this option, the designer runs the risk of such stakeholders "gaming the system." This is only worsened by the fact that such stakeholders are disproportionately likely to be in possession of other forms of power and authority.

The second approach is avoid making a unified objective function altogether or at the very least not to set the objective function in stone. Instead various concrete system objectives and form alternatives are proposed to stakeholders and compared in some form of negotiation or voting process. This option is preferred for most EVDT applications and is discussed further in the following two sections.

3.4.2.4 Select System Functions

During this step, the designer must refine System Objectives and use them to specify System Functions, the actions or processes that the system will perform to accomplish the Objectives.

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. Many but not all have the person or persons facilitating the systems architecture process to conduct some form of negotiation process, supporting each of the stakeholders as needed. Examples include multicriteria negotiations [258], pairwise comparison [322], and various forms of the Delphi method [323]. For an excellent survey of multicriteria decision-making analysis methods as applied to sustainable urban planning see Slattery, 2019 [327].

By moving stakeholder negotiations into this step (or even into the following step), the designer is able to provide more concrete examples to stakeholders, reducing the possibility of unforeseen consequences or misstated values. Where time and resources allow, it can be useful to iterate these negotiations at multiple phases: first when selecting System Objectives, again when defining System Functions, and a final time when designing the System Form.

3.4.2.5 Assign Functions to Forms

The System Form is what a system is, rather than what it does. The System Form provides the instrument necessary for the System Functions. A particular bicycle is a Form that enables the Function of converting periodic human motion (pedaling) into linear motion (actually going somewhere).

The methods outlined in the previous section are largely still applicable here, as well as some additional approaches that depend on concrete system form alternatives, such as multi-stakeholder tradespace exploration [47] and collaborative sketch planning [290]. When the system or system intervention is primarily a matter of a policy action, scenario planning workshops can be quite helpful for facilitating the expression of stakeholder preferences or even inducing stakeholders to generate new System Form proposals.

We generally recommend that Steps 1 through 5 be summarized in a concrete visual representation such as Figure 3-8. These can be useful in describing the structure and dependencies within the system, as well as distilling the key aspects of the system in an easily understandable fashion. An alternative, list-based presentation can be seen in Ovienmhada et al. [310].

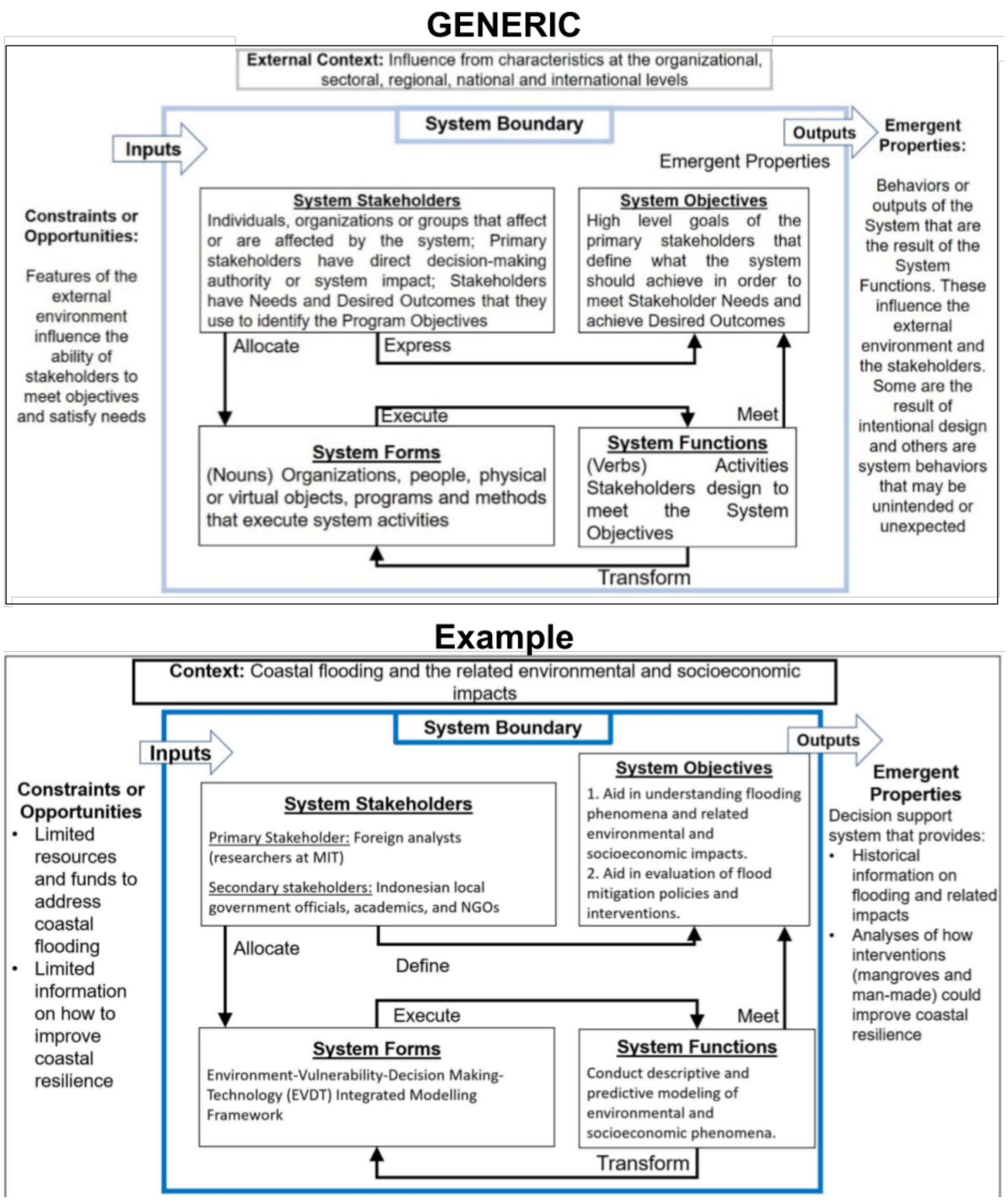


Figure 3-8: Example system diagrams. **Top:** Generic version. Credit to Danielle Wood. **Bottom:** Example from a coastal resilience EVDT project in Pekalongan, Indonesia. From [311]

3.4.2.6 Monitor and Evaluate Systems

The sixth and final step of SAF directly leads back to the first. It is a statement that the work is never complete, the system never perfected. Perhaps the system will need to be monitored to ensure that it meets its objectives and further refined if it does not. Perhaps the objectives will change. Or perhaps an additional system needs to be developed to address some of the Stakeholder Needs and Desired Outcomes that went unaddressed in the original process. Either continuous or retrospective evaluations of the system should be conducted. The exact form of these will vary depending on the system at hand but can be as simple as surveying the various stakeholders. In our case, the output of the first iteration of the SAF leads directly into the third element of the EVDT Framework. Before getting to that, however, it is worth discussing why multiple iterations of the SAF are included in Figure 3-2.

3.4.2.7 A Note on Perspective

As implied in the section "Understand System Context" above, there is a certain level of arbitrariness in defining the System Boundary. This choice affects what stakeholders are included, which stakeholder(s) are made central (if any), and has significant impact on the system objectives, functions, and forms.

When time and resources allow, it can be useful to consider the system from multiple different perspectives before settling on any particular one. As shown in Figure 3-2, for an application of the EVDT Framework, I suggest going through the SAF at twice. The first, Iteration 1, is a purely descriptive process, detailing how the system of interest currently operates. The second, Iteration 2, which will leverage the above suggested methods more fully, is then used for developing the design of the new system or intervention, be it a product, service, or policy. In projects involving the creation of a DSS (which EVDT Framework projects are), the differences between Iteration 1 and Iteration 2 can also help to distinguish the objectives, functions, and form of the DSS versus the objectives, forms, and functions of the system that the DSS is supporting decisions about.

It can also be worthwhile to conduct a separate iteration of the SAF between Iterations 1 and 2 (call this Iteration 1.5). In this iteration, situate the designer or the designers organization as the primary stakeholder. In the case of this thesis, that would be Space Enabled and/or myself. This allows the designer to clearly identify their own personal interests and objectives in the project, rather than to pretend they are a purely altruistic agent (which is rarely the case). By comparing the results of Iteration 1 and Iteration 2 with Iteration 1.5, the designer can assess whether or not this project is a good fit for themself. If their own Needs and Desired

Outcomes differ too greatly from those of the other stakeholders, it may be best to not pursue the project. See Section 2.3.1.3 for further discussion of what can occur when a system designer's personal research goals take priority over those of the other stakeholders.

3.4.3 B: 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 3-3 and discussed in Section 3.4.2. The second perspective focuses on combining the established fields of sociotechnical systems [35–37] and socio-environmental systems [38] 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 objectives identified with the SAF and develop the DSS discussed later in Section 3.4.4. The four components, shown in Figure 3-9, seek to encapsulate the major interacting aspects of sustainable development and consider them from a SETS perspective.

There are specific advantages to this perspective. As discussed in Section 2.2.2, jointly considering these four aspects is key to a proper understanding of sustainable development. Sachs used a similar framing when he wrote: "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" [22]. This is slightly different from EVDT to be clear. Sachs focuses specifically on a economics where EVDT more broadly considers vulnerability and societal impact. Sachs also, not unreasonable, breaks decision-making into two categories: social interactions and governance. Finally Sachs omits the role of technology in this list, though elsewhere he acknowledges that "technology road-mapping" is critical for the pursuit of sustainable development.

Such an approach, which seeks to simultaneously consider both humans and the

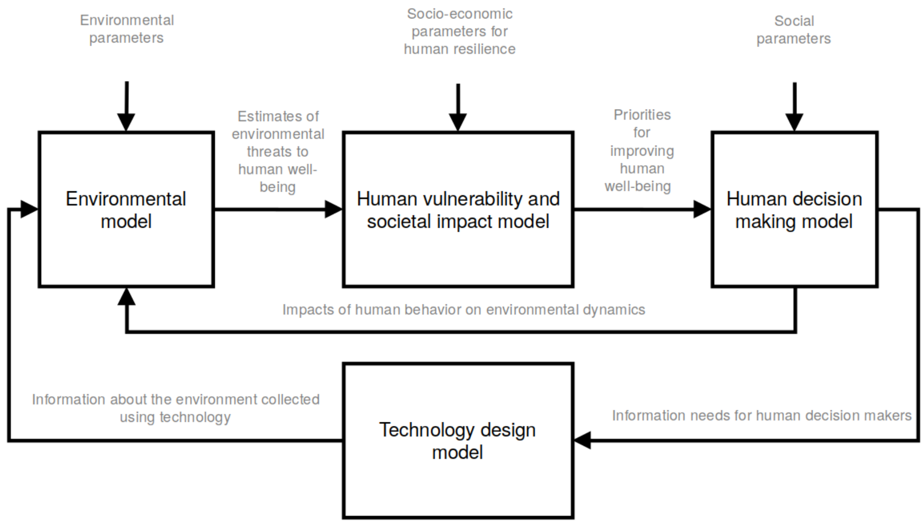


Figure 3-9: Generic version of the Environment - Vulnerability - Decision - Technology Model

environment, stands in contrast to some historical categorizations of planning models. Clifton et al., for instance, breaks down the various ways of modeling the urban form into five categories (though they do not assert that these are comprehensive), as seen in Table 3.4 [221]. Notably, each model "perspective" is associated with a "principal concern" and "disciplinary orientation" that seems to exclude the others. An EVDT approach argues that each of these modeling perspectives must be considered simultaneously as problems as "environmental protection, economic efficiency, accessibility, social welfare, and aesthetics." This is not to say that every EVDT DSS must simultaneously model landscape ecology and transportation planning, but it should acknowledge the various (competing or cooperating) concerns. 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 [328].

The set of four models with the particular linkages shown in Figure 3-9 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

Table 3.4: Five categories of urban form models. Adapted from [221]

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

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 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 3-9 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 3.5). 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.

3.4.4 C: Interactive Decision Support System

Ultimately, the goal of the two SAF iterations and E-V-D-T framing is to develop an interactive decision support system (DSS) to inform community decision-making on the topic of sustainable development.

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] [14]. 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 [329], wargaming [330–332], and role playing gaming [333, 334]. Additionally, in contrast to Crawley's definition which centers on the "efficiency of decision-makers," (see the concerns raised in Section 2.3.1) I 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.

The form and functions of the DSS may vary significantly and should be based on the results of the SAF iterations. Regarding form, both of the case studies discussed in this work (Chapters 4 and 5) present desktop-based computer applications. Jaffe used a web-based application, showin in Figure 3-10 (the full application is, at time of writing, available at `https://cranberry-land-use-explorer.herokuapp.com/`) [318]. Another potential form includes paper maps and other forms of data used as part of an interactive session. Note that paper maps are not, in and of themselves interactive, and they run the risk of merely presenting a solution to the stakeholders rather than engaging them to make a decision. In general, EVDT takes a somewhat Harleian approach to visualization, in which "*presentation* is de-emphasized in favor of *exploration* of data" [335].

It should be noted recognized that offline DSSs (be they come in the form of desktop software or pen-and-paper) come with numerous downsides. *theirwork*, an

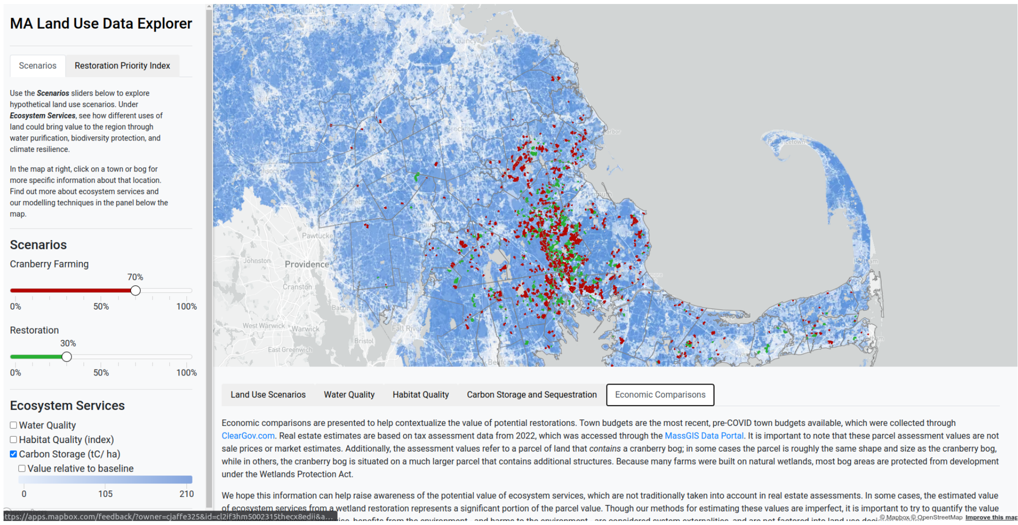


Figure 3-10: Screenshot of Jaffe's Decision Support System. See [318] for more information.

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." [130] This is not universally true, however. *theirwork* was a UK-based project (an area with high internet connectivity penetration) and started in the mid 2000's, a period with significantly less diversity of internet browsing methods compared to nowadays, 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.) [336] have been largely alleviated.

If a web app or some other form is chosen such that a user might engage with the DSS individually, the DSS should include all necessary information to provide both instruction in its use and context for the information presented. Jaffe's DSS does just this, providing instruction in the top left and contextual information across the bottom. DSSs intended for use in group workshops or with guidance can contain less of both instruction and context.

Regarding function, the case study presented in Chapter 5 does some in-app computation and simulation based on user inputs. This is preferred when the potential set of user inputs is quite vast and live computation able to be performed quickly. For Jaffe's DSS, meanwhile, she pre-computed all potential outcomes and the DSS simply presents those outcomes on demand. This is preferred when the potential set of user inputs is restricted (in Jaffe's case, there are ten possible user inputs) and/or computational speed of the models would be quite slow (as it was in Jaffe's case).

Generally an EVDT DSS should include some presentation of GIS data, be it raster data derived from EO imagery or vector demographics data. Choropleths are one of the more common types of non-imagery geospatial data used in EVDT projects. 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 [223, 337]. 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. This is also why, when possible, a zoom function should be provided so that users can focus on particular subsets of the map that are of interest (such as their home or workplace). While three dimensional data exists for both the urban environment [338] and from remote sensing [339], EVDT projects to date have focused primarily on two dimensional symbolic visualizations.

Historically, GIS implementations have often struggled to handle temporal data [135]. For this reason the DSS should not be limited to presenting information in the form of maps. Timelines, graphs, and timelapses may all be relied upon to present changes over time.

All of this points to a general rule of thumb regarding EVDT DSSs: Do not neglect visual aesthetics and usability. Technologists often focus on the underlying models and the "interesting" technical problems. The point of the EVDT Framework is not to make a DSS. The DSS is a means of helping communities to make decisions. In most EVDT projects, at least some stakeholders will not be GIS experts or professionals. Care must be taken so that the visualization is easily understandable by a lay audience. Batty et al. refers to this as the distinction between *backward visualization*, which focuses on developing tools for experts and professionals, and *forward visualization*, which supports decision-making by a less (GIS-)informed constituency, including the public [338].

For example, initial EVDT projects featured quite large graphics. Tufte argues that graphics in general should be significantly shrunk and that "many data graphics can be reduced in area to half their current published size with virtually no loss in legibility and information." [97] In accordance with this Shrink Principle, these graphics were greatly reduced in later versions.

In general, care should be taken in making fundamental architectural decisions in the development of the DSS. As with most GIS software [94], early EVDT projects 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 [104]. Similarly care, must be taken such that the form of the DSS supports the circumstances in which it will be used. Jankowski proposed four different kinds of meeting arrangements, shown in Table 3.5, each with their advantages and disadvantages. Not all DSSs forms are equally suited for each of these arrangements.

Table 3.5: Different types of meeting arrangements. Adapted from [112]

	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)

3.4.5 D: Re-use & Community Development

One of the limitations with some of the previous and current work discussed in Section 3.3, was a focus on solving a particular problem with little attention paid to how to scale or generalize the approach to other problems. This is one of the key benefits of a framework such as EVDT. This section explains how EVDT approaches such scaling beyond an individual problem.

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. Both ends are served by designing the DSS with re-use and modularity in mind. The ability to track mangrove health in Brazil [340] proved to be useful in a later application in Indonesia [311].

The intent is not for this team to develop complete, black-box products, but rather to facilitate the the tool development process for others. Part of this includes the co-design requirement, but another part is making the code itself readily available online and designing the implementation of the framework to be as reusable as possible. In this way, users in a new context may be able to reuse previous EO data processing techniques, while focusing on the vulnerability or decision-making components. This is also important to provide clarity on ultimate ownership and responsibility for the product.

The second form of capacity building is pursued by developing a community of practice around EVDT and related endeavors. This includes enabling "peer-to-peer" interactions where representatives of a community involved in an EVDT project may directly correspond with those from other projects. To this end, the Space Enabled team has been hosting approximately monthly meetings with open invites to all those currently involved in EVDT projects and those interested in becoming involved. These meetings started as part of the Vida project (discussed more in Chapter 5) before transitioning into a broader focus on EVDT projects in general. In the future we would like to have other means of interaction, such as in-person meetings, an online system for sharing information, and more one-to-one meetings that may not involve Space Enabled at all.

3.4.6 E: Collaborative Development

While the SAF specifies that the relationships and perspectives of multiple stakeholders are considered, it does not explicitly call for their participation in the development process. The EVDT Framwork, however, does. It is worth explaining exactly what this entails.

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 [130, 131]. 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 [120]. The history of this trend along with the various benefits, both practical and ethical, of the participative approach, were discussed at length in Section 2.2.6, 2.3.1, 2.3.3, and 2.4.

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 (and the world is better for it!). Collaborative development must therefore take different forms in each project, being as welcome as possible to all while accommodating stakeholder preferences and constraints.

The EVDT Framework invites participation in different forms throughout the process.

1. **Pre-Project:** Ideation through the initial, tentative definitions of the System Boundary. An EVDT project should not be conceived without some active interest from one or more local stakeholder [1]. The more local the better (i.e. a resident or member of a municipal government is to generally to be preferred over a national government minister). This initial contact should not be assumed to be the sole representative of the community but they are integral to starting to grapple with the system of interest.
2. **SAF Iterations:** This is discussed throughout Section 3.4.2. It is the stage at which a wider set of stakeholders are identified, contacted, solicited for perspectives, and invited for further participation.
3. **Development of the DSS:** This refers to the implementing of the forms and functions identified during the SAF iterations, the actual coding or creation of the DSS, including its various constituent models. This typically requires some minimum level of technical knowledge, but do not dismiss local expertise even when they lack some university degree. They are typically the only ones with the requisite knowledge of what assumptions to make in the models, how to go about validating models as necessary, what regional datasets might

[1] See *Local Context Expert* in Section 3.5.

be available, and how to translate terminology[2]. Interest in participating in the actual programming of the DSS (in the cases where the DSS is software) should be encouraged. For those with previous coding experience, numerous platforms, both asynchronous and synchronous exist to allow for collaboration, be it in-person or remote. For those who lack such experience, sufficient coding educational resources are available to help instruct a novice as necessary. Do not begrudge the extra time and effort as the goals is to not make a DSS for its own sake, but to assist the community in making its own decisions.

4. **Deploying and Evaluating the DSS:** Ideally "possession" of the resulting DSS should not reside with a particular stakeholder but instead be available to any with interest. This can include passive means such as deploying a web app (though make sure to advertise its existence) or more active means such as organizing scenario planning workshops or directly soliciting feedback.
5. **Ongoing Collaboration with the EVDT Community:** Participants in one EVDT project should be encouraged to participate in others. This is discussed further in 3.4.5.

The EVDT Framework also certainly builds upon Jankowski's and Nyerges' macro-micro strategy for participatory decision-making [112]. This strategy, shown in Table 3.6, envisions decion-making as taking place across three macro-phases (Intelligence, Design, and Choice), each of which are made up of an iteration of the same four micro-activities (Gather, Organize, Select, and Review). The first iteration of the SAF is essentially a specific approach for accomplishing Phase 1A through 2A. The second iteration of SAF results in the creation of a DSS that in turn supports the community in accomplishing Phase 2B through 3D.

3.5 Intended Applications & Users

Now that the EVDT Framework has been laid out, it is worth considering who we envision using the framework and how they might go about it. While Sections 3.2 and 3.3 established that there was a need for such a framework, we did not clearly articulate for whom this need exists.

[2]Even if you know the primary language spoken by the community, do not assume that all terms are used identically. For example, during the case study in Chapter 4, I initially translated "mangrove health" into Portuguese as "saúde do mangue," only to find out (by asking) that locals tended to use the phrase "qualidade de mangue" instead. This lead to a productive conversation about the distinctions between these phrases and which had the preferred connotation for use in the DSS.

Table 3.6: Generic macro-micro, participatory decision strategy. Adapted from [112]

	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**

First off, as a generalized and participative approach, the EVDT Framework is not intended to be a closed source, proprietary program of Space Enabled. This thesis is partially intended as a guide for others interested in using this framework. It also is 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 [341–343]), and a community of collaboration sprouted. These can be built upon for building a community of practice, where individuals can contribute in a variety of ways, as shown in Figure 3-11. In this way we can increase the number of potential users who are aware of EVDT while also scaling the capacity of facilitators to take on projects with additional communities.

Some of the categories of EVDT community members shown in the blue boxes of Figure 3-11 require further explanation. 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

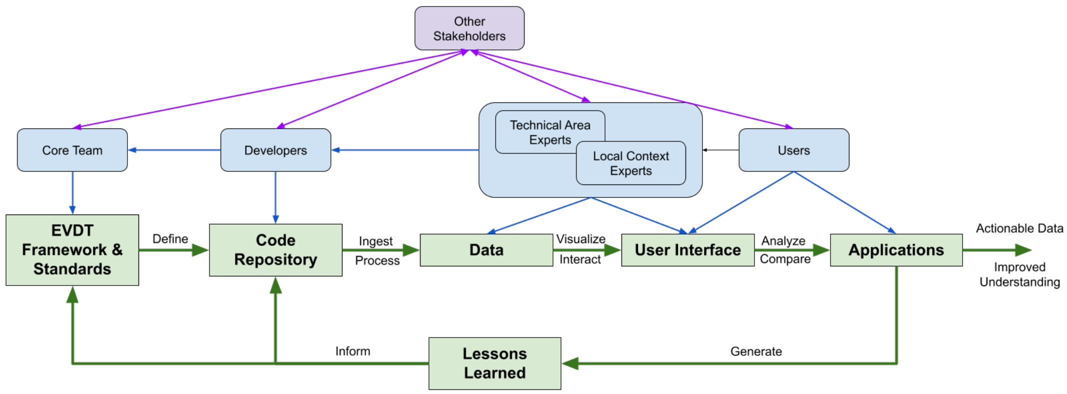


Figure 3-11: The EVDT development pipeline. Note that the different community groups, shown in blue, are not necessarily discrete and one individual could simultaneously participate in multiple.

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. As discussed in Chapter 2, sustainable development is made up of multiple domains interacting in a complex SETS. Each of these domains (including the EVDT domains) have their own disciplinary history and reservoir of technical expertise. While we cannot rely upon them to make all of society's decisions, we can and should rely upon their particular expert advice.

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. The importance of the complementary effect of having both kinds of experts is attested to throughout the literature, including in *Data Action* [120] and *Data Science in Context* [344].

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 3-11 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 3-11, 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 3-12. For instance Items 3 and 4 (best served by configuration B of Figure 3-12) 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. [345]). 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.

As explained in the introduction to Section 1.1, one of the goals of the EVDT Framework is to bring some of the benefits or EO and environmental modeling to a smaller spatial scale. When operating on such scales, we must be careful about what metrics of human wellness we use. 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 [223]. 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 [223]:

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

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 3-11, 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.

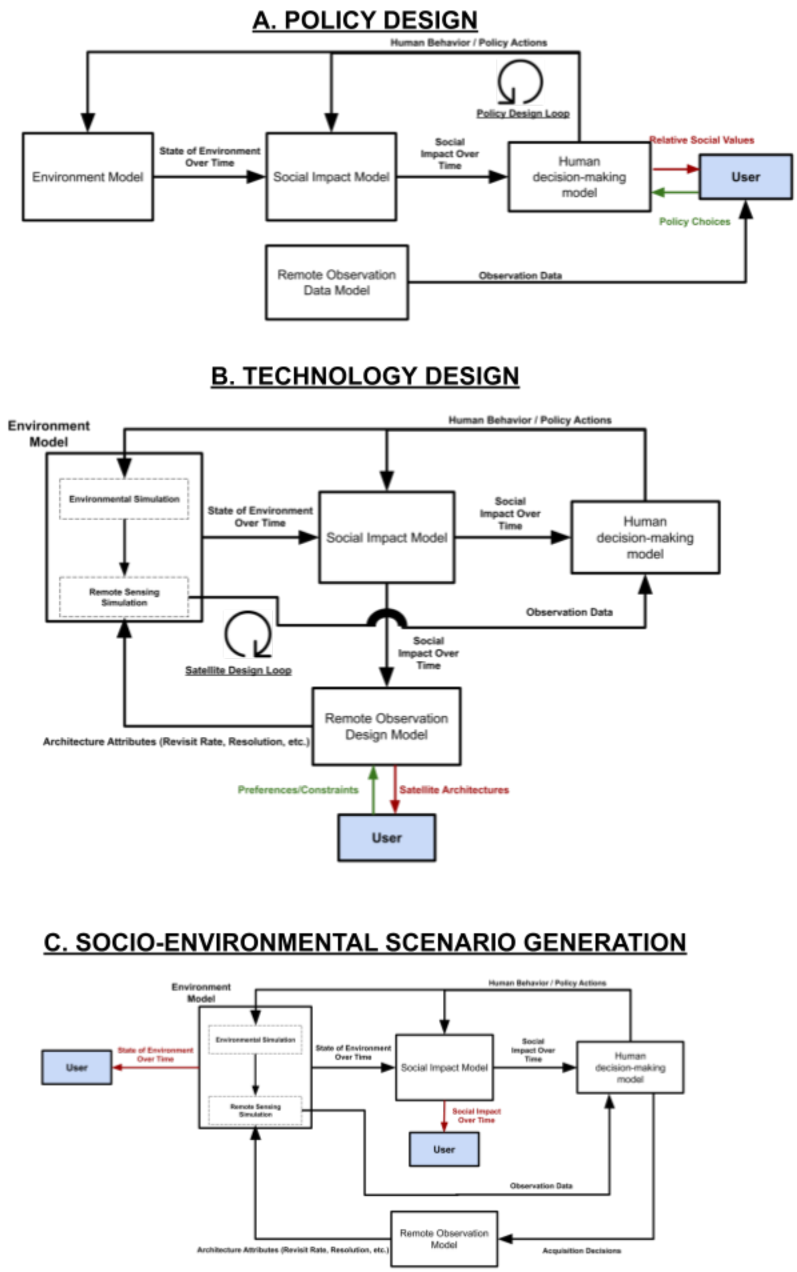


Figure 3-12: Three example EVDT research configurations

3.6 Conclusion

This chapter laid out the Environment, Vulnerability, Decision-Making, Technology (EVDT) Framework, providing detail on each of its five elements:

A The use of systems architecture & stakeholder analysis to identify needs, design the DSS, and understand the context through the use of the Systems Architecture Framework (SAF). This requires significant engagement with as many of the stakeholders as is feasible (if not more). Usually two or more iterations through the SAF cycle are required.

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

C 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 .

D 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.

E 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.

In doing so this chapter has provided Research Deliverable 1b:

> *A proposed framework for applying systems engineering for sustainable development in an participatory and social-justice-oriented manner.*

While this chapter includes some brief mentions and anecdotes about concrete applications of the EVDT Framework, it still remains to actually see EVDT in action. Such applications is precisely what the following two chapters (Chapters 4 and 5). The first is focused on mangrove conservation and economic development in a particular neighborhood of Rio de Janeiro, Brazil. The second is focused much more broadly on COVID-19 response across a variety of metropolitan areas.

Another limitation of this chapter is that it primarily considered the EVDT Framework as a static, finished creation, sprung into existence fully formed like Athena. This, of course is an oversimplification. The EVDT Framework was created in an incremental, iterative, and syncretic fashion over the course of the past few years, from early conference presentations [6] to this thesis. Similarly, the EVDT Framework is by no means final. The very case studies presented in the following chapters provided significant learning opportunities for future revision, as have projects undertaken by others such as Ovienmhada [11, 326] and Lombardo [311]. Chapter 6 will review these lessons, including discussing how the case studies would have been performed differently in retrospect. It will also provide a potential road map for how the EVDT Framework may develop in the future.

Chapter 4

Rio de Janeiro Mangroves

4.1 Chapter Purpose & Structure

The case study detailed in this chapter is in service to multiple objectives. First, it seeks to address Research Question 2: “What are the sustainability benefits of collaborative development of DSSs using the Environment, Vulnerability, Decision-Making, Technology (EVDT) Modeling Framework in complex socio-environmental- technical system (SETS)?" It accomplishes this by providing a case study demonstration of Research Deliverables 2a, 2b, and 2c:

a System architecture analyses of each of the case studies
b Development of an EVDT-based decision support system (DSS) for each of the case studies
c An interview-based assessment of the development process and usefulness of each DSS

Through these deliverables, this chapter serves as a demonstration of the EVDT Framework. The structure of this chapter thus mirrors the components of the framework laid out in Section 3.4. It starts by walking through the steps of the Systems Architecture Framework (SAF) as applied to this case study in Section 4.2. These are separated into the methodology used for each step of the SAF (Section 4.2.1) and the results of each step (Section 4.2.2. Then, in Section 4.3, it shall turn to showing relevant datasets and analysis as applied through the Environment, Vulnerability, Decision-Making, Technology (EVDT) models. These two are separated in methodology (Section 4.3.1) and results (Section 4.3.2. These are then integrated into a prototype DSS in Section 4.4. Finally Section 4.5 lays out how various stakeholders were collaborated with beyond the setting of requirements during the SAF process.

The remaining sections examine and discuss the outcomes of this case study. The following chapter will similarly present a second case study.

It should be noted that, as stated in Section 1.1, each case study also has its own objectives beyond supporting a chapter of this thesis. In this case, that means supporting policy decisions in Rio de Janeiro surrounding human wellbeing and mangrove conservation. Readers specifically interested in the socio-environmental history of the study area are pointed to Section 4.2.1.1. Those interested in environmental analyses performed in the course of this research are pointed to Sections 4.3.1.1, 4.3.2.1, and 4.6.

Finally, this research was begun in 2017. Field visits took place in 2019 and 2020, the latter of which was interrupted by the onset of the COVID-19 pandemic (as was this project in general). Our research and development priorities (both mine and those of our Rio de Janeiro colleagues) shifted to more urgent concerns. This means that aspects of this chapter are a couple of years old at the time of writing and various desired objectives were never reached. This is discussed further in Section 4.6.

4.2 Systems Architecture Framework

The following subsections work through the six steps of the SAF originally detailed in Section 3.4.2 as applied to the Rio de Janeiro mangrove case study, first as methodology and then as results. The goal is to identify what information, analyses, and other forms of decision support would be useful to stakeholders in the Guaratiba area.

4.2.1 SAF Methodology

4.2.1.1 System Context

Rio de Janeiro has a great deal of familiarity with the descriptor *iconic*. The word is frequently associated with the city's beaches, Copacabana and Ipanema, and with its festivals, such as Carnaval. So too have the city's hillside favelas found themselves as perhaps the definitive image of informal settlements and poverty in the global popular consciousness. It stands to reason that when the city hosted not just one but two megaevents in a row, the 2014 FIFA World Cup and the 2016 Summer Olympics, massive amounts of attention would be paid to the city not only by the urban planners, activists, and economists used to critiquing such endeavors, but by the international press and general public as well. As residents of distant countries, we were presented with stunning photos of the sports facilities being constructed [346] followed by equally stunning photos of their abandonment and disrepair [347]. The academic literature is full of critiques of these events, with particular focus on the processes and effects of the major projects such as the Maracanã stadium and the Porto Maravilha redevelopment [348], as well as the displacement and responses of the directly impacted communities [349, 350].

This case study does not focus these stadiums and favelas. It is not, ultimately, a further elaboration on the *iconic* Rio de Janeiro. Rather it seeks to examine and discuss a particular neighborhood, one that is (or rather, has been) in an out-of-the-way corner of the municipality, away from the gorgeous beaches and troubled favelas, more swamp and farm than urban, yet still important for reasons that will be made clear. This area, Guaratiba (and more specifically, the area stretching between Pedra de Guaratiba and Barra de Guaratiba), is, despite its relative remoteness in the southwestern corner of the city, still a part of Rio de Janeiro, and thus affected by the powers and forces at work in the city. To this end, after defining the study area, I will briefly lay out the relevant parts of recent Rio urban planning history, specifically the city's long fascination with grand plans and its oftentimes confusing overlay of government jurisdictions. Afterwards, we will dive into Guaratiba itself: its environment, its people, and its potential future.

4.2.1.1.1 Study Area

Guaratiba is a relatively rural district of Rio de Janeiro situated in the southwestern corner of the municipality. Rio de Janeiro is divided in 5 administrative zones, which are further divided into Regiões Administrativass (RAs), as seen in Figure 4-1. Guaratiba is RA XXVI, simultaneously one of the largest of the RAs by land area and one of the smallest by population, constituting only 1.9% of the municipal population as of 2018 with only has three official barrios (or neighborhoods) within it [351]. 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, contained primarily in the coastal region of the RA between the Barra de Guaratiba (152 on the map) and the Pedra de Guaratiba (153). This means that the bulk of the approximately 120,000 residents of the RA are to the north of the mangroves, but there are still approximately 20-25K people in close proximity.

These mangroves are vulnerable due to landward urbanization, including a recently opened urban transit line, and rising sea levels [352]. 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 [353]. 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 [354], made the Guaratiba mangroves a particularly suitable case study for the EVDT Modeling Framework.

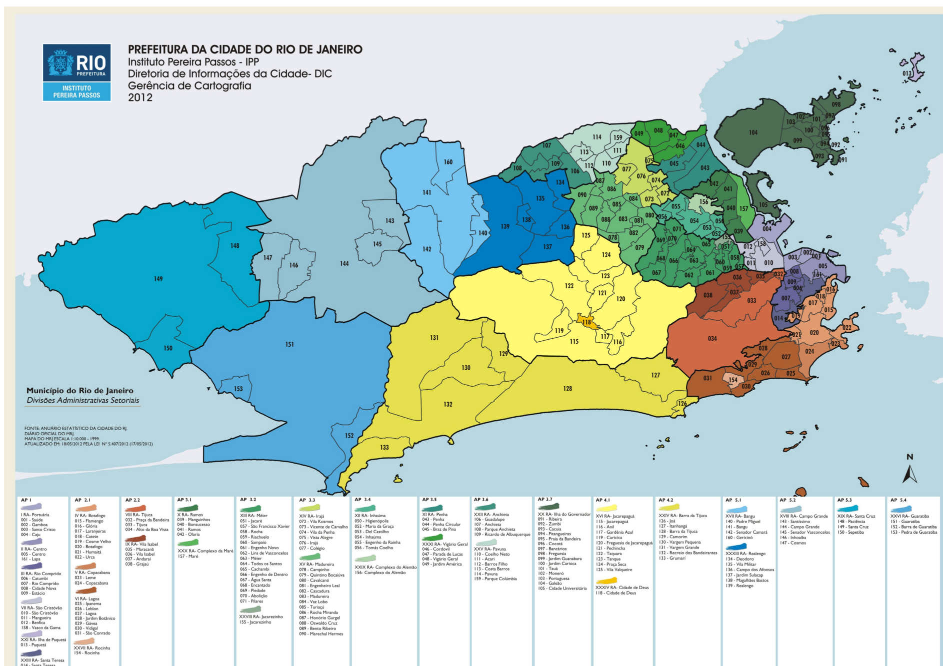


Figure 4-1: RAs of Rio de Janeiro. Guaratiba in blue and includes the barrios 151-153.

In order to further establish the system context for the Guaratiba area, I conduct a literature review and synthesis. In particular, I use four lenses to examine the system context:

1. What are the broader municipal and regional dynamics impacting Guaratiba? (Section 4.2.2.1.1)
2. What are the different government jurisdictions at play in the area? (Section 4.2.2.1.2)

3. What is the past, current, and likely future state of the environment in Guaratiba? (Section 4.2.2.1.3)
4. What is the past, current, and likely future socioeconomic state of Guaratiba? (Section 4.2.2.1.4)

4.2.1.2 Analyze System Stakeholders

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 [355, 356] and who are also familiar with examining socioeconomic impacts of environmental phenomena [353]. 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 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.

Over the course of two field visits to Rio de Janeiro and Guaratiba (one in August of 2019 and the other in March of 2020), I conducted a series of interviews and meetings with various key stakeholders in the Guaratiba system, including local fishers; local academic researchers; and municipal, state, and federal government officials. I was introduced to these stakeholders using a snowball approach, starting with connections stemming from the Space Enabled Research Group and our primary point of contacts in Rio de Janeiro. Information about both contacted and noncontacted stakeholders are summarized in Table 4.1. Clearly there are some key stakeholders listed in the noncontacted categories. This demonstrates the flaws of a snowball approach and, while I did make attempts to contact them myself, these were to no avail. Further persistence and creativity may have rectified this but unfortunately the pandemic cut the second visit short. Similarly, I intended to follow up some of the unstructured meetings with formal interviews but did not have such an opportunity.

Table 4.1: Rio de Janeiro Stakeholder Contacts. This table does not include casual interactions or discussions about unrelated topics to this project.

Contacted Stakeholders			
Stakeholder Organization/Affiliation	**Description**	**# of Individuals Contacted**	**Type of Contact**
Pedra de Guaratiba Fishing Association	local organization	1	Extended Unstructured Meeting; Site Tour
ESPAÇO Research Group of UFRJ	Academic researchers at local institution	2	Multiple Unstructured Meetings; Multiple Site Tours
IPP	Municipal government data management agency	2	1 Formal Interview; Multiple Unstructured Meetings
Secretaria Municipal de Meio Ambiente (SMAC)	Municipal government environmental agency	3	1 Formal Interview; Unstructured Meeting
Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio)	National government environmental agency	3	Unstructured Meeting
Secretaria Municipal de Urbanismo (SMU)	Municipal government planning agency	2	Multiple Unstructured Meetings

Uncontacted Stakeholders		
Stakeholder Organization/Affiliation	**Description**	**Explanation**
Comissão dos Moradores	Local resident's committees common throughout Rio de Janeiro	Unable to find online contact information; other contacts were unwilling or unable to furnish an introduction
Movimento dos Trabalhadores Rurais Sem Terra (MST)	Brazilian Marxist social movement	No response received from email queries; Other contacts were unwilling or unable to furnish an introduction
Instituto Brasileiro de Análises Sociais e Econômicas (ibase)	Local NGO / activist organization	No response to contact request via the organization's website
Instituto Estadual do Ambiente (INEA)	State Government Environmental Agency	Had brief, casual interactions with multiple officials but, after several attempts, was unable to schedule dedicated meetings

The formal interviews varied in length from 30 minutes to 1.5 hours, semi-structured, and conducted in-person. The informal meetings lasted from 30 minutes to 3 hours and were conducted in-person. Only the formal interviews were recorded For the recorded interviews, the recordings were reviewed and using to generate notes and codings. For all the others, written notes were taken during and immediately after the meeting.

The questions asked in both the formal interviews and the unstructured meetings were derived from the SAF structure. For example to address a SAF question such as “What are your (stakeholder’s) primary needs?", I asked questions such as “What is your organization’s primary goal/mission?" and “What are some questions that you would like to be able to answer but can’t? What are some challenges that your organization faces?" These questions served to supplement the System Context understanding, identify additional stakeholders, clarify the relationships between stakeholders, and identify potential Needs, Goals, Challenges, Relationships, Functions, and Forms as discussed in the subsequent sections. The list of questions for the interview and discussions can be found in Appendix B. For any given interaction, these questions were adjusted to match the stakeholder and additional followup questions were added as needed. In some cases questions were skipped when the respondent had already addressed it while answering a previous question.

4.2.1.3 Understand Desired Outcomes & Objectives

I coded the recordings and notes qualitatively based on the SAF in order to develop meaningful themes and conclusions, identify commonalities and differences across the stakeholders, and better understand the relationships between stakeholders. These were used to construct a basic stakeholder map and begin to articulate what questions a DSS could potentially answer for each stakeholder (connected to their particular Needs, Goals, and Challenges).

4.2.1.4 Select System Functions

System functions were selected by considering the various Stakeholder Needs and identifying where significant overlap existed. These were then compared with the feasibility of each function given available data and other resources. Further input from stakeholders on potential functions was solicited during the March 2020 visit, where some an initial DSS prototype and analysis was available for concrete reference. Prior to the pandemic intervening, the intent was to use this latter set of meetings to construct a definite list of potential DSS functions and have stakeholders assign importance weights to each one, in order to guide further development.

4.2.1.5 Assign Function to Forms

System functions were assigned to forms based on balancing the capabilities of the Space Enabled team with the needs and preferences of the stakeholders, particularly concerning usability. For instance, those at IPP and SMAC had significant experience working directly with remote observation imagery in GIS software, but not all stakeholders shared this competence. Forms had to thus be selected with such differences in mind.

4.2.1.6 Monitor and Evaluate Systems

The impact of the DSS, analyses, and other EVDT Framework outputs on policy cannot be directly evaluated in this case study because (a) the time scales at which mangrove conservation, urban development, and socioeconomic changes occur at are well beyond the duration of a single individual's doctoral process; and (b) there are innumerable confounding factors that make developing a reasonable counterfactual infeasible (e.g. political changes, macroeconomic changes, climate change, etc.). In lieu of such direct measurement of impact, the best alternative is to focus on perceived utility by the stakeholders. The plan to accomplish this was user study workshops in which various stakeholders would seek to answer various questions about desired policy choices both with and without the use of the DSS and other analytic products. Unfortunately the coronavirus pandemic prevented this from occurring, so only informal feedback from a subset of stakeholders was able to be solicited.

4.2.2 SAF Results

4.2.2.1 System Context

Here I present the relevant information about the System Context of this case study. This is the result of both a literature survey and several stakeholder interviews and meetings. These findings are briefly summarized in Figure 4-2

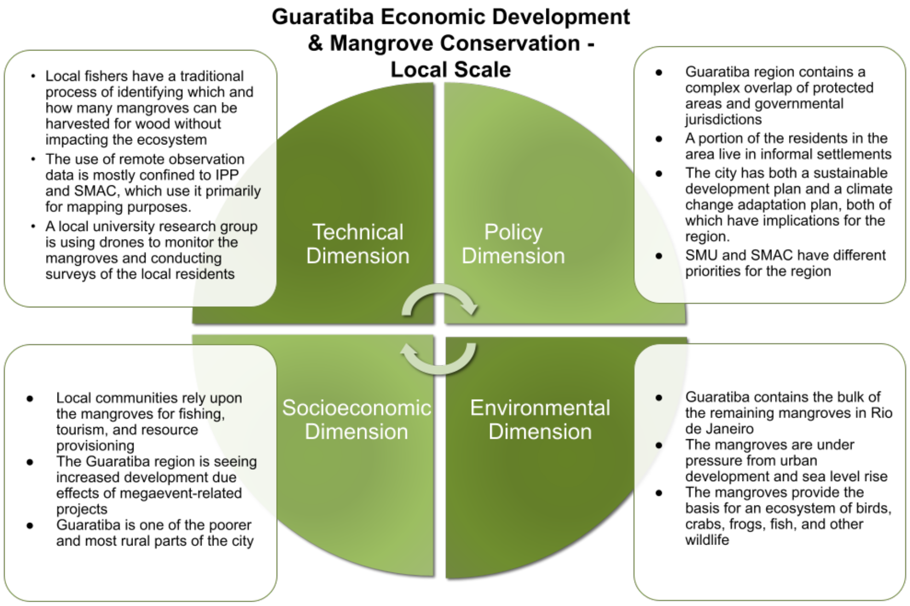


Figure 4-2: Rio de Janeiro System Context Dimensions

4.2.2.1.1 Big Plans and Megaevents in Rio de Janeiro

Rio has a history of being on the forefront of intentionality and long-term strategic thinking when it comes to urban planning. In 1995, it became the first city in Latin America to develop a strategic plan, something it continues to do in three-year increments to this day [357]. Specific programs stemming from these plans include the Favela Bairro Programme which sought to upgrade the informal settlements and the Rio-Cidade Programa which sought to revitalize certain key areas of the city [358].

This type of strategic planning took place alongside a broader effort in the city and across Brazil to increase democratic participation in the planning process, as the country transitioned out of a military dictatorship [358]. This interest in blending democracy with planning could also be seen in replacement of the government-owned Municipal Computer and Planning Company with the SMU and IPP, thereby retaining both planning and data gathering capabilities, but putting them in the hands of government offices. While Rio has never reached the same level of public participation as Porto Alegre [359], this inclination has continued to today, as seen in efforts like the Data.Rio platform, which seeks to make increasing amounts of data about the city freely available online, and the proliferation of neighborhood-level"Associação De

Moradores" (Residents' Associations).

Perhaps due to its beautiful natural environment and the importance of its tourist industry (a major focus of the 1995 strategic plan), Rio de Janeiro has long acknowledged the importance of environmental conservation and sustainability when it comes to development. Even prior to 1995, the city hosted the United Nations Conference on Environment and Development (UNCED), which gave birth to the Climate Change Convention, itself the basis for international climate change agreements. Twenty years later, the city would once again play host to such a conference, this time in the form of the 2012 United Nations Conference on Sustainable Development (UNCSD), which paved the way for the creation and adoption of the SDGs by the UN General Assembly three years later. It should be made clear that Rio de Janeiro was no mere picturesque venue for these conferences. Rather, the city has taken the UN pronouncements of sustainable development seriously, publishing a Climate Change Adaptation Strategy in 2016 (utilizing entirely intra-country expertise) [360] and a Resilience Strategy in 2017 (created in partnership with the Rockefeller Foundation) [361]. The city is currently using a participatory process to create a Sustainable Development Plan that will detail how the city intends to contribute towards the SDGs [362].

A plethora of plans does not necessarily result in smooth sailing, however (in fact, many would say that it is directly contrary to good development [173]). While the climate and sustainability-related plans advocate for environmental protections, energy efficiency, and waste controls, the strategic plans have focused more strongly on economic development and the tourist industry, which is related to but not identical with environmental conservation. These latter plans have explicitly espoused the use of sports megaevents (which manifested in the form of the 2014 FIFA World Cup and the 2016 Summer Olympics) as a way of attracting investment [348], a pursuit that has arguably done little to advance either sustainable development or climate change resilience, particularly as many of the recent venues were built directly on waterfront or on protected nature reserves [363].

Of particular relevance to Guaratiba is how the megaevent-related development reshaped transportation patterns and commercial development throughout the city. This phenomena is perhaps best explained through the use of three maps. Figure 4-3 shows the origin and destination of most of the favela relocation efforts (both voluntary and mandatory) in the years leading up to the World Cup and Olympics. Most of the new settlements were constructed under the Minha Casa Minha Vida (MCMV) program, a federal program started in 2009 that enabled the some of the poorest households in Brazil to purchase new homes with little-to-no down payments, interest rates of near-zero, and income-adjusted monthly payments. The program was initially aimed at building one million homes nationwide, then later expanded to three million, of which more than 100,000 were assigned to the city of Rio de Janeiro [364]. The city partly used this allocation of federal funds to support favela relocation efforts as part of megaevent-related development.

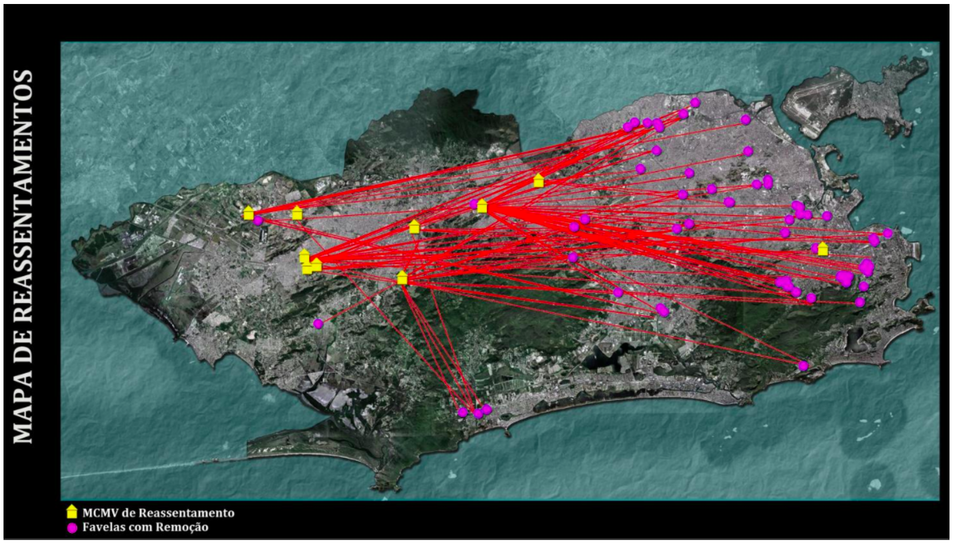


Figure 4-3: Favela Relocation Locations under MCMV between 2009 and 2013. From [365]

The relocation of favela inhabitants from east to northwest introduced problems, however. The original siting of informal settlements in Rio de Janeiro was partially driven by the availability of proximal employment. This is why historically, despite low land prices in the rural western parts of the city, most of the city's poor elected to live in high density favelas in the eastern, urban neighborhoods. Figure 4-4 shows that while the new, formal MCMV homes may have been higher quality than the old favela homes, they were also much further away from major centers of employment. Getting a nicer home is not much consolation for losing your job.

The Rio de Janeiro government was neither completely ignorant nor completely callous, however. As is common in the lead-up to sports megaevents, the city planned significant renovations, improvements, and extensions to the existing public transit system, as shown in Figure 4-5. Some of these, in particular the extension of the metro and the dedicated-lane bus Transoesto from Copacabana towards Barra Da Tijuca, were intended primarily to improve access to the major Olympic sporting venues. Many of the extensions, however were intended to better connect the northern and northwestern reaches of the city with the centers of employment, alleviating

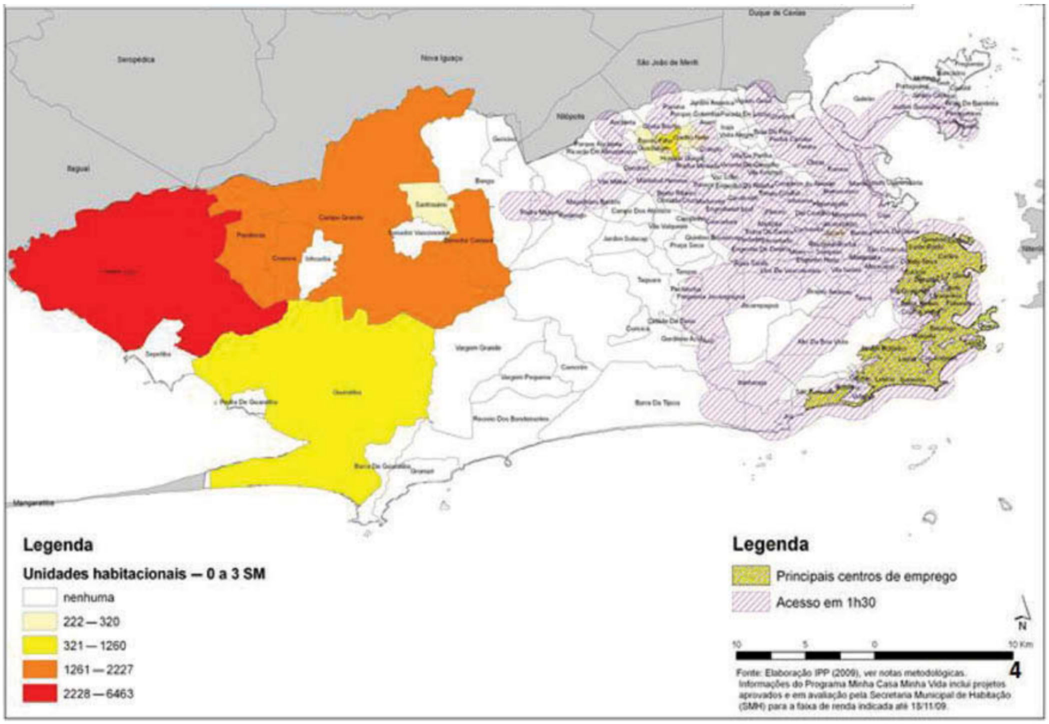


Figure 4-4: Comparison of MCMV housing units and access to major employment centers. From [348]

the concerns of those being relocated, while also improving accessibility for the existing residents of those areas.

Unfortunately the transit extensions were not as extensive, reliable, or high speed as initially promised [367] and access to jobs for poorer communities ultimately decreased [368]. None of this directly impacted Guaratibans, however, as Guaratiba, tucked in the southwestern corner of the city, was neither the source nor destination of relocation efforts. What *would* impact Guaratiba was the the Transoesto line and the related expansion of bus routes and road widths. These significantly increased the accessibility of downtown Rio de Janeiro for the largely rural Guaratibans (and vice versa). This accessibility significantly increased the value of the area for commercial activity and development, exacerbating ongoing local trends, as will be discussed further in Section 4.2.2.1.4.

4.2.2.1.2 Overlapping Jurisdictions in Guaratiba

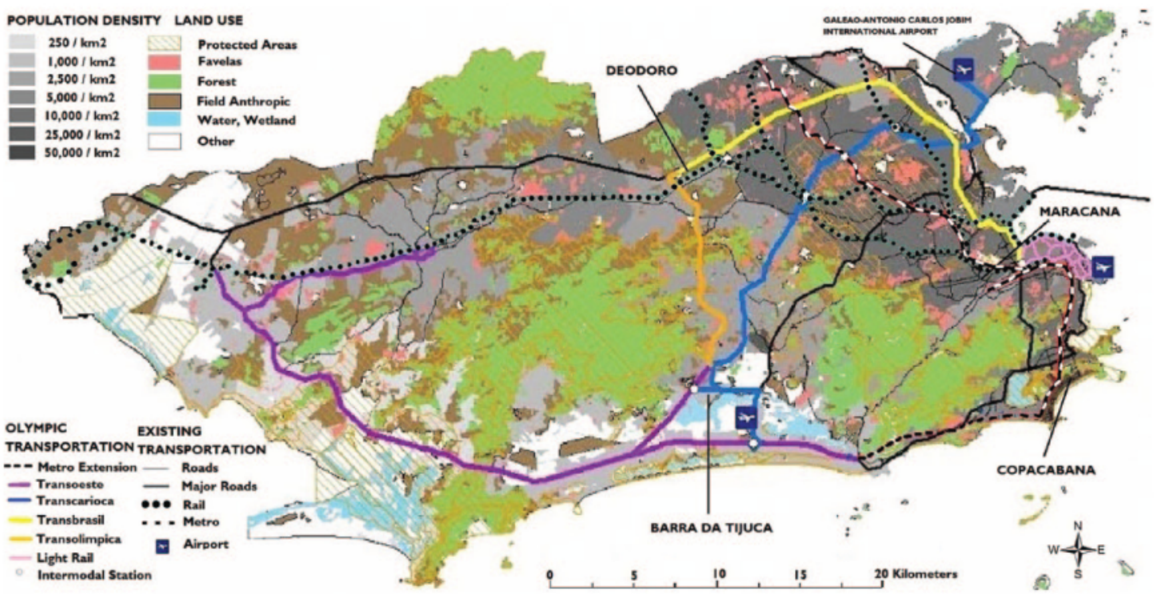


Figure 4-5: Olympic-related transportation expansions and proximity to environmental protection areas. From [366]

While the city of Rio de Janeiro has busied itself with high-level plans, the municipal government is by no means the only government player in the city. Brazil has a whole has significant amounts of jurisdictional overlap between its municipal, state, and federal levels of government, when compared to countries such as the United States [369]. This is particularly true for the city of Rio de Janeiro, which for more than 200 years until 1960, was the capital of Brazil. To this day, numerous institutions and roles within the city that elsewhere would be managed by the state or municipal governments are still federally administered. For example, there are numerous individual public schools, from primary through tertiary, that are run by either the city, state, or federal government, fairly independently of one another. In the field of environmental management, both the federal and state constitutions have chapters on the environment, and the municipality has its own an environmental secretariat. These distinct sources of authority are often visible in regulatory law, such as the separate endangered species lists maintained by the federal [370] and state governments [371].

The most relevant aspect of these overlapping environmental jurisdictions when it comes to the Guaratiba area is the Carioca Mosaic[1]. This term refers to the

[1]"Cariocan" is the demonym for inhabitants of Rio de Janeiro and "Carioca" or "Carioco" is an

federally-coordinated collection of federal, state, and municipal environmental conservation areas in the greater area of the city of Rio de Janeiro [372]. Within the Mosaic, the federal government's ICMBio administers one national park and one national monument; the state government's INEA administers one state park, two environmental protection areas, and one biological reserve; and the municipal government's SMAC administers 14 nature parks, two environmental protection areas, and a natural monument.

Of these various units, the following are in or in direct proximity to the Guaratiba area:

- Área de Proteção (APA) Ambiental das Brisas (municipal)
- APA da Orla da Baia de Sepetiba (municipal)
- Parque Natural Municipal da Serra da Capoeira Grande (municipal)
- Parque Nacional Municipal da Prainha (municipal)
- Parque Nacional Municipal de Grumari (municipal)
- Reserva Biológica Estadual de Guaratiba (RBAG)[2] (state)
- APA Sepetiba II (state)
- Parque Estadual da Pedra Branca (state)

This means that those who live and work in the Guaratiba area will regularly come into contact with eight different municipal and state-run conservation areas that are then collectively coordinated by the federal government. Such an arrangement has both benefits and costs. On the positive side, it can help ensure a certain minimum level of environmental protection amid shifting government priorities. For instance, at the time of writing, the state government of Rio de Janeiro is prioritizing security [374] while the federal government is actively scaling back environmental protections

often-used adjectival form.

[2]Until 2006, this land was controlled by the nearby Brazilian Army Centro Tecnológico do Exército (CTEx), which continues to occupy a significant amount of land in the Guaratiba area and maintains some facilities within the RBAG. Similarly to other military administered lands in various parts of the world, CTEx's control of this land results in a kind of quasi-environmental protection that is simultaneously less formally determined than actual environmental conservation areas but much more stringently enforced in practice. For example, there is an army vehicle workshop that disposes of waste directly into the mangroves, but commercial activities and unauthorized human access are strictly forbidden [373].

[375]. If one of these levels of government were solely in charge of environmental protection within the city of Rio de Janeiro, significant harm to the environment might occur, but since there are overlapping jurisdictions, the municipal government can continue to guarantee some minimum level of protections. Unfortunately, this system can (and does) not only lead to perhaps overly cumbersome permitting requirements for certain development projects, but can also lead to a diffusion of responsibility for environmental protections and inconsistent enforcement.

This confusion of jurisdiction can have real consequences for residents of the area, particularly the disenfranchised. Take the case of Araçatiba, a small favela almost completely surrounded by the RBAG. The favela ended up in its current position in the 1970s after commercial development (specifically television filming) pushed residents away from their previous location. At the time, this land was controlled by the Brazilian Army CTEx. In 2006, the CTEx transferred most of the land in this area to the state government to form the RBAG and to protect the local mangrove forests. Some additional land, including the Araçatiba favela, was transferred to the civilian federal government. Over the next several years, the federal government took various measures to formalize the settlement, only to reverse course in 2014 and seek evictions instead [376]. The mayor at the time, Eduardo Paes, promised to prevent these evictions, but his successor did not follow suit, resulting in the demolition of several homes in 2017 and the threat of continued demolitions in the months to come [377]. After protests organized by the favela residents, the federal government and INEA (the state environmental agency) apologized for the demolitions. Meanwhile, progress towards formal titling has stalled as it is dependent on homes being "upgraded," which the city government has shown little interest in pursuing. Amid all of this is a somewhat bizarre digression that the federal government claimed that proper notice had been given prior to the demolitions via a message delivered to the president of the Araçatiba Residents Association, an organization that had not met in more than ten years [378].

To summarize, the federal government tore down homes on federal land after being prevented for several years from doing so by the city government. The ensuing protests resulted in an apology by the state government and a refusal by the city government to certify the formalization of the settlement, which is still on federal land.

Of course, one favela is not necessarily representative of an entire region. The next two chapters will thus explore how the themes of this section and the previous section impact the people and environment of Guaratiba.

4.2.2.1.3 The Environment of Guaratiba

The distinguishing environmental aspect of the coastal Guaratiba area is its significant mangrove forest, made of five different mangrove species. Prior to colonization, most of the Rio de Janeiro coastal areas were either mountains or covered by mangroves. Over the centuries, the lowland mangrove forests were incrementally destroyed and filled in order to accommodate the growing city. The remaining mangrove trees of the greater Rio area, shown in Figure 4-6[3], are confined primarily to northern Guanabara Bay (outside of the municipality) and eastern Sepetiba Bay (the bay on the western side of the city). This means that the Guaratiba forest, and the RBAG in particular, is the largest copse of mangroves within the city's jurisdiction. These mangroves provide a variety of ecosystem services, including serving as a mechanism for highly efficient carbon sequestration, supporting a subsistence industry of fishing and crab catching (supporting vulnerable, juvenile shrimp in particular [379]), preventing coastal erosion, and attracting a local ecotourism industry. Even these trees are under an ongoing threat.

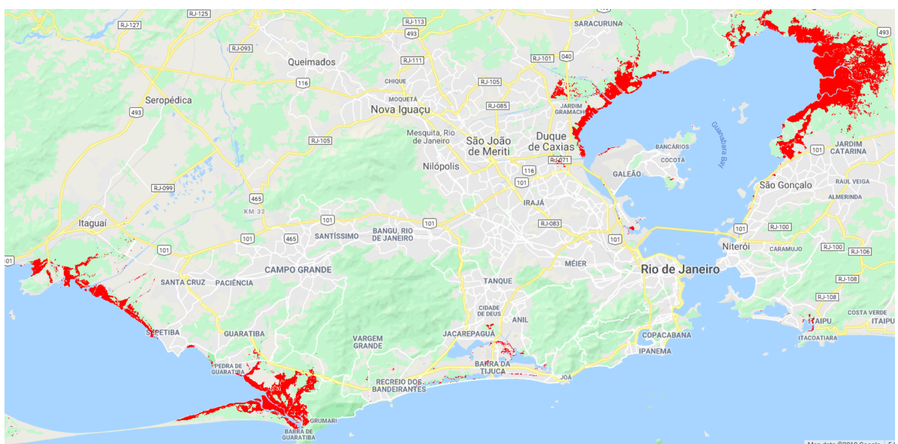


Figure 4-6: Mangrove extent in the greater Rio de Janeiro area in 2018, as estimated using a combination of Landsat, Sentinel, and PALSAR imagery.

Just up the cost from Pedra de Guaratiba, in the Santa Cruz RA, the Ternium steel mill opened in 2010[4]. This mill, along with its associated facilities, including

[3] The methodology used to generate this and other original figures in the section are presented in Section 4.3.1.1.

[4] Ternium purchased the steel mill in 2017. At its opening in 2010, the factory and associated port were operated by Thyssenküpp.

an expanded canal, a bridge, a dam, and dredging of the bay directly replaced or caused the death of a significant number of mangroves (approximately 145 hectares) [380]. Various indirect damages, including pollutants, silt disturbances, and changes in hydrology have resulted in further loses over the past several years [381]. These effects are visible in the northwest corner of Figure 4-7. In this figure, red indicates damage to mangroves, including both decay and outright losses. Green indicates growth, both of existing trees and of new trees.

Figure 4-7: Change in Guaratiba area mangrove health from 2000 to 2018, with the Gerdau Cosigua and Ternium steel mills indicated.

While outside our direct area of interest, the steel mills of Santa Cruz have indirect effects on Guaratiba and are demonstrative of the results of potential industrial development further down the coast. In Guaratiba proper, the direct human-interfaces with the RBAG include CTEx in the center of the reserve, the Barra de Guaratiba neighborhood to the southeast, the Ilha de Guaratiba neighborhood[5] to the north-

[5] Ilha de Guaratiba is technically just a subdivision of Barra de Guaratiba. That said the two names are typically used to refer to different areas that have substantially different histories and economies and are only connected by a strip of land. Barra de Guaratiba is the urban cluster on the coast at the southern tip of the RA. It was historically a fishing village and more recently a tourist destination. Ilha de Guaratiba, on the northern end of the official neighborhood along the highway, is a historical agricultural marketplace. The use of these names in this paper will stick to the common usage, particularly as we are more interested in the coastal regions rather than more

east, the Embrapa Agroindústria de Alimentos to the north, and the Araçatiba favela on the northeastern edge. Most of these areas are clearly visible in Figure 4-8.

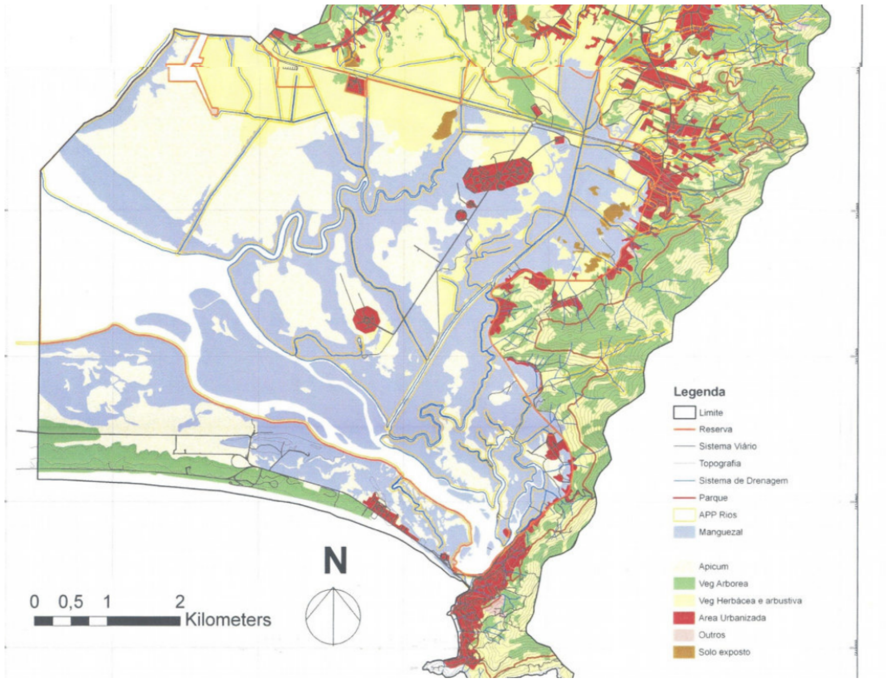


Figure 4-8: Map of RBAG and nearby urbanization. Excerpted from [373] and originally made by IPP.

The health of the RBAG mangroves is a mixed bag. There has been some damage to certain sections of the forest, partly due to an invasive insect species and partly due to the increased sewage flows created by an increasing population and increased commercial activity. The dumping of waste in informal landfills, even when outside the mangrove forest itself, can still cause damage, as flows of water can be diverted or blocked, killing off sections of mangroves [382]. All of this is driven by the fact that while there are significant legal environmental protections within RBAG, there are essentially no restrictions on development and activity just outside of the reserve, despite the fact that the mangrove forest occupies one of the primary outlets of regional drainage basin.

One component of the mangrove forest that is most directly threatened by commercial development are not the mangroves themselves, but the *apicun*, hyper-saline mudflats created by the mangroves in various places on the interior and edge of the

inland areas such as Ilha de Guaratiba.

forest. These flats provide a variety of important ecological functions, such as serving as migratory stops and breeding grounds for thirty-nine species of birds[6] and homes for twelve species of crabs (a major target of local fishers) [383]. They also represent a of land that the mangroves spread into when pressured from other directions. Despite these important functions, the apicuns are not as well protected as the mangroves themselves under the law and are commonly viewed by the public as wasted land that serves no purpose and thus ripe for development.

Additionally, part of the aforementioned transit expansion efforts was the construction of the first highway through the region, Av. D. João VI. This highways has isolated a section of mangrove forest from the main RBAG with implications that are yet to be seen. One key consequence of the highway is that the mangroves no longer have a mechanism for moving inland in the face of seaward pressures, such as a rising sea level that may take place over the coming decades.

4.2.2.1.4 The People of Guaratiba

Guaratiba has historically had such a small population largely been due to its relative isolation. Separated by mountains on the east from the primary urban core and on the north from the more heavily populated Campo Grande RA, Guaratiba is largely rural and heavily forested. Since the decline of colonial-era plantation farming, the residents have primarily engaged in subsistence and near-subsistence commercial activities, including artisanal fishing, farming, and ranching (including of frogs). The products of this economic activity were typically sold (via local distributors) in outdoor markets (called *fieras*) throughout the Rio de Janeiro city. This largely informal supply chain kept residents somewhat isolated from the globalized agricultural markets that drove industrial farming in other parts of the city [384].

By most development metrics, the inhabitants are some of the worst off in Rio de Janeiro, with low rates of education, more children per family, and poor health. An example of the latter can be found in the fact that approximately a quarter of the dogs in the area carry American visceral leishmaniasis (AVL), a typically fatal parasite, and human cases are relatively common, particularly in the Barra de Guaratiba area, despite control efforts [385]. Over the past few decades, however, the the area has been experiencing rapid growth recently, significantly outpacing the city as a whole [386]. Much of this was driven by increasing industrial employ-

[6] It is perhaps worth mentioning that this number used to be higher. For instance, Guaratiba takes its name for the local word for the scarlet ibis bird: *guarás*. This bird is no longer found in the Rio de Janeiro area, pushed out due to a declining availability of its preferred habitat, the mangroves.

ment opportunities in Campo Grande and Santa Cruz, to the north, of which the aforementioned steel mills are just one example. These areas have historically been significantly easier to reach than the core of Rio de Janeiro to the east. The more recent transit expansion projects have accelerated this trend, enabling easier access to Campo Grande and Santa Cruz. The improved connections eastward have also allowed for a more substantial ecotourism industry focused on the coastal mangrove forests and for a more substantial regional tourism (i.e. tourists from other parts or Rio de Janeiro) spending the weekends at the beaches of the area. These latter tourists have also begun purchasing second homes (vacation homes) in the area, particularly in Barra de Guaratiba, driving commercial development of condominiums and restaurants [373]. Such condominiums first entered the Guaratiba RA in the 1990s and have spread to Barra de Guaratiba in the past 15 years, as transportation infrastructure to the peninsula has improved [384].

Such growth has itself introduced certain additional problems. The area was already characterized by low levels of education (4.7 years of school on average, by some estimates), and the increased population seems likely to overwhelm the existing school system, an issue further complicated by the fact that, due to the rural nature of the region, many students are already more than three kilometers from the nearest school and thus cannot easily be reassigned to further, emptier schools. One analysis of the RA estimated a deficit of nearly 35,000 seats by 2020, despite low rates of attendance [386]. One issue is that there are few mechanisms for community organization in the area. As mentioned earlier, Araçatiba did have a Residents Association, only for it to dissolve more than ten years ago. Now they find themselves trying to work with a city-wide Conselho Popular to effectively advocate for themselves [378]. Even the more formal neighborhoods of Guaratiba typically have either ineffectual or nonexistent associations [373]. On the economic rather than residential side, frog ranchers are virtually solitary [387], as are many of the farmers. Perhaps the primary organized group in the area are the artisanal fisherman, who participate in a variety of local and regional associations of varying degrees of formality [381].

The continued commercial and industrial development threatens to displace many of the historical communities of Guaratiba. In the 1970s, Araçatiba was created after informal settlements were forced to move by a film studio. More recently, the opening of the Ternium steel mill, in addition to its environmental impacts discussed earlier, effectively excluded artisanal fishing activities in a significant portion of the Sepetiba Bay. While the effects of this are more directly born by neighboring Sepetiba, fishers from that area have been forced eastwards, thereby impacting Guaratiba fisherman, particularly the approximately 1,000 fishers who reside in Pedra de Guaratiba [381].

These fishers are also pressured due to technological adoption by the more large-scale, commercial fishers. The increasing prevalence of industrial trawl fishing over the past few decades in the Sepetiba Bay (instead of more targeted, historical fishing methods), has resulted in the increased catching of juvenile and unintended fauna, as well as stirring up the silt on the bottom of the bay. This has led to increased tensions and conflicts between the the industrial and artisanal fishers [388], somewhat attenuated by the (illegal) ability of the artisanal fishers to operate inside the mangrove forests. This ability is by no means guaranteed, however. Fishing is nominally prohibited within the RBAG. This prohibition is currently rather poorly enforced, as part of a more board set of allowances provided to local (typically informal) residents. Another example of this allowance is that the bounds of the RBAG have, during each update, been intentionally drawn to exclude existing settlements [382]. That said, a future policy change could result stricter enforcement and in yet further encroachment on locals' means of subsistence.

As Guaratiba has become more connected to the rest of the city and commercial interests have increasingly moved in, small-scale farmers have been negatively impacted as well as the fishers. The open-air fieras have been increasingly replaced by supermarkets, depriving the farmers of a means of selling their produce. Many of the farmers adapted by switching from food produce to ornamental plants, something that Guaratiba has developed a reputation for over the past several decades [384].

All of this is to say that isolated, rural, and poor Guaratiba be none of these things before too long. But will the Guaratibans benefit or merely be replaced? And what will happen to the natural environment that has supported them for so many generations?

Perhaps the primary conclusion of this high-level examination is that both the people and the environment of coastal Guaratiba are under active threat from a multitude of directions. Local environmentalists have a saying about this: "Guanabara is the past, Guaratiba is the present, Paraty is the future." By this they mean that Guanabara Bay, which downtown Rio de Janeiro sits upon, is a lost environmental cause. Paraty, an area approximately 230km to the west of Rio de Janeiro, is relatively well preserved and unlikely to face serious human pressures in the next few decades. Guaratiba is where the current fight is.

But while those who use this phrase are typically referring solely to the environment, it seems to be true for the people of Guaratiba as well. And the city, caught up in its grand Rio-wide plans for cleaning up the east and developing the north, seems not to have realized this. As one community leader recounted about an interaction with the mayor in 2018: "The mayor looked at me and asked, 'Where is Araçatiba? I don't know.' I said, 'By Barra da Guaratiba.' And he said, 'Where is Barra da

Guaratiba?'" [389] Up until now, to the extent that the environment, and the mangrove forests in particular, have been protected, it has not been through government protection, but rather due to isolation and benign neglect. While the local residents have by no means led zero-impact lives, they at least had direct economic incentive in the preservation of the flora and fauna of their region. This is not true of the industrial and commercial development rapidly occurring the region.

Analysis and reports have already been commissioned on a variety of specific topics in the area, from reforming the educational system of Guaratiba [386] to the installation of green infrastructure [373] to means of protecting both the marine life and the artisan fishers of the area [381]. A comparison of such reports does bring to light certain key themes, some high priority action items that the city or region could pursue. These include:

- Create a proper sewage and water treatment system. This would improve the health of both the people and the environment and could make use of the natural drainage geography of the Guaratiba basin.
- Create a tiered licensing authority to permit certain low-impact artisanal activities in protected areas, while maintaining restrictions on higher impact activities. Once again, this helps the environment while also providing some degree of economic security for the historical residents.
- Strengthen environmental protections in forest-adjacent areas, such as construction limits in the Barra de Guaratiba neighborhood. This would prevent indirect pressures on the mangroves and slow both real estate speculation and commercial development, thereby preventing existing residents from being forced out.

These items are merely specific, ad hoc solutions to a broader, meta-problem. Despite the overabundance of municipal, state, and federal government agencies operating in the area, there is no cohesive governance of the environment, the local residents (largely informal settlers), and their interactions. Without this, it is unlikely the any of these ideas will be properly implemented and broader economic forces healthily channeled. There are multiple options for such a governance structure. It could be a top-down entity, one that manages the entire drainage basin, such as the Tennessee Valley Authority or any of its numerous imitators around the world. It could also be a bottoms-up, mass participatory effort by the various communities of the area. Either way, such an entity would be able to not only implement these high priority items, but a host of others as well, such as managing the currently ad hoc diverting of the numerous regional waterways by government agencies, companies, and individuals, much to the detriment of the people and mangroves living downstream.

Unfortunately, neither option seems particularly likely at this time. As mentioned earlier, the city, state, and federal governments are either focused on other things or actively inamicable to such an effort. The residents, for the most part, have no tradition of collective action. Many residents have complained that, despite the relatively abundant land, there are essentially no public spaces in these communities [373]. They (rightly) decry an inattentive municipal government, but also take no action to create such spaces themselves or effectively agitate for their creation.

The author does not have the expertise or the experience with the region necessary to either recommend a specific course of action or predict the likely outcome these ongoing changes in Guaratiba. What can be said with certainty is that there is a real need for awareness raising in the area. Much of the data discussed in the past few sections and contained in most of the references, is qualitative and anecdotal. While hard facts and demonstrable harms are no substitute for an engaged populace or an interested government, they can be a first step towards creating such things. The remainder of this chapter will be aimed at this topic.

4.2.2.2 Analyze System Stakeholders

[add more discussions of who the stakeholders are]

[revisit and update stakeholder map below]

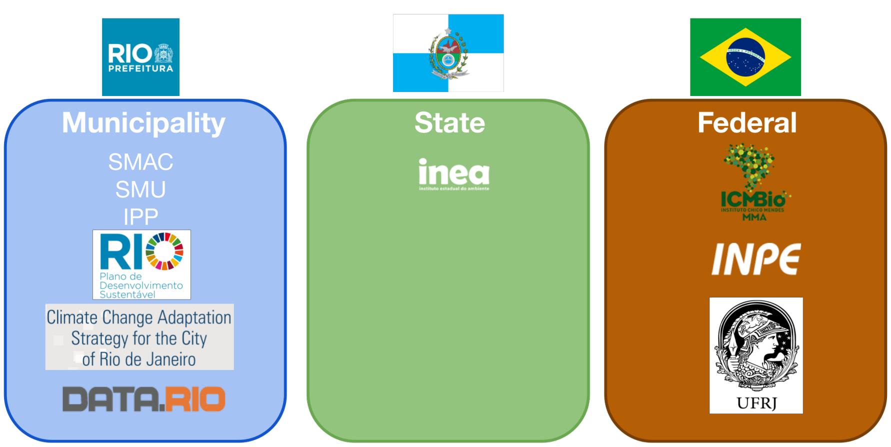


Figure 4-9: Relevant government stakeholders in Rio de Janeiro case study, organized from left to right as municipal, state, and national.

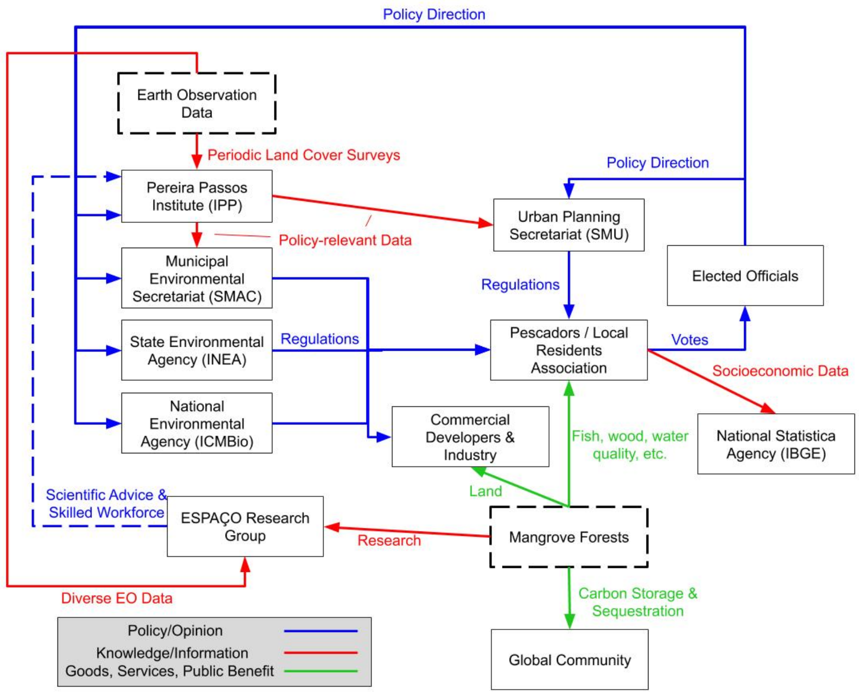


Figure 4-10: Stakeholder Map for the Mangrove Forests of Rio de Janeiro

4.2.2.3 Understand Desired Outcomes & Objectives

[walk through the summary of stakeholder needs outcomes, and objectives, as identified from the interviews; can refer back to Section 3.4.2]

[add table summarizing needs, outcomes, objectives]

4.2.2.4 Select System Functions

[explain the primary questions to be answered by the EVDT analyses and the DSS]

4.2.2.5 Assign Function to Forms

[explain the general DSS concept chosen]

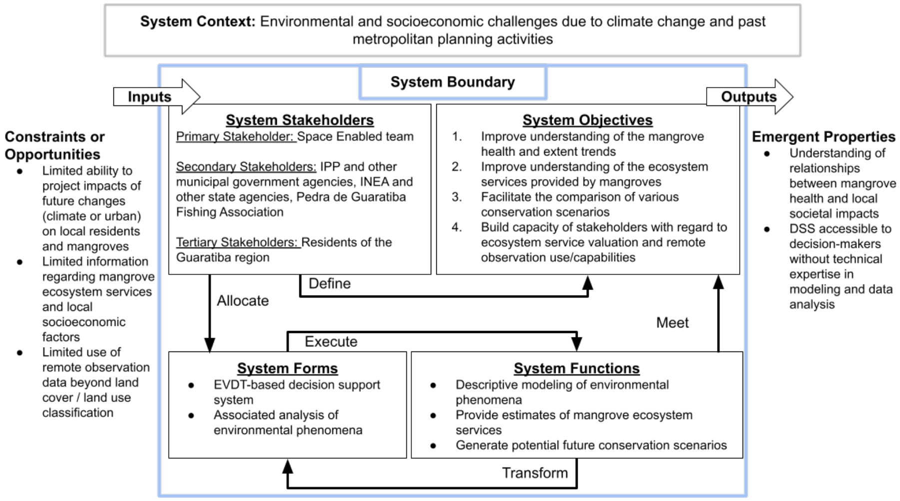


Figure 4-11: High level SAF diagram for the Rio de Janeiro case study

4.2.2.6 Monitor and Evaluate Systems

[discuss time scale and covid interruption]

[discuss evolving situation, desired outcomes]

4.3 EVDT Application

The following subsections walk through the components of the system from an Environment, Vulnerability, Decision-Making, Technology (EVDT) perspective, detailing what models were used and the results of those models. Before proceeding though, it is worth stating what exactly each of the four components of EVDT mean for this system. Returning to the four questions from Section 3.4.3, we ask the following:

1. **What is happening in the natural environment?** What are the impacts of seal-level rise and urban expansion on the mangrove forests? What role do complex secondary factors such as sedimentation change due to land use conversion and organic discharge due to agricultural activities, play in determining mangrove growth?
2. **How will humans be impacted by what is happening in the natural environment?** What impact do the designation of natural reserves have on the community? What effects would the lack of mangroves have on the city? What is the value of the carbon sink of mangrove forests?

3. **What decisions are humans making in response to environmental factors and why?** How are planning policies such as restricted land use conversion in certain protected natural reserves developed? How are other centralized and decentralized decisions made, such as the rate of urban expansion or the development of transportation infrastructure?
4. **What technology system can be designed to provide high quality information that supports human decision making?** What satellite, aerial, and in-situ sensing platforms are needed by the municipality to accomplish their mission?

With these questions and goals in mind, a specific instance of the integrated model framework can be represented as shown in Figure 4-12. In order to develop such a model, a number of steps remain to be completed. Some of the most notable include:

- Determination of certain parameters based on historical data. These include the rate of sea level rise and the rate of urban and agricultural expansion, both of which should be identifiable from a combination of satellite data and local in-situ measurements.
- Collection of various demographic and social data to improve risk estimation methods for the impact of the loss of mangroves. These include population data, urban land use types, and their differential impacts on local forests. For instance, some evidence suggests that particular residential land use types, such as favelas, may lead to more severe deforestation impacts [390].
- Better understanding of the civic decision making process in Rio de Janeiro. This is necessary in order to identify what urban development policies should be simulated using the integrated model.

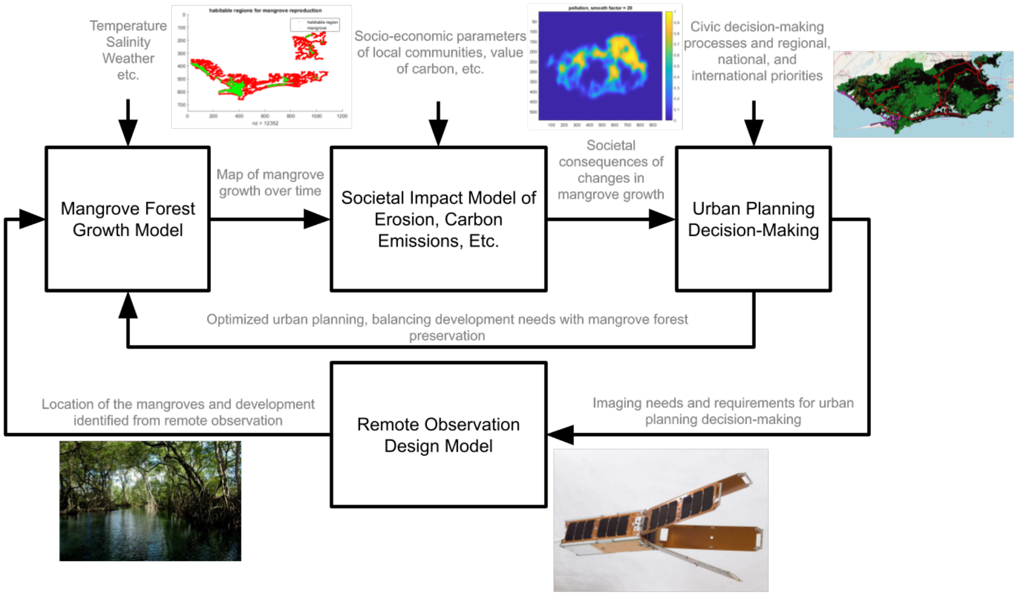


Figure 4-12: Environment - Vulnerability - Decision - Technology Model (Rio de Janeiro Mangrove Forest Case)

4.3.1 EVDT Methodology

4.3.1.1 Environment

The Environment Model of this case study is predominantly interested in the health, the size (as measured by geographic extent), and height of the mangrove forest over time.

Unlike some other forms of natural resources, which were extensively surveyed and quantified by colonial conquerors and explorers, historical information on pre-industrial Mangrove forest cover tends to be vague, primarily characterizing Mangroves as barriers to settlement [391], likely due to historical perceptions of mangroves by colonists, who, as opposed to native inhabitants of the Americas, tended to view mangroves as gloomy sources of disease rather than as natural resources to be exploited [392]. Retroactive understanding of Rio de Janeiro area mangrove cover in this era has been supplemented by palaeoecological studies [393] but only in a highly incomplete manner. This disregard for mangrove forests largely continued until, after a UN-led effort in the 1980s, international concern over their degradation increased, leading to greater efforts to monitor mangroves. In the second half of the 20th century, mangrove mapping efforts relied primarily on a combination of in-situ surveys and aerial and satellite photography. Investigations were typically site-specific, relied on human interpretation of images, and commonly only had one measurement every 1-2 decades [394, 395]. These factors limited both spatial scalability and the potential for timely forest management. In the past decade, significant progress has been made to address these limitations by creating spatially explicit global mangrove forest cover, loss, drivers of loss, and carbon sequestration maps [396–400]. Due to both new remote observation datasets and novel analysis techniques, spatial and temporal accuracy and resolution have significantly increased. The first global mangrove extent map with a consistent methodology and a spatial resolution of $<$1km was published in 2011 by Giri et al. using data from the Landsat series of EOSs processed by hybrid supervised and unsupervised classification techniques [401]. This map represented mangrove forest cover in the year 2000 specifically. More recently, the Global Mangrove Watch (GMW) published an extent map with an improved classification methodology covering the years 1996, 2007, 2008, 2009, 2010, 2015, and 2016 [402]. This was accomplished by combining SAR data from the Advanced Land Observation Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) platform with the Landsat data used by Giri et al. In 2010, the Ice, Cloud, and land Elevation Satellite (ICESat) with its Geoscience Laser Altimeter System (GLAS) was launched. The lidar data generated, when combined with the radar interferometry data from the Shuttle Radar Topography Mission (SRTM) in 2000, has similarly enabled the creation of global mangrove height maps [399], improving carbon storage estimates. Similar advances, often driven by improvements in machine learning, have yielded global maps of human land use, which can be combined with mangrove-related data products to accurately identify drivers of loss [400]. Most recently, these tools have been used to generate global datasets in which the specific years of degradation and regrowth are mapped [403].

A multi-step process was used to assess the state of the mangroves, as seen in Figure . This process relied upon everal different sources of EO and derived data, summarized in Table 4.2

Table 4.2: Rio de Janeiro Stakeholder Contacts. This table does not include casual interactions or discussions about unrelated topics to this project.

Data Source	Full Year Data Availability	Extent	Health	Carbon	Reference
Landsat 5 Thematic Mapper (TM) Collection 2 Surface Reflectance	1984 - 2012	×	×		
Landsat 7 Enhanced Thematic Mapper Plus (ETM+) Collection 2 Surface Reflectance	1999 - 2022	×	×		
Landsat 8 Operational Land Imager (OLI) Collection 2 Surface Reflectance	2013 - 2022	×	×		
ALOS PALSAR/PALSAR-2 Yearly Mosaic	2007 - 2010, 2015 - 2020	×			[404]
Sentinel-2 Multi-Spectral Instrument (MSI) Harmonized Surface Reflectance	2018 - 2022	×			
Giri et al.'s Global Mangrove Forests Distribution, v1	2000	×			[401]
GMW V2	1996, 2007 - 2010, 2015 - 2016	×			[402]
Simard et al.'s Canopy Height	2000			×	[399]

4.3.1.1.1 Mangrove Extent

[** insert diagram of data processing flow, can adapt from one of the conference presentations, see draft in google drive folder]

Regarding extent, the widely-used global mangrove extent maps such as Giri and GMW, are typically representative of specific years and, due to their global-scale, often have higher errors in specific localities, particularly involving the landward edge of mangrove forests and smaller copses of trees. In order to conduct extent-change tracking and to identify such copses, it is sometimes preferred to conduct more targeted estimations, as was done in this case. Mangrove extent was estimated using a Random Forest Classifier (100 trees, 8 variables per split) utilizing both single-band surface reflectance imagery and several multi-band indices from Landsat 7 ETM+, Landsat 8 OLI, Sentinel-2 MSI, and ALOS PALSAR. Training and validation data was identified using a combination of Giri's 2000 map, GMW's 2015 map, and first-hand field visits.

[** insert table / figure summarizing training and validation data]

Table 4.3: Indices used for mangrove classification. Each of these were computed for both the Landsat and Sentinel-2 imagery.

Index	**Description**	**Equation**	**Reference(s)**
normalized difference vegetation index (NDVI)	Popular index used to identify vegetation and monitor changes in vegetation health	$\frac{R_{NIR}-R_{red}}{R_{NIR}+R_{red}}$	[405–407]
Normalized Difference Mangrove Index (NDMI)	Used to distinguish mangroves from terrestrial forests	$\frac{R_{SWIR2}-Rgreen}{R_{SWIR2}+R_{green}}$	[408]
Modified Normalized Difference Water Index (MNDWI)	Used to identify water, particularly in areas with significant vegetation, soil, and built-up noise.	$\frac{R_{green}-R_{SWIR1}}{R_{green}+R_{SWIR1}}$	[409]
Simple Ratio (SR)	An old and popular index used to identify vegetation and monitor changes in vegetation health	$\frac{R_{NIR}}{R_{red}}$	[410]
Band Ratio 54	Used to monitor soil moisture	$\frac{R_{SWIR1}}{R_{NIR}}$	[411]
Band Ratio 35	Extension of the SR concept to examine vegetation moisture	$\frac{R_{Red}}{R_{SWIR1}}$	[412]

In order to eliminate false positives, a mask was used to filter out flagged pixels at over 40m in elevation, as determined by the SRTM dataset [413], and a kernel filter was used to eliminate solitary and near solitary pixels that were erroneously classified as mangroves. This classification, for the year 2018, can be seen in Figure 4-13. For a more detailed explanation of random forest classifier algorithms and their relevance to forest identification, see [414].

Figure 4-13: Classification of mangrove extent in western Rio de Janeiro for the year 2018.

Planet Lab's PlanetScope surface reflectance imagery was also experimented with, but ultimately was determined to not provide sufficient identification improvements to warrant continued use.

4.3.1.1.2 Mangrove Health

The Rio de Janeiro area contains three different species of mangroves (*Avicennia schaueriana*, *Laguncularia racemosa*, *Rhizophora mangle*), each of which have somewhat different spectral reflectance properties, making exact identification and health tracking somewhat more difficult. Ultimately we elected to use the relatively simple and robust NDVI, a normalized difference ratio of near infrared (NIR) and red surface reflectance, as seen in Equation 4.1. NDVI returns a value between -1 and 1, with 1 indicating a high likelihood of healthy vegetation, -1 indicating an absence of vegetation, and intermediate values indicating either possible vegetation or unhealthy vegetation, as seen in Figure 4-14. In Landsat 8's OLI, the primary instrument used for tracking NDVI in this case study, the NIR band captures 0.845 μm to 0.885 μm light while the red band captures 0.630 μm to 0.680 μm light. Landsat 5 and 7 surface reflectance imagery were used as well, harmonized according to Roy et al. [415]. NDVI is the most commonly used surface reflectance index for tracking vegetation presence and health via remote observation, as well as being one of the more commonly used EO indices overall [405–407].

$$\text{NDVI} = \frac{NIR - Red}{NIR + Red} \tag{4.1}$$

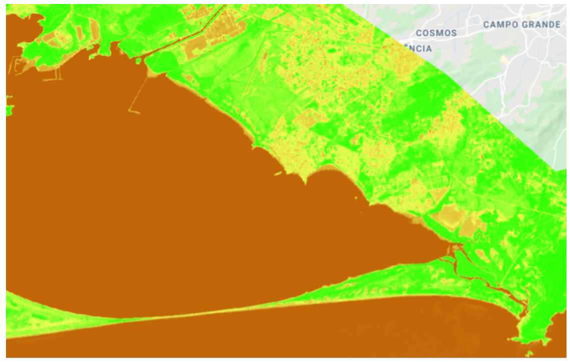


Figure 4-14: False-Color image of area of interest showing an NDVI composite. The greenest pixels indicate healthy vegetation presence

In order to focus on significant, secular changes in mangrove health rather than cyclical or temporary changes, NDVI mean anomaly was used, rather than a straightforward NDVI time series. The equation for this can be seen in equation 4.2. Here $NDVI_{Ref}$ refers to the median NDVI value at a specific location (an individual pixel in this case) over a specified reference period. $NDVI_i$ refers to the NDVI value at that location for each of the images taken during the observation period, and n refers to the number of usable images (i.e. clear, no clouds, etc.) at a specific location. As mentioned earlier, NDVI is not a perfect measure of mangrove health in a multi-species ecosystem, but it is broadly accurate. With greater number of bands (more than 10) in the visual spectrum, it is sometimes possible to differentiate vegetation species in some cases, but existing free hyperspectral platforms have some combination of poor spatial resolution and insufficient coverage, making them inadequate for this application [416]. The upcoming launch of the Planet Tanager constellation may alter this situation [417].

$$Anomaly = \frac{\sum_{i=0}^{n}(NDVI_i - NDVI_{Ref})}{n} \tag{4.2}$$

For this analysis, a reference period of August 31, 1999 to August 31, 2001 and an observation period was September 1, 2001 to September 1, 2018. It should be noted that mean anomaly is sensitive to the selection and duration of these periods, so the presented figures alone should not be taken as indicative of trends outside of the specified periods.

This EO data was accessed and proceed using Google Earth Engine (GEE), prior to being exported for use as part of the broader EVDT Modeling Framework. GEE is a free, cloud-based, geospatial programming platform that hosts free satellite imagery from a variety of sources. This platform obviates the need to download such imagery onto a computer for individual manual analysis. This method of extent and health tracking is largely based upon methods used by Lagomasino et al. [418]. Once this historical mangrove data has been processed, it serves as the foundation of estimating causal impacts between the EVDT components.

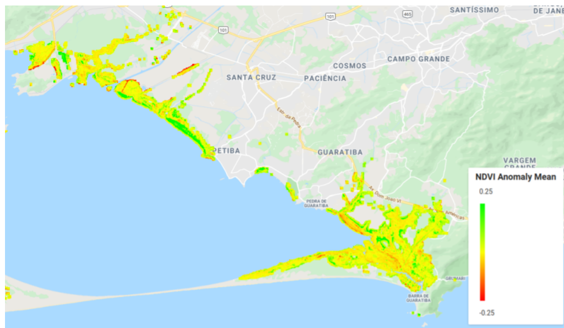


Figure 4-15: False-Color image depicting NDVI mean anomaly. Green indicates new or healthier mangroves, red indicates reduction in extent or in health, yellow indicates no measured change.

4.3.1.1.3 Mangrove Height

More specifically to the Rio de Janeiro area, height of mangrove trees can be measured using aerial LIDAR [419] and Rio de Janeiro has recently conducted such a survey of the entire municipality, though the data was not available in time for this work. Once it is, the height can be used to estimate above ground biomass (AGB) [420, 421], which is important for improving estimates of the forests' carbon sequestration capabilities [81]. Historical height data can be estimated using space-based LIDAR and SAR data [422], though this method lacks the spatial resolution of aerial methods.

[** add more text and figures about the height statistics in this region specifically]

4.3.1.1.4 Mangrove Carbon Stocks

For mangrove soil carbon, I used an estimate of 270.1 MgC/ha. This is based on 19 samples taken by Jennerjahn et al. 2002 [423] in Sepetiba bay (as reported in [424, 425]), making it directly relevant to this case study. Total root biomass was estimated at 49% of the AGB, as is specified by Intergovernmental Panel on

Climate Change (IPCC) guidelines [426]. This accounting process is modeled after the methodology used in Simard et al. [399].

$$\text{AGB}_{density} = 1.418 * H_{ba}^{1.6038} \tag{4.3}$$

$$C_{stock} = (1.49 * \text{AGB}_{density} + 270.1) * Area \tag{4.4}$$

For annual rate of carbon export, I used 2.2 MgC/ha. This is based on Lacerda, 1992 which also took samples from along the coast of Sepetiba bay [427] (as reported in [423]).

4.3.1.2 Vulnerability

[** summarize the datasets and outputs discussed in this section in a table]

Social impact and vulnerability in this case study has several different forms. First there are general socioeconomic trends and pressures in the Guaratiba area. A qualitative history of these was presented in Section 4.2.1.1. In addition to this history, various quantitative socioeconomic and demographic data, including employment rates and population density, were collected at several geographic scales, including bairros (neighborhoods), census blocks, and census microgrids. Much of this data was sourced from the national statistics agency, the Brazilian Institute of Geography and Statistics (IBGE). These were supplemented with municipally collected data, organized by IPP. Such data includes a UN-developed Multidimensional Poverty Index (IPM) [428], a municipally-customized social progress index [429], and detailed land use / land cover maps [430]. This data varies significantly in its geographic and temporal resolution.

The second form of social impact and vulnerability comes in the form of ecosystem services provided, directly or directly, by the mangroves. Ecosystem services are often sorted into three categories: provisioning (providing some raw material), regulating (moderating the ambient environment in a helpful manner), and cultural (non-material benefits) [431]. Mangrove forests around the world provide each of these:

- Provisioning: Fuelwood / timber
- Regulating: Water filtration, protection from coastal erosion and storms[7], hosting fisheries

[7]Some studies place protection from coastal erosion and storms into a fourth category, supporting/maintaining, rather than in regulating [432].

- Cultural: Tourism, general biodiversity

As mentioned previously, it is known that the local communities in the Guaratiba area benefit from various ecosystem services provided by the mangroves, but the exact forms these services take are unknown and their values have not been quantified. Some bounds on these values can be estimated from valuation studies focusing on mangroves elsewhere in the region and elsewhere around the world. To this end, we examined mangrove ecosystem services valuations from the ESVD [33] (an open source database maintained by the Foundation for Sustainable Development) and nine meta-analyses or review papers [283, 432–439] in order to determine a potential range of values for the various mangrove ecosystem services in the Guaratiba area. Additionally, we use Simard et al.'s global map of mangrove canopy height, AGB, and carbon stock per hectare in the year 2000 [399] to provide a baseline carbon storage estimate for the Guaratiba mangroves. We can use changes in mangrove extent over the 2000-2018 period to estimate likely changes in carbon stocks. In the future, when the aforementioned aerial LIDAR survey data becomes available, these estimates can be revised.

4.3.1.3 Decision-making

Two primary policy decisions are currently included in this EVDT application: conservation status and urban zoning. The histories of these are provided by the municipal Environmental Secretariat and Urban Planning Secretariat and accessed via the Data.Rio platform. The urban zoning categories are broadly similar to those in many cities around the world and include the types of commercial and industrial activity permitted and maximum floor area ratio allowed, among other factors.

Conservation status, on the other hand, is more complicated, as discussed in Section 4.2.2.1.2. Some of these protected areas are classed as "integral protection," meaning little or no development and resource extraction is allowed. In addition to these areas (and often surrounding them), there are various municipally-defined "sustainable use" areas that allow for certain, restricted forms of development and resource extraction. There are also two different classes of "boundary zones" with yet fewer protections.

In addition to conservation, there is the potential for replanting and restoration of mangroves. Numerous replanting and restoration projects have taken place in the Rio de Janeiro area in recent years, both in dedicated conservation areas [440] and in more urban and peri-urban areas [441, 442]. Siting of these restoration areas ideally depends both on the environmental viability of a potential site and its likely ecosystem service impacts.

The selection of these two axes of policy decisions (conservation status and urban zoning) was based on meetings and discussions with government officials from several municipal and federal agencies, university researchers, and local community members. Other axes were discussed and were of interest to particular audiences (such as transit network changes and conservation policy enforcement stringency), but these two held broad appeal and relative accessibility, while still having concrete historical data that are either quantitative or code-able qualitative in nature.

4.3.1.4 Technology

[will look at the history of remote sensing use in Rio de Janeiro]

[consider possible additional sensing uses/platforms in the future]

[discuss options future steps beyond the scope of this thesis (tradespace exploration)?]

4.3.2 EVDT Results

4.3.2.1 Environment

[quantitative changes in mangrove extent]

Net increase of approximately 290 ha from 2000 to 2018.

[compare changes in protected areas to changes outside of protected areas]

[discuss areas of particularly notable gain or loss, tie into other developments] [steel mill construction] [highway and rapid transit line] [potential wood beetle infestation]

Figure 4-16: Changes in mangrove extent in western Rio de Janeiro as classified by the Landsat-only process.

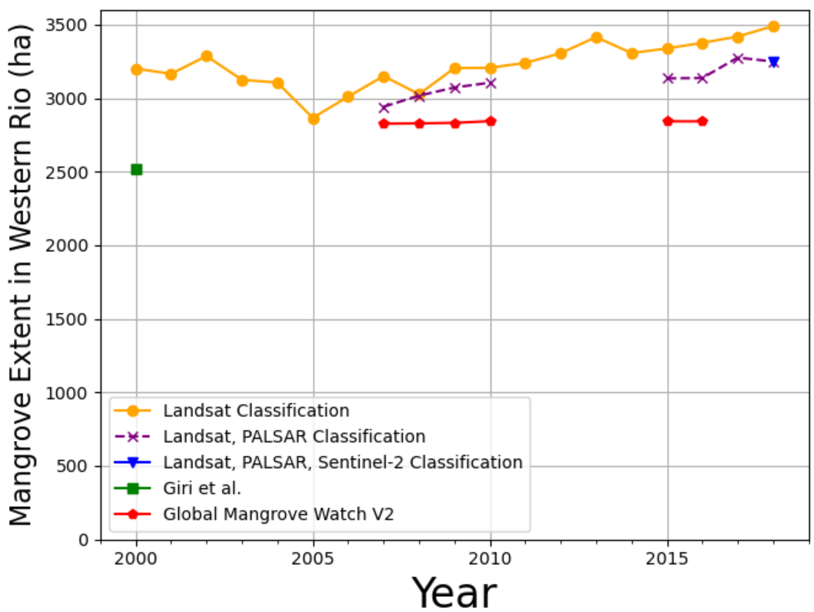


Figure 4-17: Mangrove extent in western Rio de Janeiro lha 2000 to 2018 as measured by several different classification methods. Left: Ilha da Madeira, Santa Cruz, and Sepetiba. Right: Guaratiba and Pedra de Guaratiba.

4.3.2.2 Vulnerability

[quantitative socioeconomic/demographic data from IBGE census and multidimensional poverty index]

[estimates of mangrove ecosystem services from review of valuation studies]

[calculation of year 2000 carbon stock, then how changes in extent could have impacted that]

4.3.2.3 Decision-making

[revisit how mangroves fared inside and outside of protected areas]

[discuss enforcement, including differential enforcement]

[fishers want control over where mangrove replanting occurs]

[consider moving the recommendations synthesized from previous reports in the System Context section here]

4.3.2.4 Technology

The city of Rio de Janeiro has made significant use of EO data dating back to 1975, as can be seen in Table 4.4, but it is only in recent years that this data usage has become fairly regular. Even now, there has not been any particular consistency with the choice of imagery source, with the city switching back and forth between aerial and satellite surveys every few years. And there has been a significant lack in the use of civil scientific satellites such as Landsat for mapping and decision-making purposes, further pointing towards the need for tools to facilitate the use of such satellite data.

Table 4.4: EO data use by the municipal Urban Planning Secretariat of Rio de Janeiro

Year	Product	Platform
1975	Ortophoto	Aerial (???cm)
1999	Ortophoto	Analog camera (scanned to 85cm)
2004	Ortophoto	Analog camera (scanned to 50cm)
2006	Satellite imagery	Quickbird (60 cm)
2008	Satellite imagery	Quickbird (60 cm)
2009	Ortophoto	Digital camera (25 cm)
2010	Lidar survey	Aerial (10 pts/m2)
2010	Ortophoto	Digital camera (25 cm)
2011	Ortophoto	Digital camera (20 cm)
2012	Ortophoto	Digital camera (20 cm)
2013	Lidar survey	Aerial (2 pts/m2)
2013	Ortophoto	Digital camera (10 cm)
2015	Ortophoto	Digital camera (15 cm)
2016	Satellite imagery	Worldview 3 (30 cm)
2017	Satellite imagery	Worldview 2 (46 cm)
2018	Satellite imagery	Worldview 3 (32 cm)
2019	True Ortophoto	Digital camera (15 cm)
2019	Lidar survey	Aerial (8 pts/m2)

[research and mapping programs by espaco and others]

4.4 Decision Support System

4.4.1 DSS Methodology

[explain process and software used for the DSS]

4.4.2 DSS Results

[explain the state of the prototype]

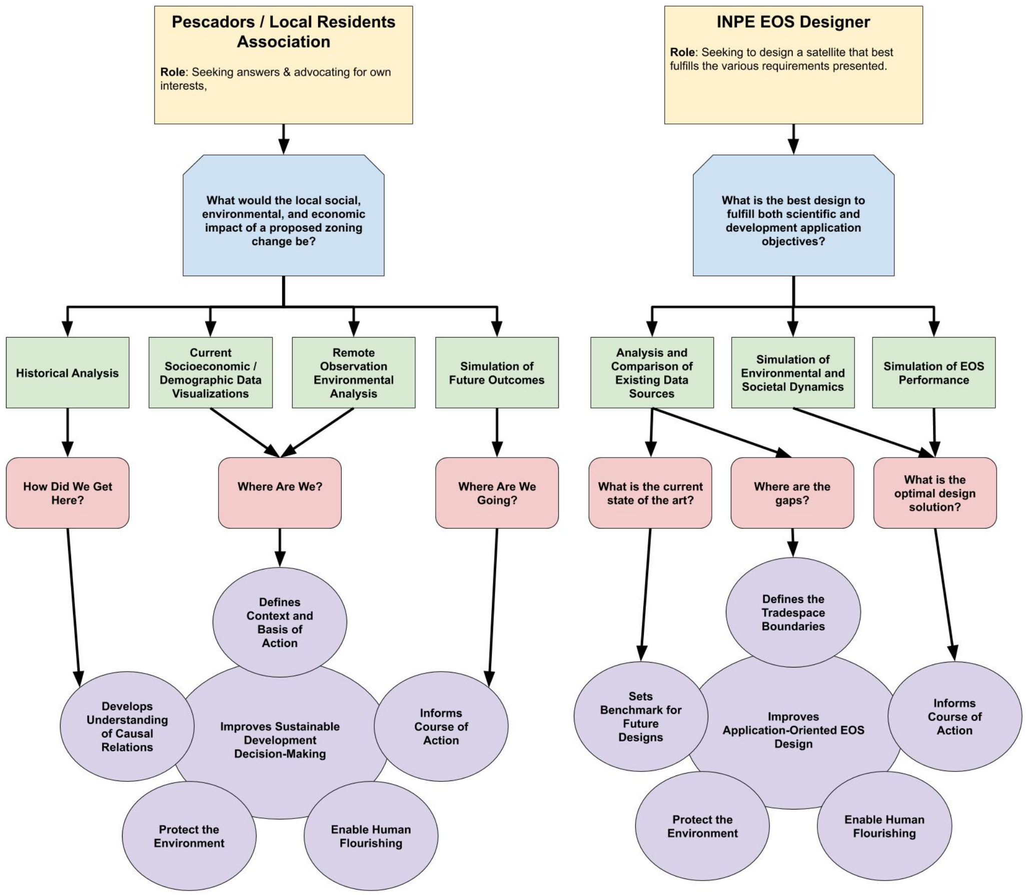


Figure 4-18: Two potential user experience concepts for this case study

[insert screenshots]

[insert link to code]

4.5 Collaborative Development Process

[discuss ongoing collaboration beyond the initial interviews]

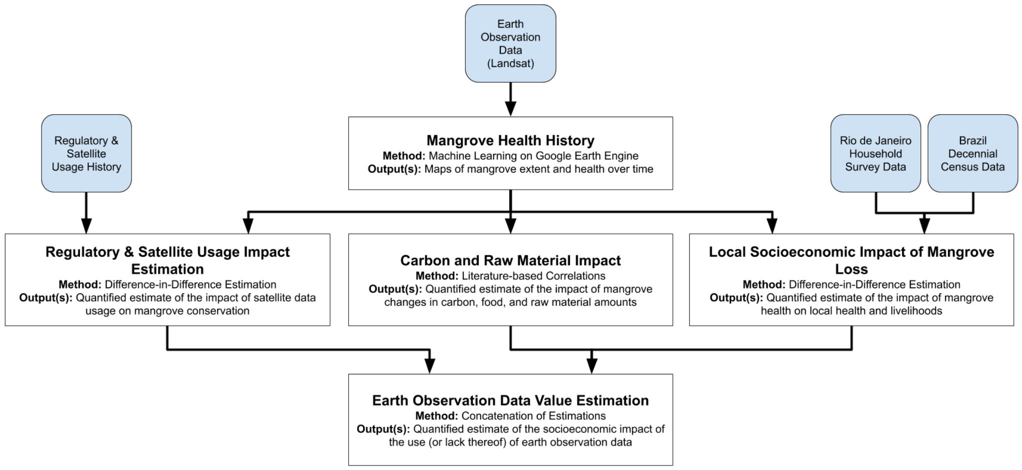


Figure 4-19: Flowchart indicated various ways of estimating causal impact of one EVDT component on another

4.6 Discussion

evidence that the protected areas in the greater Rio de Janeiro have helped the mangroves [443]

replanting mangroves helps the soil [444]

[lessons learned] [pros and cons of having a fairly neutral (at least as far as the government is concerned) primary point of contact]

[potential for future development] [moving online] [informing the bounds of APA da Orla da Baía de Sepetiba] [household survey studies to inform ecosystem services] [use aerial lidar survey to revise height / biomass estimates] [use of Planet Tanager for species differentiation]

Beyond the scope of this thesis, in order to better understand and quantify the dynamics linking mangrove health and conservation policies with local socioeconomic impact, the team is currently pursuing collaborating with an ecosystem services economist to analyze historical data and potentially to conduct household surveys. This historical data will be used in conjunction with the mangrove health history to estimate the "Carbon and Raw Material Impact" and "Local Socioeconomic Impact of Mangrove Loss," as shown in Figure 4-19. For more details on these types of methods, see [445, 446]. Once these historical dynamics are better understood, we can progress to predictive simulation of vulnerability.

The history of these two policy axes over the past several decades will be used in conjunction with the Environment and Vulnerability Models to estimate the regulatory impact on these two domains, as shown in Figure 4-19.

4.7 Conclusion

Chapter 5

Vida Decision Support System

5.1 Chapter Purpose & Structure

Like Chapter 4, the case study detailed in this chapter is in service to multiple objectives. First, it seeks to address Research Question 2: “What are the sustainability benefits of collaborative development of DSSs using the Environment, Vulnerability, Decision-Making, Technology (EVDT) Modeling Framework in complex socio-environmental- technical system (SETS)?" It accomplishes this by providing a case study demonstration of Research Deliverables 2a, 2b, and 2c:

a System architecture analyses of each of the case studies
b Development of an EVDT-based decision support system (DSS) for each of the case studies
c An interview-based assessment of the development process and usefulness of each DSS

Through these deliverables, this chapter serves as a demonstration of the EVDT Framework. The structure of this chapter thus mirrors the components of the framework laid out in Section 3.4. It starts by walking through the steps of the Systems Architecture Framework (SAF) as applied to this case study in Section 5.3. These are separated into the methodology used for each step of the SAF (Section 5.3.1) and the results of each step (Section 5.3.2. Then, in Section 5.4, it shall turn to showing relevant datasets and analysis as applied through the Environment, Vulnerability, Decision-Making, Technology (EVDT) models. These two are separated in methodology (Section 5.4.1) and results (Section 5.4.2. These are then integrated into a prototype DSS in Section 5.5. Finally Section 5.6 lays out how various stakeholders were collaborated with beyond the setting of requirements during the SAF process.

The remaining sections examine and discuss the outcomes of this case study. The following chapter will similarly present a second case study.

It should be noted that, as stated in Section 1.1, each case study also has its own objectives beyond supporting a chapter of this thesis. In this case, that means supporting COVID-19 pandemic response in each of the participating metropolitan areas. Readers interested in environmental analyses performed in the course of this research are pointed to Sections 5.4.1.1, 5.4.2.1, and 5.7.

5.2 A Note on Credit / Contributions

All EVDT projects, by their nature, involved a large number of participants. That said, in Chapter 4, the primary Space Enabled participant was myself and, while Technical Area Experts provided advice and actionable information, I conducted the direct implementation of the analyses and the DSS. This is not the case in the Vida case study. Various other individuals provided analysis and coding labor throughout the process. I will do my best to refer to them by name throughout the chapter, but here is a brief summary of direct contributions:

- Seamus Lombardo: Served as the point-of-contact for the Indonesia and(sometimes) the Angola collaborators; Contributed code to the desktop DSS; Conducted nightlights analysis for the Indonesia location
- Amanda Payton: Conducted analysis of ships presence and air quality near Luanda, Angola
- Eric Ashcroft and his team at Blue Raster: Coded and hosted the online DSS
- Maggie Zheng: Conducted much of the air quality analysis

5.3 Systems Architecture Framework

The following subsections work through the six steps of the SAF originally detailed in Section 3.4.2 as applied to the Vida COVID-19 response case study, first as methodology and then as results. The goal is to identify what information, analyses, and other forms of decision support would be useful to stakeholders in the various metropolitan areas involved in this case study.

5.3.1 SAF Methodology

5.3.1.1 System 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 [447]. This project, which ultimately became known as the Vida DSS International Network (or just Vida for short), constitutes the second case study of this thesis. It came to involve six metropolitan areas:

1. Luanda, Angola
2. Rio de Janeiro, Brazil
3. Región Metropolitana de Santiago, Chile
4. Java & Sulawesi, Indonesia
5. Querétaro de Arteaga, Mexico
6. Boston, USA

These are shown in Figure 5-1. In each of these areas, Vida was developed in collaboration with local government officials, university researchers, and general community members.

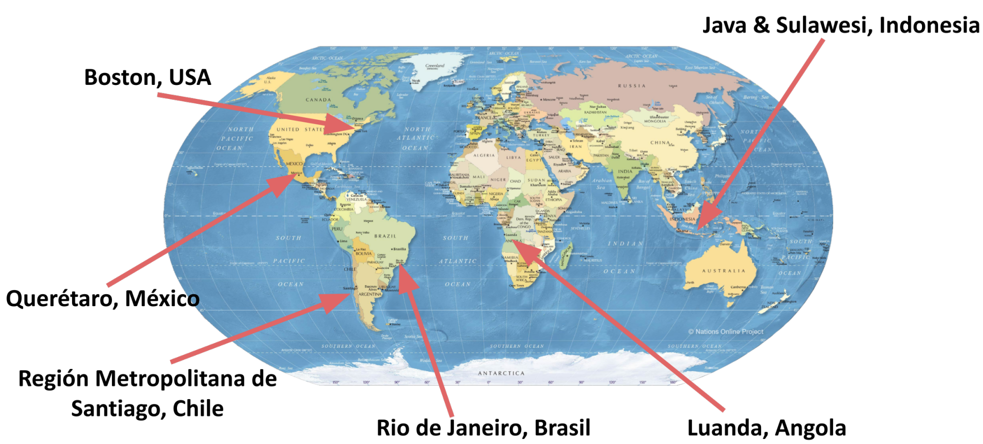


Figure 5-1: Metropolitan areas participating in the Vida DSS International Network

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 analysis of System Context will include existing public health infrastructure in these metropolitan areas, how vulnerable they are to epidemics, and how decision-making occurs.

5.3.1.2 Analyze System Stakeholders

The Technical Area Experts on this project included researchers from Harvard Medical School and NASA Goddard Space Flight Center. Meanwhile the Local Area Experts (many of whom are technical experts in their own right) included a mix of government officials and academic researchers, most of whom work in the public health and/or in GIS. The government officials themselves span several different offices, including public health departments, data management authorities, science ministries, and space agencies. The full list of Technical Area Experts and Local Area Experts are shown in Table [**insert table number] The intended Users are those same individuals as well as the various public health agencies / task forces that they are affiliated with. Participation in the Vida DSS International Network was directed at two ends: (1) development of the Vida DSS to conduct analyses and presentations that can inform pandemic response; and (2) sharing more general information and resources among the participants for responding to the pandemic [448].

[** insert table listing all experts]]

The Network is constituted by a mix of academic researchers, government officials, and private consultants, chosen for both their field-specific expertise and their familiarity with one or more of these locations of interest.

5.3.1.3 Understand Desired Outcomes & Objectives

5.3.1.4 Select System Functions

5.3.1.5 Assign Functions to Forms

5.3.1.6 Monitor and Evaluate Systems

5.3.2 SAF Results

5.3.2.1 System Context

The second was a recognition that the impacts of and responses to the pandemic can be characterized as a complex system, thus warrenting the kind of multidisciplinary, model-based approach of which EVDT is an example [447].

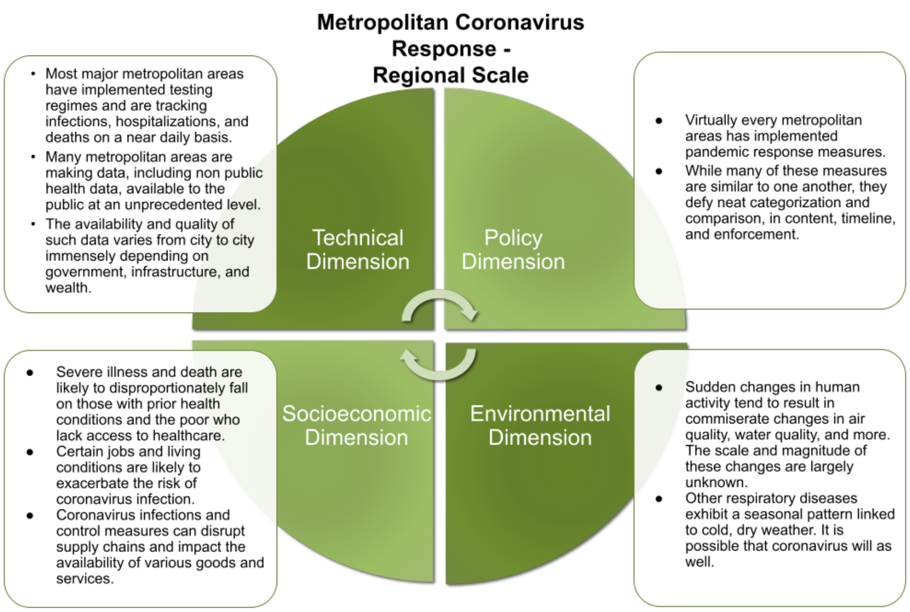


Figure 5-2: Vida System Context Dimensions

5.3.2.2 Analyze System Stakeholders

5.3.2.3 Understand Desired Outcomes & Objectives

5.3.2.4 Select System Functions

5.3.2.5 Assign Functions to Forms

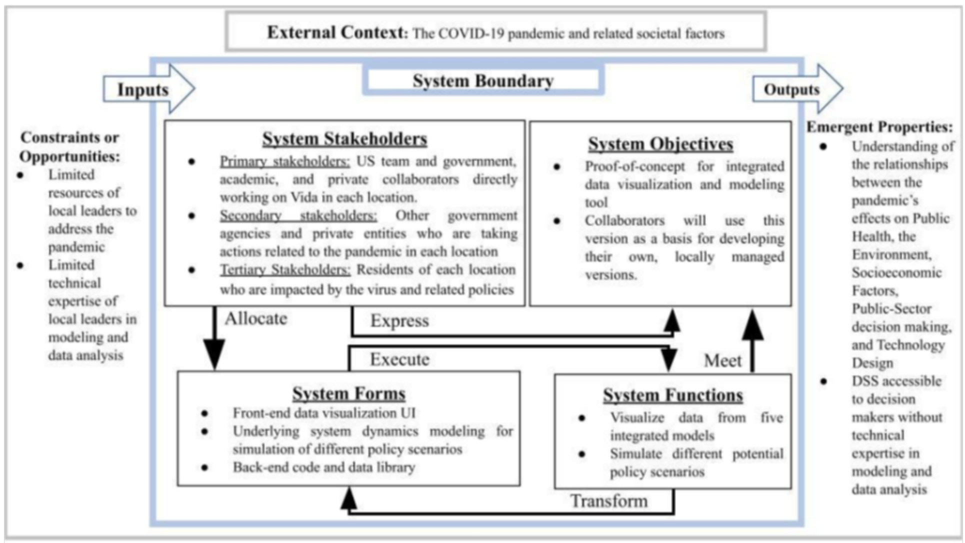


Figure 5-3: The high-level functional systems architecture of the Vida DSS.

5.3.2.6 Monitor and Evaluate Systems

5.4 EVDT Application

he following subsections walk through the components of the system from an Environment, Vulnerability, Decision-Making, Technology (EVDT) perspective, detailing what models were used and the results of those models. Before proceeding though, it is worth stating what exactly each of the four components of EVDT mean for this system. The onset of the COVID-19 pandemic was an immensely significant event around the world. Thus, while it would have been possible to consider public health as a component of the Vulnerability model, in order to properly center and prioritize the public health aspects of the pandemic, a dedicated Public Health Model was added to the default EVDT arrangement, as shown in Figure 5-4. Returning to the four questions from Section 3.4.3 (plus one additional one), we ask the following:

1. **What is happening in in public health?** How is the COVID-19 pandemic spreading through the community? What portion of the infected are being hospitalized or dying? What factors impact transmission?
2. **What is happening in the natural environment?** How are air quality, water quality, and nightlights being altered by pandemic-related changes in human activity? What role does weather, smog, and other aspects of the environment have on COVID-19 transmission and symptoms?
3. **How will humans be impacted by what is happening in the natural environment and in public health?** Who is at most risk of falling ill or suffering from severe symptoms? How are pandemic response policies affecting different populations? Do pandemic-related changes in air quality have a noticeable impact on the residents of these metropolitan areas? How are different industries impacted by such sudden changes in both supply and demand?
4. **What decisions are humans making in response to environmental factors and why?** What are the different forms of pandemic response measures being taken by governments, both local and national? How are individual people altering their patterns of work, shopping, and recreation?
5. **What technology system can be designed to provide high quality information that supports human decision making?** What testing regime is needed to effectively reduce the spread of the virus and resultant deaths? What other data sources are useful for informing decision-making?

We can now discuss what approaches were taken for each of these components before presenting their outcomes.

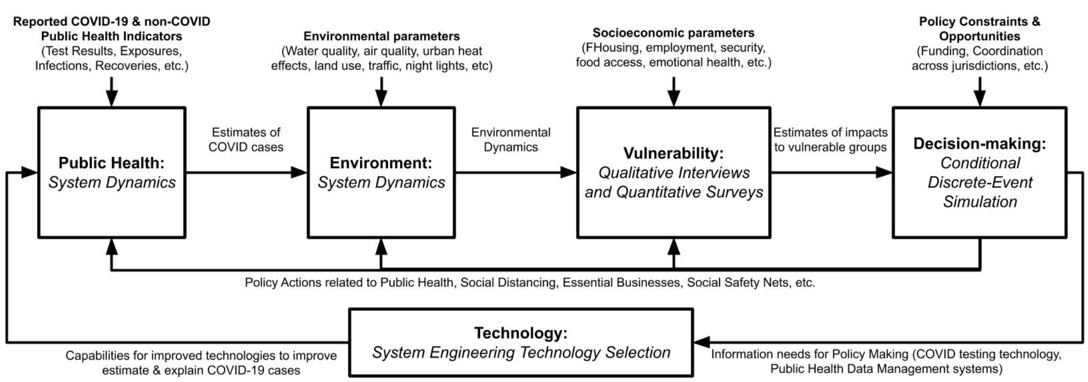


Figure 5-4: The Vida variant of the EVDT model, designed to support decision making by governments during COVID-19

5.4.1 EVDT Methodology

5.4.1.1 Environment

Unlike the previous case study, which focused on a particular aspect of the environment (mangroves) that had an established literature, the onset of the COVID-19 pandemic resulted in many disparate impacts on the environment in quick succession. As discussed earlier, it also was not immediately clear what topics were the highest priority to stakeholders. As a result, many areas were explored and only some pursued in detail.

Urban nighttime lighting patterns changed and (generally) dimmed [449]. Air quality noticeably improved as traffic patterns changed and work-related emissions declined [450]. In many places, water quality noticeable improved and noise diminished [451]. We pursued these using both remote sensing data (Landsat and Sentinel for air and water quality estimations, VIIRS for nighttime lighting, Planet and Sentinel SAR for traffic pattern changes) and in-situ sensors (such as the Rio de Janeiro MonitorAr program's air quality sensors).

For nightlights, the VIIRS VNP46A2 dataset was used [452]. This dataset contains daily panchromatic (visible and NIR) imagery at at a resolution of 15 arcseconds (approximately 450m for the locations of interest) that has been corrected for atmospheric interference and moonlight variation. It is thus well suited for examining artificial lights, such as those generated by cities. We process it by masking out clouds and water (thereby eliminating transient lights from ships) using the supplied quality flag, then taking weekly median values to reduce intraweek variation, before calculating the relative anomaly compared to the 2019 median value for each pixel, thereby standardizing comparisons across time and space. We can then compare specific pre-and-post pandemic time periods to identify changes. Further normalization can be performed by identifying any long term trend from Jan 1st, 2019 to March 1st, 2020 (the approximate start of the pandemic) and subtracting this extrapolated trend from the post-pandemic data. This methodology is summarized below in Figure 5-5.

For air quality, data from Rio de Janeiro MonitorAr air monitoring stations was used. In-situ sensors take hourly measurements to monitor a range of air quality parameters (e.g O3, CO, SO2, PM10, etc.) in 8 different barrios, or neighborhoods, of Rio de Jeneiro. The dataset is provided publicly and freely through Rio de Janeiro's Data.Rio website [453]. For the purposes of this study, we focused on changes in the measured PM10 pre-and-post pandemic. We process the data for each barrio by first calculating weekly averages to reduce intraweek variation, as we would expect there to be a difference in air emissions throughout the week (for instance, weekends

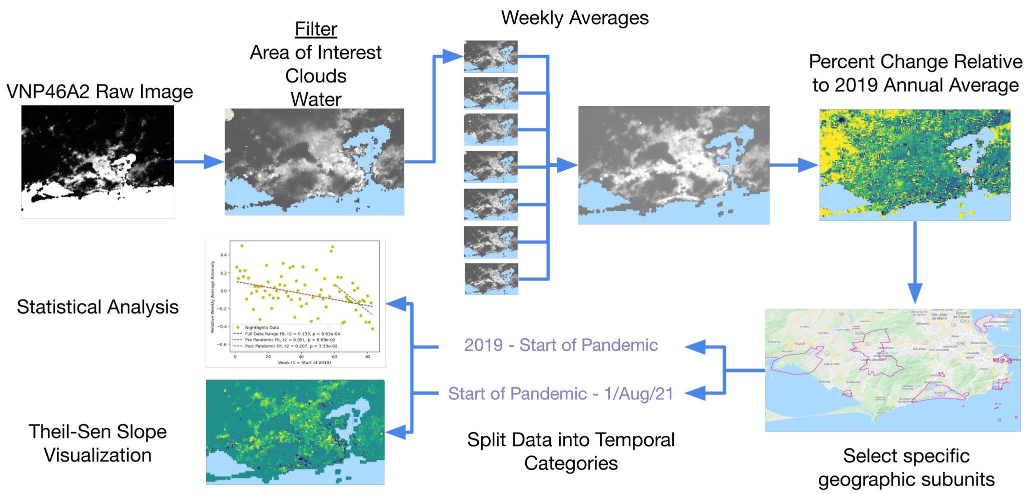


Figure 5-5: Method for processing and analyzing nightlight data

versus weekdays). Then the data was fit using a least-squares estimate to a sinusoidal wave with an annual period. This sinusoidal curve is the average seasonal variation in PM10 for that barrio, and it is subsequently subtracted out from the data. A best-fit line is then calculated for this seasonally-corrected data. The best-fit line is long-term (multi-year) trend in PM10 measurements, and it is also subtracted out. At this point, the data is corrected for intraweek, seasonal, and annual trends, and we can then construct normalized histograms and compare the pre-and-post pandemic distributions to identify changes and trends. Similar analyses have been conducted using Chile's Sistema de Información Nacional de Calidad del Aire [454] for the Santiago area.

Some experimentation was performed in assessing changes in air quality and traffic patterns in Rio de Janerio using EO imagery. Further meetings with stakeholders suggested that this was of limited usefulness, particularly in the other locations. This, coupled with a lack of accessible validation data, resulted in us abandoning such efforts.

5.4.1.2 Public Health

The most notable variation that Vida has compared to previous EVDT applications is the addition of a dedicated Public Health Model. While the specific data collection definitions, coverage, and update cycles vary, each of the participant locations collected and published coronavirus-related epidemiological data on a regular basis, including newly identified infections, deaths, hospitalizations, etc. Vida ingests this data and uses it both to display historical trends alongside the other components and to conduct simulations of potential future behavior, with an emphasis on future trajectories of infections and hospitalizations. The Public Health component is based on a Susceptible-Infected-Recovered (SIR) system dynamics model. SIR is a compartmental epidemiological model and one of the most commonly used variants, due to its relative simplicity and flexibility. System dynamics is a modeling approach commonly used in both 'pure' epidemiological contexts [455] and in broader public health policy contexts [456]. Figure 5-6 shows a diagram depicting the layout of the Vida Public Health Model. In addition to the three traditional SIR components, it has two other health compartments: Hospitalizations and Deaths. These reflect some of the primary decision points and metrics of performance that policymakers are using. In most of our application contexts, population counts for each of these compartments is readily available on a daily or weekly basis.

In the top left and bottom left of the diagram, the initial inclusions of Environment and Vulnerability components are shown. These are obviously cursory and highly assumptive. Air pollutants, for example, are not merely a function of closure policy. In most locations that we have examined, and in research conducted by others [450], initial coronavirus-related closures resulted in a sudden drop of emissions (further discussion on this in the Section 5.4.2). Furthermore, there is some evidence that weather and air pollution have a modest impact on COVID-19 transmission [457], leading to the inclusion of such an element in the top left of the diagram.

This model is non-spatial, though in some locations of interest with distinct geographies (such as the Indonesian islands of Java and Sulawesi), multiple independent instances of the model are generated.

5.4.1.3 Vulnerability

Traditional, government-collected socioeconomic impact data largely does not exist at the fine temporal resolution required for coronavirus-related assessment, so we had to develop the Invisible Variables Initiative (not discussed at length in this thesis) to work with our collaborators to develop surveys and interview procedures to elicit needed information. This initiative is led by Dr. Katlyn Turner and funded by the Natural Hazards Center at the University of Colorado, Boulder. As the pandemic progressed, however, some more traditional metrics, such as unemployment data, that show responses to the crisis began to be released.

Another aspect of societal impact and vulnerability that Vida monitors is mobility. This includes movement as demonstrated by telecommunications activity,

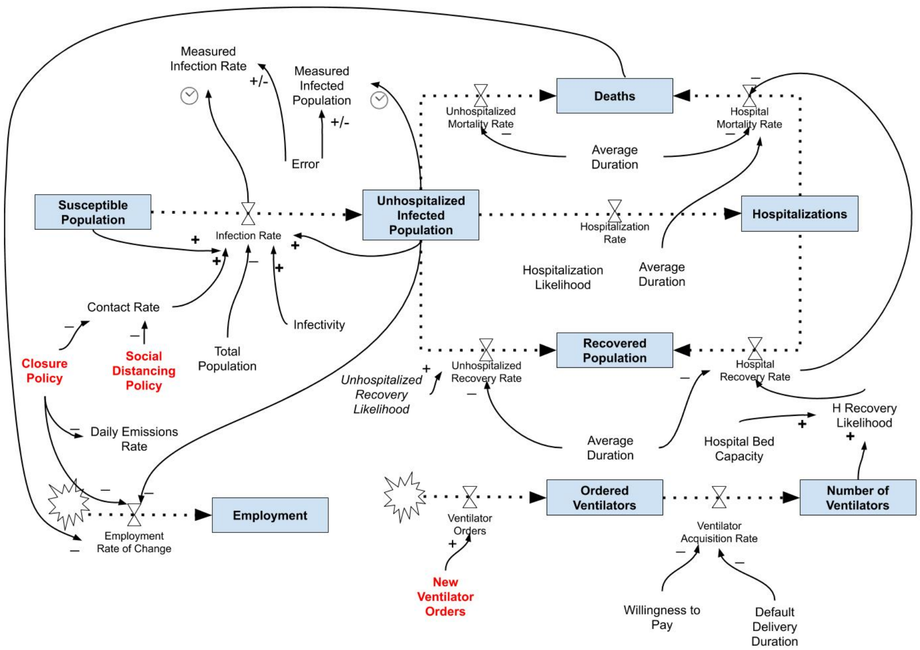


Figure 5-6: Current version of the Vida SIR system dynamics model

automobile traffic, air traffic, and ship activity, the last of these primarily of relevance to the Luanda stakeholders. Telecommunications activity is being made in numerous jurisdictions either directly by private companies [458] or via government data repositories [454] and integrated into Vida. Data on air traffic is commonly collected and published by local government authorities. Data on ship activity can be generated through the use of Sentinel radar imagery by masking out land and permanent structures, then looking for transient bright spots on navigable bodies of water, particularly around major ports. This process can be seen in Figure 5-7. The period of 2018 through the start of the pandemic was used to establish a baseline of ship presence. This was then compared with activity after the onset of the pandemic to identify changes.

[** add explanation of the mobility methodology]

5.4.1.4 Decision-making

Obviously the primary decision axis is containing the spread of coronavirus and properly treating those who are infected. In practice this tends to express itself as various forms of public area and business closures and restrictions, individual social

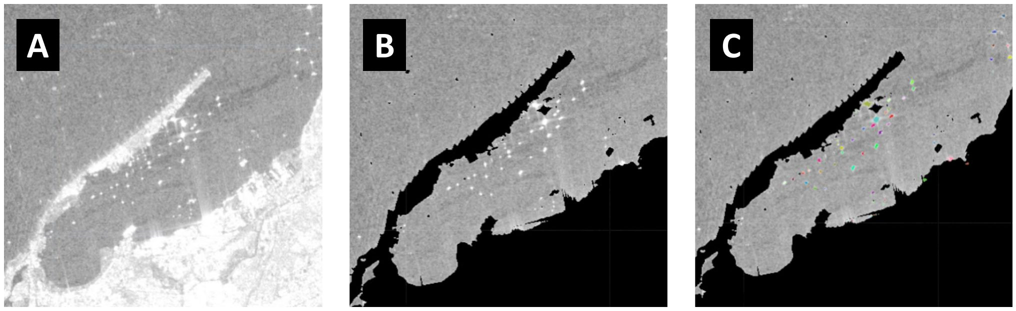


Figure 5-7: Ships identification process. A: Sentinel-1 SAR imagery of the Luanda area. B: Masking out land and permanent structures. C: Identifying individual ships. Figure created by Amanda Payton.

distancing requirements (such as mask wearing), and medical equipment acquisition and allocation. In Rio de Janeiro, for example, many of these policies have been grouped together into a six phase Resumption Plan that has clear indicator-based conditions for when to advance to the next phase [459], which facilitates visualization and simulation in Vida. Most of the locations of interest have similar qualitative, ordinal policy categories, with varying numbers of steps or details.

We spent some effort at developing a consistent process for transforming such policies from qualitative ordinal categories into quantitative scores, building upon such projects as the CoronaNet Research Project [460]. This was done both to enable consistent visualizations where various quantitative metrics (active coronavirus cases, air quality, mobility indices, etc.) can be directly compared to policy actions over time (e.g. in Fig 5-12). It also would enable some level of comparison across locations of interest in order to help draw causal relationships and identify the impacts, both positive and negative, of certain policies. Our approach to this was to break policies into different categories (e.g. social distancing / masking requirements, business closures or capacity limitations, travel restrictions, etc.) and define specific ranks within such category (e.g. no outdoor events with greater than 15 people vs no outdoor events with greater than 50 people). The local teams for each location of interest were involved in both the definition of these ranks and the categorization of local policies into them. Ultimately the Vida project concluded prior to this quantification process being completed.

5.4.1.5 Technology

Various forms of sensing technology are relevant during a viral epidemic. While our team has remained primarily focused on satellite-based earth observation technology and in-situ environmental sensors, another key form of relevant sensing technology is coronavirus testing (both the technology of the individual tests and the social technology that is the regional testing regime). Rates of testing can be integrated into the public health model through its influence on the difference (or lack thereof) and delay between the estimated number of active infections and the measured infections.

5.4.2 EVDT Results

5.4.2.1 Environment

We ran two-samples t-tests and Anderson Darling tests on the normalized histograms of the pre-and-post pandemic variation-corrected PM10 data, assuming that the pre-pandemic distribution was approximately normally distributed. These tests determine if the pre-pandemic and post-pandemic PM10 measurements are actually different. In particular, as seen in Figure 5-8, we found that tourist areas had a significant decrease in measured PM10 post-pandemic, while some rural or residential areas had slight decreases. We found a significant increase in PM10 measurements post-pandemic in the downtown/business district, with some smaller increases in mixed use/residential and recreational areas.

Similarly to other researchers, we detected significant changes in nightlights due to the onset of COVID-19 and later policy changes [449, 461]. In particular, areas associated with air travel and tourism experienced significant decreases in nightlights and associated human activity (areas in purple along the eastern and southern edges of Rio de Janeiro in Figure 5-9). Downtown and commercial areas experienced a similar, though less dramatic decrease. Primarily residential areas (the yellow, east-west arc across the middle of Figure 5-9), meanwhile, significantly brightened. These trends are apparent both for relative percentage change across these areas and when the changes are normalized for long term trends. Graphs showing such changes for airports and specific tourist-centric areas in Rio de Janeiro, Brazil and Bali, Indonesia can be seen in Figure 5-11 of the Appendix. The results of basic statistical analysis, particularly t-tests to determine if pre-pandemic and post-pandemic brightness are actually different, for various bairros and areas of Rio de Janeiro can be seen in Figure 5-10.

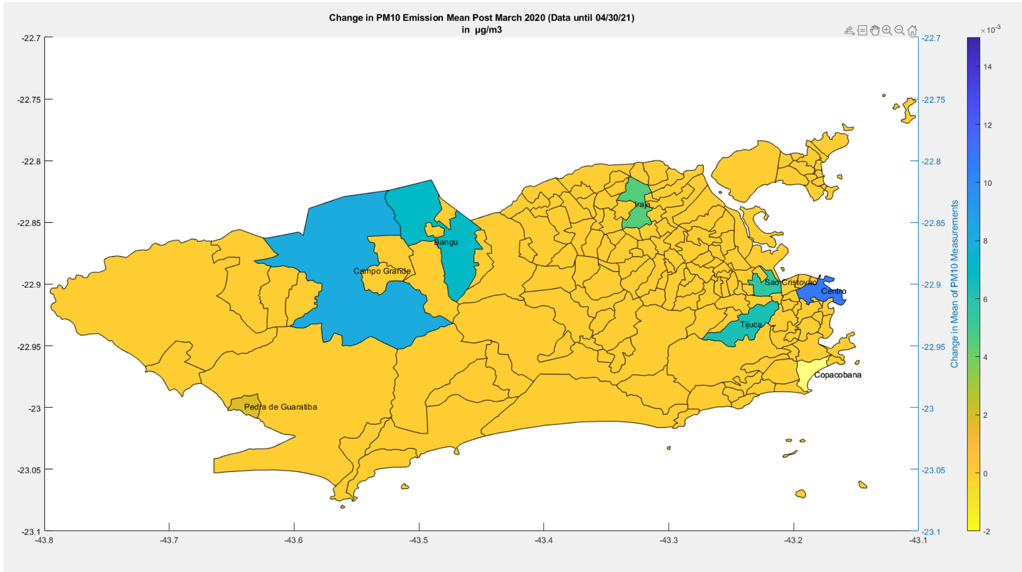


Figure 5-8: Changes in PM10 levels in several bairros of Rio de Janeiro during the first two months of the pandemic, normalized for intraweek, seasonal, and annual trends.

Area	Type	Pre vs Post T-Test P-Value	Normalized Data Linear Fit P-Value	Pre Pandemic Trend (*1000)	Post Pandemic Trend (*1000)
Barra da Tijuca	Tourist	0.000	0.11	-0.64	-3.73
Campo Grande	Suburb	0.503	0.93	0.25	0.62
Centro	Downtown	0.115	0.97	-0.67	0.40
Cidade de Deus	Mixed Use / Residential	0.433	0.01	-0.50	6.92
Cidade Nova	Downtown	0.604	0.88	-3.76	-3.27
City	Entire City	0.347	0.45	0.58	4.78
Copacabana	Tourist	0.769	0.90	-1.44	-0.71
Galeao Airport	Airport	0.000	0.24	-2.57	-7.22
Industrial Area	Heavy Industry	0.395	0.04	0.41	-7.00
Ipanema	Tourist	0.063	0.08	0.38	-6.00
Pedra de Guaratiba	Rural / Residential	0.052	0.70	-0.76	-2.40
Santos Dumont Airport	Airport	0.005	0.12	-3.38	-15.00

Figure 5-10: Statistics for nightlight trends in several bairros (neighborhoods) and areas of Rio de Janeiro. Greens indicate stronger statistical significance, red less. Yellows indicate negative trends, blue positive.

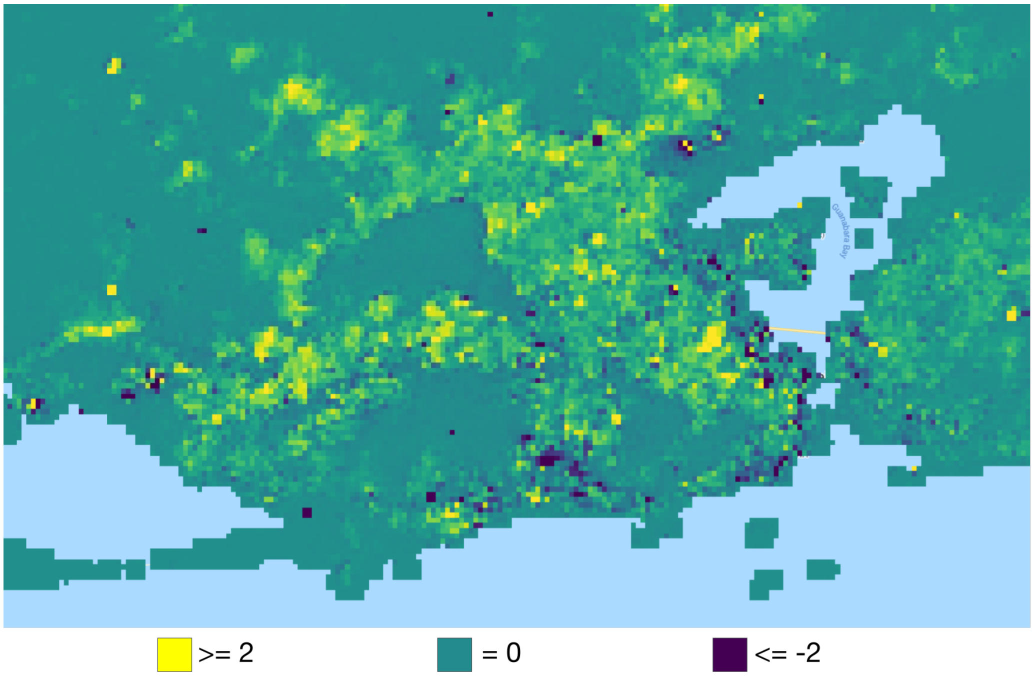
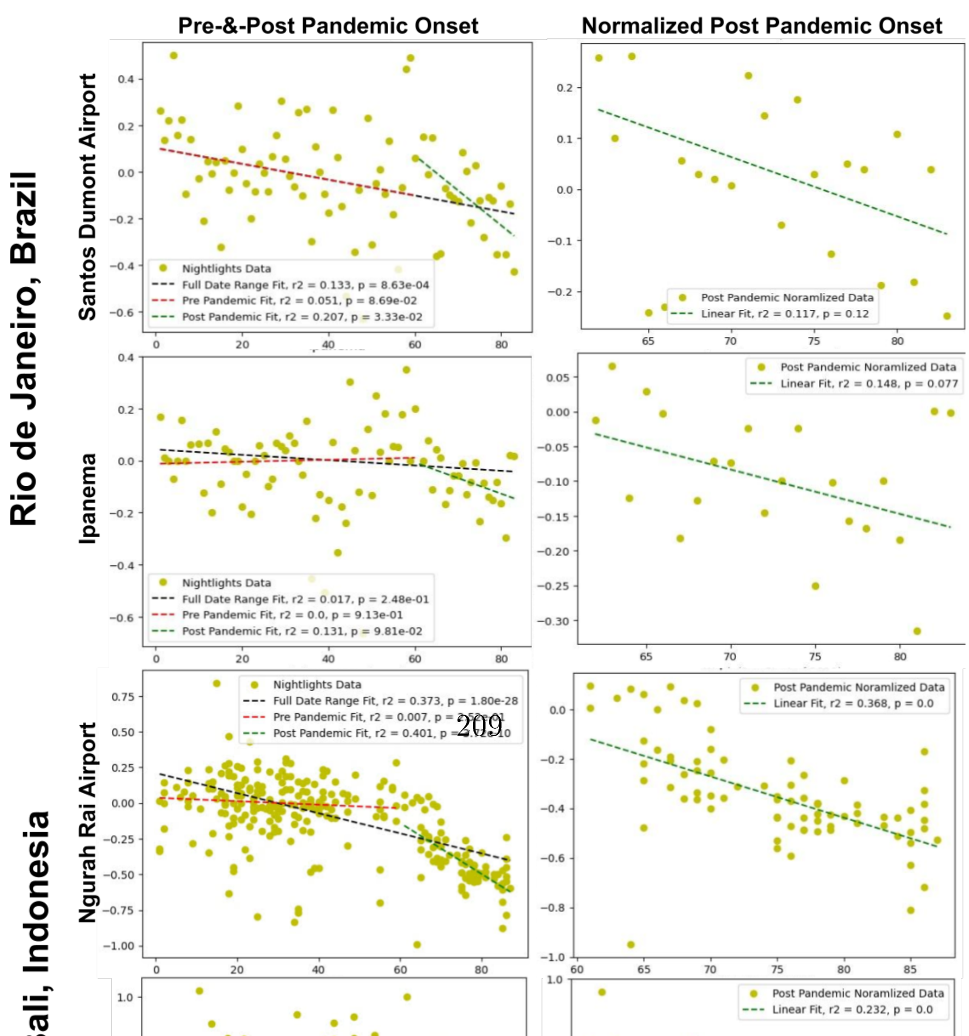


Figure 5-9: Theil-Sen trend estimator for normalized changes in nightlights in Rio de Janeiro during the initial phases of the pandemic (March 1st to August 30th, 2020).



5.4.2.2 Public Health

In addition to presenting historical data, the desktop version of the DSS can also conduct public health simulations, using the system dynamics SIR model presented earlier. This simulations can either be run manually, with the user selecting specific policies at each week using the controls in the bottom left, or automatically for specified time periods, according to certain pre-coded decision rules (listed in the bottom right) based on the official policies of the location of interest.

This model is currently being calibrated using historical data, expanded as new dynamics become evident, and examined by public health experts. Various potential improvements are evident, including combining the SIR system dynamics model with an agent-based model to help address some of the deficiencies of the system dynamics approach [462], such as the lack of a spatial component.

5.4.2.3 Vulnerability

Telecommunications-based measurements of Vida have also provided insightful for decision-makers. Figure 5-12 compares mobility with active coronavirus cases and policy status in Santiago, Chile and Rio de Janeiro, Brazil. Some variations are unsurprising: a upward spike during Chile's constitutional referendum, downward spikes for the winter holidays. Others are more relevant for policy-making. Specifically, once the number of active cases declines, mobility increases even if policies remain restrictive.

Initial results regarding ship tracking in the harbor of Luanda, Angola suggest that there may be a visible change in ship number and location related to the pandemic. Compared to the preceding two years, the monthly average number of ships within the Bay increased slightly after the onset of the pandemic and continued to remain higher throughout the year. In the offshore area outside of the bay, the average monthly number of ships was lower than in the two years preceding the pandemic. As the number of COVID-19 cases in the country climbed, the number of ships within the bay further increased, while the number of ships in the offshore area decreased (as shown in Figure 5-13). The extended docking within the harbor could reflect a reduction in ships conducting trade or delays in the process of loading and unloading ships due to COVID-19. Further investigation is needed into the accuracy and statistical significance of these results in order to draw conclusions. However, at this early stage of analysis it appears that detecting changes in economic proxies such as ship movement using satellite imagery is possible and we plan to extend our analysis to other regions for comparison.

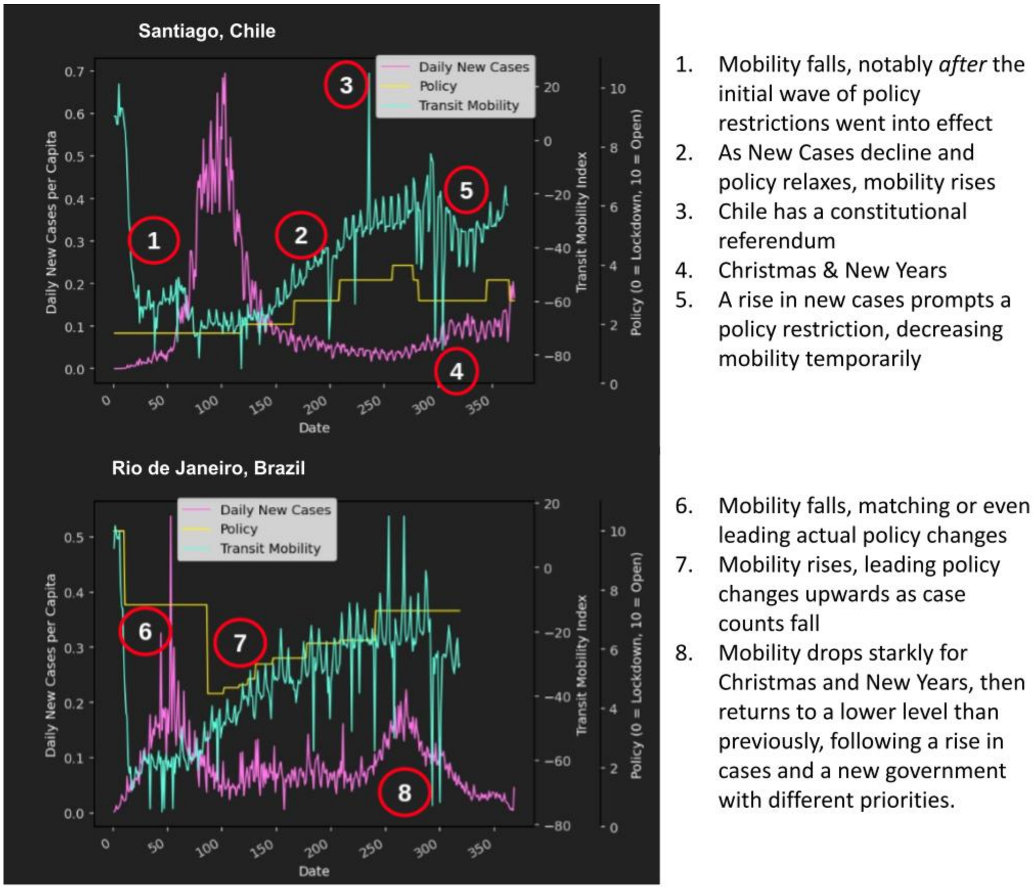


Figure 5-12: Comparisons of coronavirus cases, policy changes, and mobility for Santiago and Rio de Janeiro. Day 0 is set at the first confirmed COVID-19 case in that location (04/Mar/20 for Santiago, 07/Mar/20 for Rio de Janeiro).

5.4.2.4 Decision-Making

5.4.2.5 Technology

5.5 Decision Support System

At the time of writing, two distinct versions of the Vida DSS exist, both of which are undergoing active development and should not be viewed as final products. The first, shown in Figure 5-14, is an open-source, desktop-based version written in Python (the code is available online [343]), that can be run on various operating systems

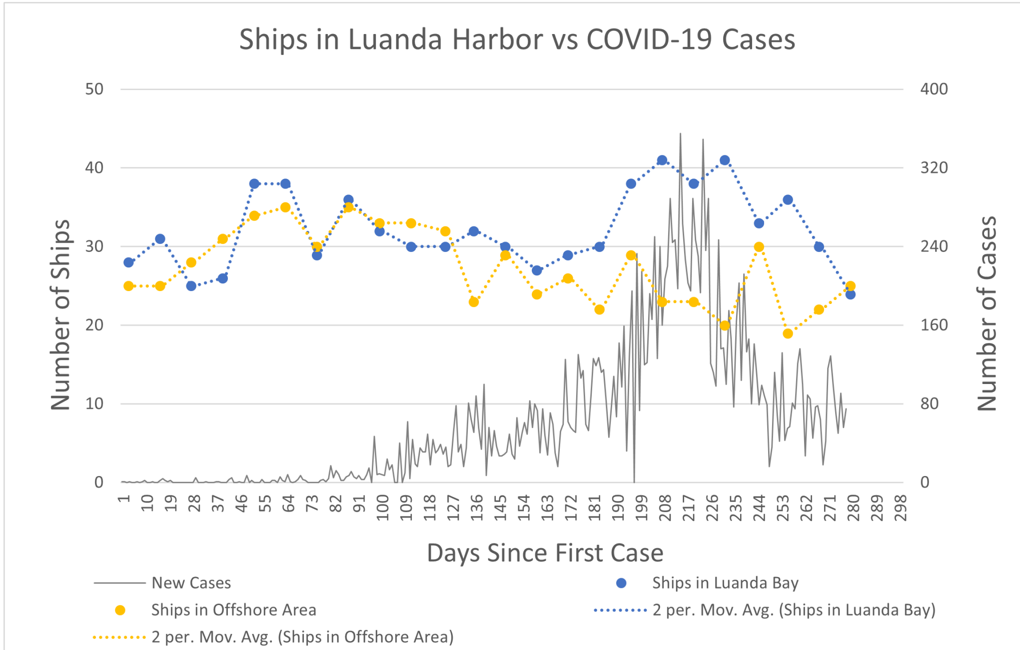


Figure 5-13: Ship presence over time for the Luanda area.

(recent versions of Windows, MacOS, and various Linux distros have been tested).

The user interface can be easily switched between languages (English, Spanish, and Portuguese are currently available, with easy functionality for adding additional languages) and between the locations of interest.

This version can present temporal data, spatial data, and spatiotemporal data. The first of these is done through plots (visible on the left of Figure 5-14, but the placement of the plots can be reconfigured by the user), with the data visible in the plots controllable through dropdown menus. The other two kinds of data are presented in the kinds of maps shown on the right, which is currently displaying visual imagery of the Rio de Janeiro area overlaid with the most recent PM10 measurements from in-situ monitoring stations. Should either the raster imagery or the vector geographic data be available at multiple points in time, additional slides appear at the bottom of the image to allow the user to select specific dates. Non-spatial data are saved in CSVs, vector spatial data in shapefiles, and raster spatial data in GeoTIFF format.

The goal is not for the authors to continue development of this model indefinitely ourselves, but rather to hand over the model and its associated user interface to local collaborators in each of the application areas, so that they can continue to adjust it to their local circumstances. Other future improvements include more automated ingestion of data from online data repositories, streamlined exporting of visualizations, and making this version accessible online.

The second version of the Vida is online, created in collaboration with Blue Raster and hosted by Esri's ArcGIS Online [463], and has somewhat different functionality. This version, shown in Figure 5-15 (using the Boston areas as an example), focuses on the presentation of historical data and thus lacks simulation capability. It does however have the capability of showing more graphs at the same time, including allowing the user to merge multiple graphs into one for easy comparison, and an overall more streamlined interface.

The remaining portions of the Results section will focus on several specific insights and analysis that have arisen out of the Vida development and use processes.

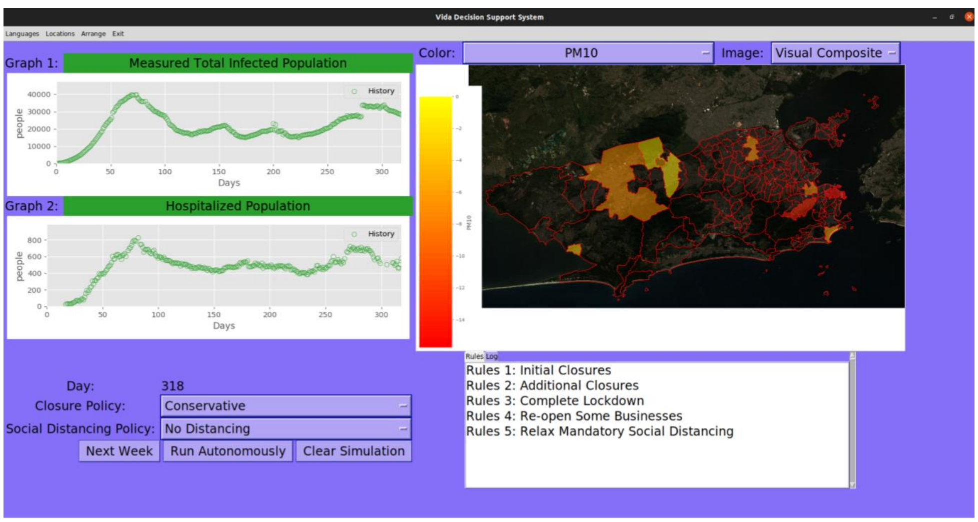


Figure 5-14: Prototype of the desktop version of the Vida user interface for Rio de Janeiro.

5.6 Collaborative Development Process

The second objective of the Network is primarily accomplished through monthly, full Network meetings, at which participants present and discuss useful lessons and tactics for addressing coronavirus response, including topics not directly related to Vida. Examples of such topics are how to implement wastewater viral testing and how to integrate the data generated into decision-making, how to approach health

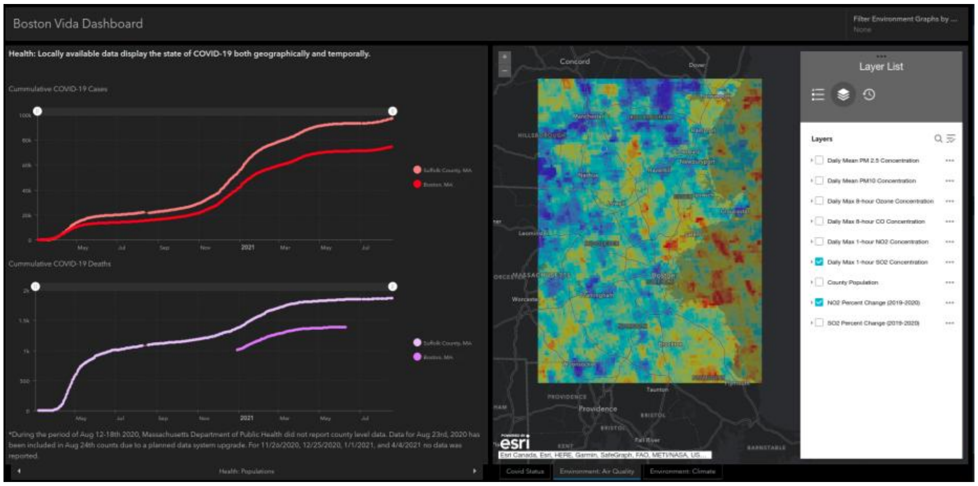


Figure 5-15: Prototype of the online version of the Vida user interface for Boston.

surveillance in elderly care facilities, and how to identify high vulnerability neighborhoods. These discussions promote innovation and enable cross-location learning that may not otherwise occur.

These activities are conducted through weekly or biweekly meetings between the Boston-based research team and individual site representatives and through online collaboration via the local collaborators own online data repositories (e.g. Rio de Janeiro's Data.Rio [453] or Chile's Datos-COVID19 [454]), the Vida project's own code repository [343], and through interaction with the browser-based version of the Vida DSS prototype [463].

5.7 Discussion

Moving forward, work is ongoing to improve the Vida DSS in several regards. This includes:

1. Automating data updates and ingestion
2. Standardizing architecture and implementation to facilitate reuse of model components
3. Add simulation capabilities to the online version
4. Improving visualizations

5. Adding a spatial component to the epidemiological model

6. Continue air quality, nightlight, and mobility analysis with the potential for integrating these into the simulation capability

Furthermore, the Vida development process has had numerous ancillary benefits beyond the actual DSS. As mentioned earlier, the Vida International Network has facilitated international collaboration, allowing participants to share innovations and insights from their COVID-19 efforts. It has also encouraged intra-country collaboration but providing a motivation for outreach between government officials, academic researchers, and community leaders in order to fill data gaps and answer pressing questions. This process has also raised awareness of the utility of space-based EO data, potentially preparing participants for future pandemic and non-pandemic applications.

We are actively working to conduct more systematic analysis in this domain as well as examining the possibility of linking telecommunications-based mobility with nightlight measurements and thereby make spatial extrapolations.

5.8 Conclusion

Chapter 6

Discussion

[** discuss evdt with regard to EO value chain]

Figure 6-1: Generic Earth Observation Data Value Chain

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* [464] or the significantly less elegant *socio-environmental-technical system* used in this document).

Accessibility: The degree to which something (usually data in this thesis) is easy to access for a given person or group. Greater accessibility means that a larger set of people can access and use the data with minimal difficulty. To be compared with *availability*.

Availability: The degree to which something (usually data in this thesis) is available for use by someone. Barriers to availability include a time delay and lack of sensors. Availability is primarily based on what data is "out there" independent of how easy it is to gain access to it or to use it. To be compared with *accessibility*.

Context: See *System Context*.

Critical Remote Sensing: A new field, most clearly laid out by Bennet et al. that reconsiders the rationales for the use of satellite data in a more critical light than has been common [83]. 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.

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): As defined by GEO, the data and information collected about our planet, whether atmospheric, oceanic or terrestrial. This includes space-based or remotely-sensed data, as well as ground-based or in situ data [55]. As defined by Mather and Koch, the interpretation and understanding of measurements of the Earth's land, ocean, or ice surfaces or within the atmosphere, together with the establishment of relationships between the measurements and the nature and distribution of phenomena on the Earth's surface or within the atmosphere [56]. Either definition is applicable, though typically EO in this work refers to data collected via remote observation.

Ecosystem Services: The various benefits that humans are provided by the natural environment and healthy ecosystems in particular. Ecosystem services are often sorted into three categories: provisioning (providing some raw material), regulating (moderating the ambient environment in a helpful manner), and cultural (non-material benefits) [431]. See Sections 2.2.2.1, 2.3.2, and 4.3.1.2 for more detailed discussion.

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: See *System Form.*

Function: See *System 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 [90]. For more discussion of this definition, see Section 2.2.5.

Multidisciplinary Optimization: A methodology for the design of systems in which strong interaction between disciplines motivates designers to simultaneously manipulate variables in several disciplines [465].

Multi-Stakeholder Decision-Making: Any decision-making process in which more than one stakeholder must collaborate to reach a decision [47]. This can take a variety of forms, including cooperation, negotiation, voting, or consultation [466].

Objective: See *System 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 [297] .

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 [119]. It should be noted that these means involvement in both the production of data and in its application, not merely one or the other [113, 123]. 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 [119]. For more discussion of this and related terms, see Section 2.2.6.

Planning: "the premeditation of action, in contrast to management [which is] the direct control of action" [135]. 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.

Primary Stakeholder: Those who make direct decision on the design or operation of the system.

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 [141]. These futures are often generated by models such as EVDT.

Secondary Stakeholder: Those who have direct influence on the Primary Stakeholders, typically via authority or funding.

Socio-environmental System: The complex phenomena that occurs due to the interactions of human and natural systems [38].

Sociotechnical System: Technical works involving significant social participation, interests, and concerns [13].

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: The people, organizations, and communities that either influence the design and operation of the system or are impacted by the system. For more discussion, including alternative definitions, see Sections 3.4.2 and 3.4.2.2.

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 [252] and Stakeholder Value Network Analysis [253]. 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. For more discussion, see Section 3.4.2.2.

Sustainable Development: The integration of three separate, previously separate fields: economic development, social development and environmental protection [21]. For a more detailed discussion of the history of this term, see Section 2.2.2.1.

Systems Architecture/Architeting: 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 [14]. For more discussion including alternative definitions, see Section 3.4.2.2.

System Boundary: The limit demarcating the system of interest from the rest of the universe. The System Boundary determines what is considered part of the system (and thus subject to the decisions of the designer and stakeholders) and what is not (and is thus considered beyond their control, for the purposes of this project at least). See Section 3.4.2.1 for more details.

System Context: The external factors that influence and constrain the system. For more discussion, see Section 3.4.2.1.

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 [44]. For a more detailed discussion of this definition, including its flaws, see Section 2.2.3.

System Form: The approaches and structures used to enable the System Functions (i.e. the physical "stuff" of the system).

System Function: The specific actions or processes that the system performs, with a particular emphasis on those in service of the System Objectives.

System Objective: The high level description of what the system will do.

Tertiary Stakeholder: Those that exert either little control or primarily indirect control on the system, but ae impacted by the system.

Tradespace: The space spanned by the completely enumerated design variables, i.e. the set of possible design options [467].

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 [467].

Appendix B

Stakeholder Interview Questions

The following questions were used during the stakeholder interviews and meetings conducted during field visits to Rio de Janeiro in August of 2019 and March of 2020. This list does not include followup questions triggered by stakeholder responses.

1. To confirm, are you okay being recorded?
2. What is your name?
3. What organization are you associated/work with?
4. What is your role there?
5. What is your organization's primary goal/mission? How does it usually pursue that goal?
6. What are some example projects/activities?
7. How do individual projects in your organization originate?
8. What stakeholders does your organization work with?
9. What do you view as the primary pressures on mangroves in the Rio de Janeiro area?
10. What do you view as the primary pressures on the people living near the mangroves?
11. What, if any, interest does your organization have in the Rio de Janeiro mangroves?
12. Does your organization use any remote sensing data?
13. Has your organization ever participated in the design of an earth observation satellite? Or considered doing so?
14. What other sources of data does your organization rely upon?
15. What are some questions that you would like to be able to answer but can't? What are some challenges that your organization faces?

16. How much are you or your organization able to explore new data sources or data analysis methods, as opposed to continuing to rely upon your current methods?
17. Anything else you want to add?

Bibliography

[1] Alan S. Belward and Jon O. Skøien. Who launched what, when and why; trends in global land-cover observation capacity from civilian earth observation satellites. *ISPRS Journal of Photogrammetry and Remote Sensing*, 103:115–128, May 2015.

[2] John Jensen. *Remote Sensing of the Environment: An Earth Resource Perspective*. Pearson, Upper Saddle River, NJ, 2nd edition edition, May 2006.

[3] Mariel Borowitz. *Open Space : The Global Effort for Open Access to Environmental Satellite Data*. MIT Press, Cambridge, MA, 2017.

[4] Jennifer S. Light. *From Warfare to Welfare: Defense Intellectuals and Urban Problems in Cold War America*. JHUP, Baltimore, Md., August 2005.

[5] Boyd Cohen. Top 10 Climate Change Strategy Consultancies. https://www.triplepundit.com/story/2011/top-10-climate-change-strategy-consultancies/79586, March 2011.

[6] Jack Reid, Cynthia Zeng, and Danielle Wood. Combining Social, Environmental and Design Models to Support the Sustainable Development Goals. In *IEEE Aerospace Conference Proceedings*, volume 2019-March, Big Sky, Montana, March 2019. IEEE Computer Society.

[7] Elinor Ostrom. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press, Cambridge, United Kingdom, reissue edition edition, September 2015.

[8] Sherry Turkle. *The Empathy Diaries: A Memoir*. Penguin, March 2021.

[9] Lorna Duffin. The Conspicuous Consumptive : Woman as an Invalid. In Sara Delamont and Lorna Duffin, editors, *The Nineteenth-century Woman*. Routledge, 2012.

[10] Jane Jacobs. The Death and Life of Great American Cities. In Susan Fainstein and James DeFilippis, editors, *Readings in Planning Theory*. Wiley-Blackwell, Hoboken, NJ, fourth edition, January 2016.

[11] Ufuoma Ovienmhada and Danielle Wood. The Environment-Vulnerability-Decision-Technology Modeling Framework Applied to Environmental Justice Activism in Carceral Landscapes. In *AGU Fall Meeting*, volume 2021, pages GC25G–0723, December 2021.

[12] Audre Lorde. The Master's Tools Will Never Dismantle The Master's House. In *Sister Outsider: Essays and Speeches*, pages 110–114. Crossing Press, Berkeley, CA, 1984.

[13] Mark W. Maier and Eberhardt Rechtin. *The Art of Systems Architecting*. CRC Press, Boca Raton, 3 edition edition, January 2009.

[14] Edward Crawley, Bruce Cameron, and Daniel Selva. *System Architecture: Strategy and Product Development for Complex Systems*. Pearson, Boston, 1 edition edition, April 2015.

[15] Sebastian M. Pfotenhauer, Danielle Wood, Dan Roos, and Dava Newman. Architecting complex international science, technology and innovation partnerships (CISTIPs): A study of four global MIT collaborations. *Technological Forecasting and Social Change*, 104:38–56, 2016.

[16] Anita K. Jones. Gaining a Seat at the Policy Table. In *Engineering and Environmental Challenges: Technical Symposium on Earth Systems Engineering*, pages 59–64. The National Academies Press, Washington, DC, 2002.

[17] Ida R. Hoos. *Systems Analysis in Public Policy: A Critique*. University of California Press, January 1983.

[18] Definition of sustainable | Dictionary.com. https://www.dictionary.com/browse/sustainable.

[19] World Commission on Environment and Development. Our Common Future. Technical report, United Nations, Oxford, UK.

[20] United Nations Conference on Environment and Development. Rio Declaration on Environment and Development. Technical report, United Nations, Rio de Janeiro, Brazil, June 1992.

[21] World Summit on Sustainable Development. Plan of Implementation of the World Summit on Sustainable Development. Technical report, United Nations, Johannesburg, South Africa, September 2002.

[22] Jeffrey Sachs. *The Age of Sustainable Development*. Columbia University Press, 2015.

[23] Johan Rockström, Will Steffen, Kevin Noone, Åsa Persson, F. Stuart Chapin, Eric F. Lambin, Timothy M. Lenton, Marten Scheffer, Carl Folke, Hans Joachim Schellnhuber, Björn Nykvist, Cynthia A. de Wit, Terry Hughes, Sander van der Leeuw, Henning Rodhe, Sverker Sörlin, Peter K. Snyder, Robert Costanza, Uno Svedin, Malin Falkenmark, Louise Karlberg, Robert W. Corell, Victoria J. Fabry, James Hansen, Brian Walker, Diana Liverman, Katherine Richardson, Paul Crutzen, and Jonathan A. Foley. A safe operating space for humanity. *Nature*, 461(7263):472–475, September 2009.

[24] G. Yohe, E. Malone, A. Brenkert, M. Schlesinger, H. Meij, X. Xing, and D. Lee. Synthetic Assessment of Global Distribution of Vulnerability to Climate Change: Maps and Data, 2005, 2050, and 2100, 2006.

[25] Johan Rockström, Jeffrey D. Sachs, Marcus C. Öhman, and Guido Schmidt-Traub. Sustainable Development and Planetary Boundaries. Technical report, Sustainable Development Solutions Network, 2013.

[26] James C. Scott. *Seeing Like a State: How Certain Schemes to Improve the Human Condition Have Failed*. Yale University Press, March 2020.

[27] Chris Philol. Animals, Geography, and the City: Notes on Inclusions and Exclusions. *Environment and Planning D: Society and Space*, 13(6):655–681, December 1995.

[28] J.L WESTCOAT, C. PHILO, F. M. UFKES, J. EMEL, J. R. WOLCH, K. WEST, and T. E. GAINES. Bringing the animals back in. *Bringing the animals back in*, 13(6):631–760, 1995.

[29] Jennifer R. Wolch and Jody Emel. *Animal Geographies: Place, Politics, and Identity in the Nature-culture Borderlands*. Verso, 1998.

[30] Leila Harris and Helen Hazen. Rethinking maps from a more-than-human perspective. In Martin Dodge, Rob Kitchin, and Chris Perkins, editors, *Rethinking Maps: New Frontiers in Cartographic Theory*, pages 50–67. Routledge, June 2011.

[31] Douglas J. McCauley. Selling out on nature. *Nature*, 443(7107):27–28, September 2006.

[32] Jessie Guo, Daniel Kubli, and Patrick Saner. The economics of climate change: No action not an option. Technical report, Swiss Re Institute, Zurich, Switzerland, April 2021.

[33] R. de Groot, L. Brander, and S. Solomonides. Ecosystem Services Valuation Database (ESVD). Technical report, Ecosystem Services Partnership, December 2020.

[34] W. V. Reid, H. A. Mooney, A. Cropper, D. Capistrano, S. R. Carpenter, K. Chopra, P. Dasgupta, T. Dietz, A. K. Duraiappah, R. Hassan, R. Kasperson, R. Leemans, R. M. May, A. J. McMichael, P. Pingali, C. Samper, R. Scholes, R. T. Watson, A. H. Zakri, Z. Shidong, N. J. Ash, E. Bennett, P. Kumar, M. J. Lee, C. Raudsepp-Hearne, H. Simons, J. Thonell, and M. B. Zurek. *Ecosystems and Human Well-Being - Synthesis: A Report of the Millennium Ecosystem Assessment*. Island Press, 2005.

[35] William B Rouse and Nicoleta Serban. Understanding change in complex sociotechnical systems. *Information Knowledge Systems Management*, 2012.

[36] Afreen Siddiqi and Ross D. Collins. Sociotechnical systems and sustainability: Current and future perspectives for inclusive development. *Current Opinion in Environmental Sustainability*, 24:7–13, 2017.

[37] Joseph M Sussman. Teaching about Complex Sociotechnical Systems. Technical report, 2010.

[38] Sondoss Elsawah, Tatiana Filatova, Anthony J. Jakeman, Albert J. Kettner, Moira L. Zellner, Ioannis N. Athanasiadis, Serena H. Hamilton, Robert L. Axtell, Daniel G. Brown, Jonathan M. Gilligan, Marco A. Janssen, Derek T. Robinson, Julie Rozenberg, Isaac I. T. Ullah, and Steve J. Lade. Eight grand challenges in socio-environmental systems modeling. *Socio-Environmental Systems Modelling*, 2:16226, January 2020.

[39] Inter-Agency and Expert Group on MDG Indicators. The Millennium Development Goals Report. Technical report, United Nations, 2015.

[40] United Nations. Transforming Our World: The 2030 Agenda for Sustainable Development, 2015.

[41] Therese Bennich, Nina Weitz, and Henrik Carlsen. Deciphering the scientific literature on SDG interactions: A review and reading guide. *Science of The Total Environment*, 728:138405, August 2020.

[42] United Nations General Assembly. Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development, 2017.

[43] International Organization for Standardization, International Electrotechnical Commission, and Institute of Electrical and Electronics Engineers. Systems and Software Engineering - System and Software Engineering Vocabulary (SE-Vocab). Technical Report ISO/IEC/IEEE 24765:2010, Geneva, Switzerland, 2010.

[44] Systems Engineering Body of Knowledge. Systems Engineering (glossary). https://www.sebokwiki.org/wiki/Systems_Engineering_(glossary), May 2021.

[45] Olivier L. de Weck, Adam Michael Ross, and Donna H. Rhodes. Investigating Relationships and Semantic Sets amongst System Lifecycle Properties (Ilities). Working Paper, Massachusetts Institute of Technology. Engineering Systems Division, March 2012.

[46] Matthew E Fitzgerald and Adam M Ross. Effects of Enhanced Multi-party Tradespace Visualization on a Two-person Negotiation. *Procedia Computer Science*, 44:466–475, 2015.

[47] Matthew E Fitzgerald and Adam M Ross. Recommendations for framing multi-stakeholder tradespace exploration. In *INCOSE International Symposium*, Edinburgh, UK, 2016.

[48] O. Weck. MULTI-STAKEHOLDER SIMULATION AND GAMING ENVIRONMENT FOR A FUTURE RESOURCE ECONOMY IN SPACE. /paper/MULTI-STAKEHOLDER-SIMULATION-AND-GAMING-ENVIRONMENT-Weck/8d4c0bf1b644a5fa0e6d8f9ef02e7054d89be124, 2012.

[49] Paul T Grogan, Olivier L De Weck, Adam M Ross, and Donna H Rhodes. Interactive models as a system design tool: Applications to system project management. In *Conference on Systems Engineering Research*, Hoboken, NJ, 2015. Elsevier.

[50] Adam M. Ross, Daniel E. Hastings, and Joyce M. Warmkessel. Multi-Attribute Tradespace Exploration as Front End for Effective Space System Design. *Journal of Spacecraft and Rockets*, 41(1):20–28, 2004.

[51] Daniel Selva Selva Valero. *Rule-Based System Architecting of Earth Observation Satellite Systems*. PhD thesis, Massachusetts Institute of Technology, 2012.

[52] Adam M Ross and Donna H Rhodes. Using Natural Value-Centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis. In *INCOSE International Symposium*, Utrecht, the Netherlands, 2008.

[53] Peter Vascik, Adam M. Ross, and Donna H. Rhodes. A Method for Exploring Program and Portfolio Affordability Tradeoffs Under Uncertainty Using Epoch-Era Analysis: A Case Application to Carrier Strike Group Design:. In *Proceedings of the 12th Annual Acquisition Research Symposium*, Fort Belvoir, VA, April 2015. Defense Technical Information Center.

[54] Marco Te Brömmelstroet and Pieter M Schrijnen. From Planning Support Systems to Mediated Planning Support: A Structured Dialogue to Overcome the Implementation Gap. *Environment and Planning B: Planning and Design*, 37(1):3–20, February 2010.

[55] Group on Earth Observations. GEO at a Glance. https://earthobservations.org/geo_wwd.php, 2019.

[56] Paul M. Mather and Magaly Koch. *Computer Processing of Remotely-Sensed Images: An Introduction*. John Wiley & Sons, July 2011.

[57] Greg Shirah. NASA's Earth Observing Fleet: March 2017. https://svs.gsfc.nasa.gov/4558, 2017.

[58] Melissa Healy. Rep. Brown Quits House Intelligence Panel, Claims Abuses of Secrecy. *Los Angeles Times*, November 1987.

[59] J Barry. Mappings–a chronology of remote sensing. *Incorporations Zone*, 6:570–1, 1992.

[60] Patrick McHaffie. Manufacturing Metaphors. In John Pickles, editor, *Ground Truth: The Social Implications of Geographic Information Systems*, pages 113–129. The Guilford Press, New York, 1st edition edition, December 1994.

[61] M M Waldrop. Landsat commercialization stumbles again. *Science (New York, N.Y.)*, 235(4785):155, January 1987.

[62] Gabriel Popkin. US government considers charging for popular Earth-observing data. *Nature*, 556(7702):417–418, April 2018.

[63] Fitz Tepper. Satellite Maker Planet Labs Acquires BlackBridge's Geospatial Business. *TechCrunch*, July 2015.

[64] Jonathan Shieber and Ingrid Lunden. Astro Digital launched its first imaging satellites. *TechCrunch*, July 2017.

[65] B. Zhang, S. Wdowinski, T. Oliver-Cabrera, R. Koirala, M. J. Jo, and B. Osmanoglu. Mapping the extent and magnitude of sever flooding induced by hurricane Irma with multi-temporal Sentinel-1 SAR and InSAR observations. *Department of Earth and Environment*, April 2018.

[66] Wilfrid Schroeder, Patricia Oliva, Louis Giglio, and Ivan A. Csiszar. The New VIIRS 375m active fire detection data product: Algorithm description and initial assessment. *Remote Sensing of Environment*, 143:85–96, 2014.

[67] Arthur Y. Hou, Ramesh K. Kakar, Steven Neeck, Ardeshir A. Azarbarzin, Christian D. Kummerow, Masahiro Kojima, Riko Oki, Kenji Nakamura, and Toshio Iguchi. The global precipitation measurement mission. *Bulletin of the American Meteorological Society*, 95(5):701–722, 2014.

[68] John Wahr, Sean Swenson, Victor Zlotnicki, and Isabella Velicogna. Time-variable gravity from GRACE: First results. *Geophysical Research Letters*, 31(11):20–23, 2004.

[69] Matthew Mcgill, Thorsten Markus, Stanley S. Scott, and Thomas Neumann. The multiple altimeter beam experimental lidar (MABEL): An airborne simulator for the ICESat-2 mission. *Journal of Atmospheric and Oceanic Technology*, 30(2):345–352, 2013.

[70] Gabriela Quintana Sánchez. SAR in Support of the War in Ukraine, June 2022.

[71] Maudood Khan, Ashutosh Limaye, William Crosson, Alper Unal, nancy Kete, and Douglas Rickman. The Long, Hard Journey: Expanding the Use of NASA Data and Models for Sustainable Development Planning Around the World. In *The International Geoscience and Remote Sensing Symposium (IGARSS) 2009*, Cape Town, July 2009.

[72] NASA Applied Sciences Program. What We Do | NASA Applied Sciences. http://appliedsciences.nasa.gov/what-we-do.

[73] NASA Earth Science Applied Sciences. NASA Applied Sciences.Strategic Plan 2021-2026. Technical Report NP-2021-00-000-AS, National Aeronautics and Space Administration, Washington D.C., 2021.

[74] Dan Irwin and Jenny Frankel-Reed. SERVIR's Service Planning Toolkit: Lessons on Building Capacity along the Pathway to Development Impact. In *AGU Fall Meeting*, page 10, December 2017.

[75] NASA Jet Propulsion Laboratory. Satellite Radar Detects Damage from Sept. 19, 2017 Raboso, Mexico, Quake. https://www.jpl.nasa.gov/spaceimages/details.php?id=pia21963, 2017.

[76] NASA Jet Propulsion Laboratory. Satellite Data of Puerto Rico Identifies Possible Damage Areas – NASA Disaster Response. https://blogs.nasa.gov/disaster-response/2017/09/27/satellite-data-of-puerto-rico-identifies-possible-damage-areas/, 2017.

[77] Matt Finer, Sidney Novoa, Mikaela J. Weisse, Rachael Petersen, Joseph Mascaro, Tamia Souto, Forest Stearns, and Raúl García Martinez. Combating deforestation: From satellite to intervention. *Science*, 6395(360):1303–1305, 2018.

[78] M Overton and PJ Taylor. Further thoughts on geography and GIS: A preemptive strike? *Environment and Planning A*, 23:1087–1094, 1991.

[79] Peter Taylor and Ronald Johnston. Geographic Information Systems and Geography. In John Pickles, editor, *Ground Truth: The Social Implications of Geographic Information Systems*, pages 51–67. The Guilford Press, New York, 1st edition edition, December 1994.

[80] Signe Stroming, Molly Robertson, Bethany Mabee, Yusuke Kuwayama, and Blake Schaeffer. Quantifying the Human Health Benefits of Using Satellite Information to Detect Cyanobacterial Harmful Algal Blooms and Manage Recreational Advisories in U.S. Lakes. *GeoHealth*, 4(9):e2020GH000254, 2020.

[81] David Lagomasino, Temilola Fatoyinbo, SeungKuk Lee, Emanuelle Feliciano, Carl Trettin, Aurélie Shapiro, and Mwita M. Mangora. Measuring mangrove carbon loss and gain in deltas. *Environmental Research Letters*, 14(2):025002, January 2019.

[82] Southern Hemisphere Summer space Program 2013. Common Horizons White Paper. Technical Report SHS-SP13, International Space University, Mawson Lakes, Australia, 2013.

[83] Mia M Bennett, Janice K Chen, Luis F Alvarez León, and Colin J Gleason. The politics of pixels: A review and agenda for critical remote sensing. *Progress in Human Geography*, page 03091325221074691, January 2022.

[84] Molly K. Macauley. The value of information: Measuring the contribution of space-derived earth science data to resource management. *Space Policy*, 22(4):274–282, 2006.

[85] Roger Cooke, Alexander Golub, Bruce A. Wielicki, David F. Young, Martin G. Mlynczak, and Rosemary R. Baize. Using the social cost of carbon to value earth observing systems. *Climate Policy*, 3062(January):1–16, 2016.

[86] Willam M. Forney, Ronald P. Raunikar, Richard L. Bernkopf, and Shruti K. Mishra. An Economic Value of Remote-Sensing Information — Application to Agricultural Production and Maintaining Groundwater Quality. *U.S. Geological Survey Professional Paper*, (1796), 2012.

[87] Afreen Siddiqi, Sheila Baber, Olivier de Weck, Chris Durell, Brandon Russell, and Jeff Holt. Integrating Globally Dispersed Calibration in Small Satellites Mission Value. In *Small Satellite Conference*, Logan, Utah, August 2020.

[88] Afreen Siddiqi, Sheila Baber, and Olivier De Weck. Valuing Radiometric Quality of Remote Sensing Data for Decisions. In *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS*, pages 5724–5727, Brussels, Belgium, July 2021.

[89] Jamie Kruse, Joep Crompvoets, and Françoise Pearlman, editors. *GEOValue: The Socioeconomic Value of Geospatial Information*. CRC Press, New York, NY, 2017.

[90] Eric Sheppard. GIS and Society: Towards a Research Agenda. *Cartography and Geographic Information Systems*, 22(1):5–16, January 1995.

[91] M Goodchild and D.W. Rhind. An overview and definition of GIS. In *Geographical Information Systems: Principles and Applications*, pages 31–45. 1992.

[92] John Pickles. Tool or Science? GIS, Technoscience, and the Theoretical Turn. *Annals of the Association of American Geographers*, 87(2):363–372, June 1997.

[93] Nicholas R. Chrisman. What Does 'GIS' Mean? *Transactions in GIS*, 3(2):175–186, 1999.

[94] Eric J. Heikkila. GIS is Dead; Long Live GIS! *Journal of the American Planning Association*, 64(3):350–360, September 1998.

[95] Michael F. Goodchild. Geographical information science. *International Journal of Geographical Information Systems*, 6(1):31–45, January 1992.

[96] Michael F. Goodchild. Twenty years of progress: GIScience in 2010. *Journal of Spatial Information Science*, 2010(1):3–20, July 2010.

[97] Edward R. Tufte. *The Visual Display of Quantitative Information*. Graphics Press, Cheshire, Conn, 2nd edition edition, February 2001.

[98] Michael Friendly. A Brief History of Data Visualization. In Chun-houh Chen, Wolfgang Härdle, and Antony Unwin, editors, *Handbook of Data Visualization*, Springer Handbooks Comp.Statistics, pages 15–56. Springer, Berlin, Heidelberg, 2008.

[99] William Davenport. Marshall islands navigational charts. *Imago Mundi*, 15(1):19–26, January 1960.

[100] Michael Goodchild. Geographic Information Systems and Geographic Research. In John Pickles, editor, *Ground Truth: The Social Implications of Geographic Information Systems*, pages 31–50. The Guilford Press, New York, 1st edition edition, December 1994.

[101] Roger F. Tomlinson. PRESIDENTIAL ADDRESS: GEOGRAPHIC INFORMATION SYSTEMS and GEOGRAPHERS IN THE 1990s. *The Canadian Geographer / Le Géographe canadien*, 33(4):290–298, 1989.

[102] Howard Veregin. Computer Innovation and Adoption in Geography. In John Pickles, editor, *Ground Truth: The Social Implications of Geographic Information Systems*, pages 88–112. The Guilford Press, New York, 1st edition edition, December 1994.

[103] A. Stewart Fotheringham and John P. Wilson. Geographic Information Science: An Introduction. In *The Handbook of Geographic Information Science*, pages 1–7. John Wiley & Sons, Ltd, 2007.

[104] Michael Goodchild. Modeling the earth. In Martin Dodge, Rob Kitchin, and Chris Perkins, editors, *Rethinking Maps: New Frontiers in Cartographic Theory*, pages 83–96. Routledge, June 2011.

[105] C. Dana Tomlin. *GIS and Cartographic Modeling*. Esri Press, Redlands, Calif, illustrated edition edition, October 2012.

[106] David J. Maguire, Michael F. Goodchild, and David Rhind. *Geographical Information Systems: Principles*. Longman Scientific & Technical, 1991.

[107] Stephen Goldsmith and Susan Crawford. *The Responsive City: Engaging Communities Through Data-Smart Governance*. Jossey-Bass, San Francisco, CA, 1st edition edition, August 2014.

[108] Michael F. Goodchild, Luc Anselin, Richard P. Appelbaum, and Barbara Herr Harthorn. Toward Spatially Integrated Social Science. *International Regional Science Review*, 23(2):139–159, April 2000.

[109] David J. Cowen. The Availability of Geographic Data: The Current Technical and Institutional Environment. In *The Handbook of Geographic Information Science*, chapter 1, pages 11–34. John Wiley & Sons, Ltd, 2007.

[110] John Pickles, editor. *Ground Truth: The Social Implications of Geographic Information Systems*. The Guilford Press, New York, 1st edition edition, December 1994.

[111] David L. Tulloch. Institutional Geographic Information Systems and Geographic Information Partnering. In *The Handbook of Geographic Information Science*, chapter 25, pages 449–465. John Wiley & Sons, Ltd, 2007.

[112] Piotr Jankowski and Timothy Nyerges. *GIS for Group Decision Making*. CRC Press, London ; New York, 1st edition edition, January 2001.

[113] Emily Talen. Bottom-Up GIS. *Journal of the American Planning Association*, 66(3):279–294, September 2000.

[114] Dijilali Benmouffok. Information for Decision Making. *IDRC Reports*, 29(4):4–5, January 1993.

[115] Matthew H Edney. Strategies for maintaining the democratic nature of geographic information systems. In *Papers and Proceedings of the Applied Geography Conferences*, volume 14, pages 100–108, 1991.

[116] Trevor Harris, Daniel Weiner, Timothy Warner, and Richard Levin. Pursuing social Goals Through Participatory Geographic Information Systems. In John Pickles, editor, *Ground Truth: The Social Implications of Geographic Information Systems*, pages 196–222. The Guilford Press, New York, 1st edition edition, December 1994.

[117] Jeremy W Crampton and John Krygier. An Introduction to Critical Cartography. *ACME: An International Journal for Critical Geographies*, 4(1):11–33, 2005.

[118] Annette M. Kim. Critical cartography 2.0: From "participatory mapping" to authored visualizations of power and people. *Landscape and Urban Planning*, 142:215–225, October 2015.

[119] Renee Sieber. Public Participation Geographic Information Systems: A Literature Review and Framework. *Annals of the Association of American Geographers*, 96(3):491–507, September 2006.

[120] Sarah Williams. *Data Action: Using Data for Public Good*. The MIT Press, Cambridge, Massachusetts, December 2020.

[121] Catherine D'Ignazio and Lauren F. Klein. *Data Feminism*. The MIT Press, Cambridge, Massachusetts, March 2020.

[122] Sasha Costanza-Chock. *Design Justice: Community-Led Practices to Build the Worlds We Need*. The MIT Press, Cambridge, Massachusetts, March 2020.

[123] Daniel Weiner and Trevor M. Harris. Participatory Geographic Information Systems. In *The Handbook of Geographic Information Science*, chapter 26, pages 466–480. John Wiley & Sons, Ltd, 2007.

[124] Crystal Bond. The Cherokee Nation and tribal uses of GIS. In *Community Participation and Geographical Information Systems*. CRC Press, 2002.

[125] R E Klosterman. The What If? Collaborative Planning Support System. *Environment and Planning B: Planning and Design*, 26(3):393–408, June 1999.

[126] Michael Curry. Geographical Information Systems and the Inevitability of Ethical Inconsistency. In John Pickles, editor, *Ground Truth: The Social Implications of Geographic Information Systems*, pages 68–87. The Guilford Press, New York, 1st edition edition, December 1994.

[127] Amartya Sen. Freedom of choice: Concept and content. *European Economic Review*, 32(2):269–294, March 1988.

[128] W.J. Drummond and S.P. French. The Future of GIS in Planning: Converging Technologies and Diverging Interests. *Journal of the American Planning Association*, 7(2), 2008.

[129] Marco te Brömmelstroet. The Relevance of Research in Planning Support Systems: A Response to Janssen Et Al. *Environment and Planning B: Planning and Design*, 36(1):4–7, February 2009.

[130] Dominica Williamson and Emmet Connolly. Theirwork: The development of sustainable mapping. In Martin Dodge, Rob Kitchin, and Chris Perkins, editors, *Rethinking Maps: New Frontiers in Cartographic Theory*, pages 97–112. Routledge, June 2011.

[131] Martin Dodge, Chris Perkins, and Rob Kitchin. Mapping modes, methods and moments: A manifest for map studies. In Martin Dodge, Rob Kitchin, and Chris Perkins, editors, *Rethinking Maps: New Frontiers in Cartographic Theory*, pages 220–243. Routledge, June 2011.

[132] Z. Aslıgül Göçmen and Stephen J. Ventura. Barriers to GIS Use in Planning. *Journal of the American Planning Association*, 76(2):172–183, March 2010.

[133] Josh Lerner and Jean Tirole. Some Simple Economics of Open Source. *The Journal of Industrial Economics*, 50(2):197–234, 2002.

[134] Arpit Verma. Ubuntu Linux is the Most Popular Operating System in Cloud. https://fossbytes.com/ubuntu-linux-is-the-most-popular-operating-system-in-cloud/, August 2015.

[135] Britton Harris and Michael Batty. Locational Models, Geographic Information and Planning Support Systems. *Journal of the American Planning Association*, 55(1), 1993.

[136] J. Krutilla. Welfare Aspects of Benefit-Cost Analysis. *Journal of Political Economy*, 1961.

[137] Morris Hill. A Goals-Achievement Matrix for Evaluating Alternative Plans. In Ira Robinson, editor, *Decision-Making in Urban Planning: An Introduction to New Methodologies*. SAGE Publications, Inc, Beverly Hills, CA, first edition, 1972.

[138] W. Ross Ashby. Requisite Variety and Its Implications for the Control of Complex Systems. In George J. Klir, editor, *Facets of Systems Science*, International Federation for Systems Research International Series on Systems Science and Engineering, pages 405–417. Springer US, Boston, MA, 1991.

[139] Brian J. McLoughlin. System Guidance, Control, and Review. In *Decision-Making in Urban Planning: An Introduction to New Methodologies*. SAGE Publications, Inc, Beverly Hills, CA, first edition, 1972.

[140] Lena Börjeson, Mattias Höjer, Karl-Henrik Dreborg, Tomas Ekvall, and Göran Finnveden. Scenario types and techniques: Towards a user's guide. *Futures*, 38(7):723–739, September 2006.

[141] Robert Goodspeed. *Scenario Planning for Cities and Regions: Managing and Envisioning Uncertain Futures*. Lincoln Institute of Land Policy, Cambridge, May 2020.

[142] Richard E. Klosterman. *Community Analysis and Planning Techniques*. Rowman & Littlefield Publishers, Savage, Md, 50185th edition edition, April 1990.

[143] Doug Walker. *The Planners Guide to CommunityViz: The Essential Tool for a New Generation of Planning*. Routledge, November 2017.

[144] Ron Bradfield, George Wright, George Burt, George Cairns, and Kees Van Der Heijden. The origins and evolution of scenario techniques in long range business planning. *Futures*, 37(8):795–812, October 2005.

[145] Franz Tessun. Scenario analysis and early warning systems at Daimler-Benz aerospace. *Competitive Intelligence Review*, 8(4):30–40, 1997.

[146] Uri Avin and Robert Goodspeed. Using Exploratory Scenarios in Planning Practice. *Journal of the American Planning Association*, 86(4):403–416, October 2020.

[147] Oregon Sustainable Transportation Initiative. Scenario Planning Guidelines. Technical report, Oregon Department of Transportation, Salem, OR, August 2017.

[148] H. R. Maier, J. H. A. Guillaume, H. van Delden, G. A. Riddell, M. Haasnoot, and J. H. Kwakkel. An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? *Environmental Modelling & Software*, 81:154–164, July 2016.

[149] Bruce Mazlish. The Idea of Progress. *Daedalus*, 92(3):447–461, 1963.

[150] danah boyd and Kate Crawford. Critical Questions for Big Data. *Information, Communication & Society*, 15(5):662–679, June 2012.

[151] John Maynard Keynes. Economic Possibilities for Our Grandchildren. In John Maynard Keynes, editor, *Essays in Persuasion*, pages 321–332. Palgrave Macmillan UK, London, 2010.

[152] Rob Kitchin, Chris Perkins, and Martin Dodge. Thinking about maps. In Martin Dodge, Rob Kitchin, and Chris Perkins, editors, *Rethinking Maps: New Frontiers in Cartographic Theory*, pages 1–25. Routledge, June 2011.

[153] Constance Penley and Andrew Ross. *Technoculture*. U of Minnesota Press, 1991.

[154] Lewis Mumford. Authoritarian and Democratic Technics. *Technology and Culture*, 5(1):1–8, 1964.

[155] D. Hayes. Rays of hope: The transition to a post-petroleum world. January 1977.

[156] Langdon Winner. Do Artifacts Have Politics? *Daedalus*, 109(1):121–136, 1980.

[157] Jeffrey D. Sachs. Optimism for the New Year | by Jeffrey D. Sachs. https://www.project-syndicate.org/commentary/five-reasons-for-optimism-in-2021-by-jeffrey-d-sachs-2021-01, January 2021.

[158] Tom Simonite. What Really Happened When Google Ousted Timnit Gebru. *Wired*.

[159] John Pickles. Representations in an Electronic Age: Geography, GIS, and Democracy. In John Pickles, editor, *Ground Truth: The Social Implications of Geographic Information Systems*, pages 1–30. The Guilford Press, New York, 1st edition edition, December 1994.

[160] Shannon Jackson. The City from Thirty Thousand Feet: Embodiment, Creativity, and the Use of Geographic Information Systems as Urban Planning Tools. *Technology and Culture*, 49(2):325–346, 2008.

[161] Sean McDonald. Ebola: A Big Data Disaster. Technical report, The Centre for Internet & Society, Bengaluru, India, January 2016.

[162] David L. Tulloch. Theoretical Model of Multipurpose Land Information Systems Development. *Transactions in GIS*, 3(3):259–283, 1999.

[163] Mark Monmonier and H. J. de Blij. *How to Lie with Maps.* University of Chicago Press, Chicago, 2nd edition edition, May 1996.

[164] John Krygier and Denis Wood. Ce n'est pas le monde (This is not the world). In Martin Dodge, Rob Kitchin, and Chris Perkins, editors, *Rethinking Maps: New Frontiers in Cartographic Theory*, pages 189–219. Routledge, June 2011.

[165] Arnold Pacey. *The Culture of Technology.* MIT Press, 1983.

[166] Safiya Umoja Noble. *Algorithms of Oppression: How Search Engines Reinforce Racism.* NYU Press, New York, illustrated edition edition, February 2018.

[167] Amy Propen. Cartographic representation and the construction of lived worlds. In Martin Dodge, Rob Kitchin, and Chris Perkins, editors, *Rethinking Maps: New Frontiers in Cartographic Theory*, pages 113–130. Routledge, June 2011.

[168] Laura Kurgan. *Close Up at a Distance: Mapping, Technology, and Politics.* MIT Press, 2013.

[169] Mark Weiner. The computer for the 21st century. *Scientific American*, 265(3):94–103, September 1991.

[170] Virginia Eubanks. *Automating Inequality: How High-Tech Tools Profile, Police, and Punish the Poor.* St. Martin's Press, New York, NY, January 2018.

[171] Alan K. Henrikson. The Power and Politics of Maps. In *Reordering the World.* Routledge, second edition, 1994.

[172] Richard E. Klosterman. Arguments for and against planning. *Town Planning Review*, 56(1):5, January 1985.

[173] William Easterly. *The White Man's Burden: Why the West's Efforts to Aid the Rest Have Done So Much Ill and So Little Good.* Penguin Books, New York City, NY, 2007.

[174] William Easterly. *The Tyranny of Experts: Economists, Dictators, and the Forgotten Rights of the Poor.* Basic Books, 1 edition edition, March 2015.

[175] Leonie Sandercock. Commentary: Indigenous planning and the burden of colonialism. *Planning Theory & Practice*, 5(1):118–124, March 2004.

[176] Theodore M Porter. Objectivity as standardization: The rhetoric of impersonality in measurement, statistics, and cost-benefit analysis. *Annals of Scholarship*, 9(1/2):19–59, 1992.

[177] T.J. Barnes and M.W. Wilson. Big Data, social physics, and spatial analysis: The early years - Trevor J Barnes, Matthew W Wilson, 2014. *Big Data & Society*, 1(1), 2014.

[178] Alexi Yurchak. *Everything Was Forever, Until It Was No More.* Princeton University Press, Sun, 10/23/2005 - 12:00.

[179] Ira M. Robinson. Section 2 - Plan Formulation: Introductory Note. In Ira M. Robinson, editor, *Decision-Making in Urban Planning: An Introduction to New Methodologies.* Sage Publications, Beverly Hills, January 1972.

[180] Nina Munk. *The Idealist: Jeffrey Sachs and the Quest to End Poverty.* Anchor, Penguin Random House, October 2014.

[181] Peter Marcuse. The Three Historic Currents of City Planning. In Susan Fainstein and James DeFilippis, editors, *Readings in Planning Theory.* Wiley-Blackwell, Hoboken, NJ, fourth edition, January 2016.

[182] Susan Fainstein. Spatial Justice and Planning. In Susan Fainstein and James DeFilippis, editors, *Readings in Planning Theory*, pages 258–272. Wiley-Blackwell, Hoboken, NJ, fourth edition, January 2016.

[183] Faranak Miraftab. Insurgent Planning: Situating Radical Planning in the Global South. In Susan Fainstein and James DeFilippis, editors, *Readings in Planning Theory.* Wiley-Blackwell, Hoboken, NJ, fourth edition, January 2016.

[184] William L.C. Wheaton and Margaret F. Wheaton. Identifying the Public Interest: Values and Goals. In Ira M. Robinson, editor, *Decision-Making in Urban Planning: An Introduction to New Methodologies.* Sage Publications, Beverly Hills, January 1972.

[185] John Forester. Planning in the Face of Power. In *Classic Readings in Urban Planning.* Routledge, 2001.

[186] Eric Gordon and Edith Manosevitch. Augmented deliberation: Merging physical and virtual interaction to engage communities in urban planning. *New Media & Society*, 13(1):75–95, February 2011.

[187] Sherry R. Arnstein. A Ladder Of Citizen Participation. *Journal of the American Institute of Planners*, 35(4):216–224, July 1969.

[188] Victor Bekkers and Rebecca Moody. Visual events and electronic government: What do pictures mean in digital government for citizen relations? *Government Information Quarterly*, 28(4):457–465, October 2011.

[189] Jonathan Furner. Dewey deracialized: A critical race-theoretic perspective. *KO Knowledge Organization*, 34(3):144–168, 2007.

[190] R. G. Smith. The Systems Approach and the Urban Dilemma. Staff Discussion Paper 181, The George Washington University, United States, July 1968.

[191] Richard Foster. Urban development applications project Quarterly report, 1 Oct. - 31 Dec. 1970. Contractor Report NASA-CR-119025, National Aeronautics and Space Administration, New York City, December 1970.

[192] A. Karen, D. Orrick, and T. Anuskiewicz. Technology transfer in New York City - The NASA/NYC Applications Project. In *3rd Urban Technology Conference and Technical Display*, Boston, MA, September 1973. American Institute of Aeronautics and Astronautics.

[193] Jay W. Forrester. Systems Analysis as a Tool for Urban Planning. *IEEE Transactions on Systems Science and Cybernetics*, 6(4):258–265, October 1970.

[194] Donella Meadows, Dennis Meadows, Jorgen Randgers, and William Behrens. *The Limits to Growth*. Potomac Associates, Washington D.C., 1972.

[195] Jay W. Forrester. System dynamics—a personal view of the first fifty years. *System Dynamics Review*, 23(2-3):345–358, 2007.

[196] Kenneth L. Kraemer and John Leslie King. A Requiem for USAC. *Policy Analysis*, 5(3):313–349, 1979.

[197] A. G. Wilson. Modelling and Systems Analysis in Urban Planning. *Nature*, 220, December 1968.

[198] John Friedmann. Two Centuries of Planning: An Overview. In Seymour Mandelbaum, Luigi Mazza, and Robert Burchell, editors, *Explorations in Planning Theory*, pages 10–29. Routledge, New York, New York, USA, September 2017.

[199] Peter L. Szanton. Analysis and Urban Government: Experience of the New York City-Rand Institute. *Policy Sciences*, 3(2):153–161, 1972.

[200] M. Rush and A. Holguin. Remote sensing utility in a disaster struck urban environment. Technical Report NASA-CR-149103, National Aeronautics and Space Administration, Houston, TX, September 1976.

[201] James Haggerty. Spinoff 1980. Technical report, National Aeronautics and Space Administration, Washington D.C., 1980.

[202] Eden Medina. *Cybernetic Revolutionaries: Technology and Politics in Allende's Chile*. MIT Press, Cambridge, MA, USA, October 2011.

[203] Eden Medina. Designing Freedom, Regulating a Nation: Socialist Cybernetics in Allende's Chile. *Journal of Latin American Studies*, 38(3):571–606, August 2006.

[204] Ira M. Robinson, editor. *Decision-Making in Urban Planning: An Introduction to New Methodologies*. Sage Publications, Beverly Hills, January 1972.

[205] Alex Gorod, Brian Sauser, and John Boardman. System-of-Systems Engineering Management: A Review of Modern History and a Path Forward. *IEEE Systems Journal*, 2(4):484–499, December 2008.

[206] Richard C. Booton and Simon Ramo. The Development of Systems Engineering. *IEEE Transactions on Aerospace and Electronic Systems*, AES-20(4):306–310, July 1984.

[207] Arthur D. Hall. *Hall's A Methodology for Systems Engineering: 1962 Edition*. van Nostrand, 1966th edition edition, January 1962.

[208] James H. Brill. Systems engineering? A retrospective view. *Systems Engineering*, 1(4):258–266, 1998.

[209] Eric C. Honour. INCOSE: History of the International Council on Systems Engineering. *Systems Engineering*, 1(1):4–13, 1998.

[210] Marvin Talbott. Why Systems Fail (viewed from Hindsight). *INCOSE International Symposium*, 3(1):721–728, 1993.

[211] A. Terry Bahill and Steven J. Henderson. Requirements development, verification, and validation exhibited in famous failures. *Systems Engineering*, 8(1):1–14, 2005.

[212] Henry Petroski. *To Engineer Is Human: The Role of Failure in Successful Design*. Vintage, New York, March 1992.

[213] Henry Petroski. *Design Paradigms: Case Histories of Error and Judgment in Engineering*. Cambridge University Press, Cambridge England ; New York, N.Y, May 1994.

[214] Nathan J. Slegers, Ronald T. Kadish, Gary E. Payton, John Thomas, Michael D. Griffin, and Dan Dumbacher. Learning from failure in systems engineering: A panel discussion. *Systems Engineering*, 15(1):74–82, 2012.

[215] Jack Reid and Danielle Wood. Systems Engineering Applied to Urban Planning & Development: A Review & Research Agenda. *Systems Engineering*, 2022.

[216] Douglass B. Lee Lee Jr. Requiem for Large-Scale Models. *Journal of the American Institute of Planners*, 39(3):163–178, May 1973.

[217] K. L. Rider. A Parametric Model for the Allocation of Fire Companies. Technical report, United States, April 1975.

[218] Jay W. Forrester. *Urban Dynamics*. Pegasus Communications, Inc., Waltham, MA, January 1969.

[219] G. D. Brewer. Systems Analysis in the Urban Complex: Potential and Limitations. Technical report, RAND Corporation, Santa Monica, CA, December 1973.

[220] David Boyce. Toward a Framework for Defining and Applying Urban Indicators in Plan-Making. In Ira Robinson, editor, *Decision-Making in Urban Planning: An Introduction to New Methodologies*, pages 62–84. SAGE Publications, Inc, Beverly Hills, CA, first edition, 1972.

[221] Kelly Clifton, Reid Ewing, and Gerrit-Jan Knapp. Quantitative analysis of urban form: A multidisciplinary review. *Journal of Urbanism*, 1(1):17–45, 2008.

[222] A Read, K Takai, H Wolford, and E Berman. Asset-based economic development: Building sustainable small and rural communities. *Retrieved April*, 7:2015, 2012.

[223] David S. Sawicki and Patrice Flynn. Neighborhood Indicators: A Review of the Literature and an Assessment of Conceptual and Methodological Issues. *Journal of the American Planning Association*, 62(2):165–183, June 1996.

[224] Avrom Bendavid Val. *Regional and Local Economic Analysis for Practitioners: Fourth Edition*. Praeger, New York, 4 edition edition, February 1991.

[225] Michael Batty. *Cities and Complexity*. The MIT Press, Cambridge, MA, September 2005.

[226] S. Lauf, D. Haase, P. Hostert, T. Lakes, and B. Kleinschmit. Uncovering land-use dynamics driven by human decision-making – A combined model approach using cellular automata and system dynamics. *Environmental Modelling & Software*, 27–28:71–82, January 2012.

[227] Marisa A Zapata and Nikhil Kaza. Radical uncertainty: Scenario planning for futures. *Environment and Planning B: Planning and Design*, 42(4):754–770, July 2015.

[228] Eric J. Miller. Integrated urban modeling: Past, present, and future. *Journal of Transport and Land Use*, 11(1):387–399, 2018.

[229] Rolf Moeckel, Carlos Llorca Garcia, Ana T. Moreno Chou, and Matthew Bediako Okrah. Trends in integrated land-use/transport modeling: An evaluation of the state of the art. *Journal of Transport and Land Use*, 11(1):463–476, 2018.

[230] Harutyun Shahumyan and Rolf Moeckel. Integration of land use, land cover, transportation, and environmental impact models: Expanding scenario analysis with multiple modules. *Environment and Planning B: Urban Analytics and City Science*, 44(3):531–552, May 2017.

[231] Peter Checkland. *Systems Thinking, Systems Practice: Includes a 30-Year Retrospective*. Wiley, Chichester ; New York, 1st edition edition, September 1999.

[232] John McDermid. Complexity: Concept, causes and control. In *Engineering of Complex Computer Systems, 2000. ICECCS 2000. Proceedings. Sixth IEEE International Conference On*, pages 2–9. IEEE, 2000.

[233] Joseph M. Sussman. Collected Views on Complexity in Systems. Technical report, 2002.

[234] Chih-Chun Chen, Sylvia B Nagl, and Christopher D Clack. Complexity and Emergence in Engineering Systems. In A. Tolk and L.C. Jain, editors, *Complex*

Systems in Knowledge-based Environments: Theory, Models and Applications, pages 99–127. Springer Science & Business Media, 2009.

[235] Joris Deguet, Yves Demazeau, and Laurent Magnin. Elements about the Emergence Issue: A Survey of Emergence Definitions. *Complexus*, 3:24–31, 2006.

[236] Office of the Director of Systems and Software Engineering. Systems Engineering Guide for Systems of Systems, 2008.

[237] Robert J Glass, Arlo L Ames, Theresa J Brown, S Louise Maffitt, Walter E Beyeler, Patrick D Finley, Thomas W Moore, John M Linebarger, Nancy S Brodsky, Stephen J Verzi, Alexander V Outkin, and Aldo A Zagonel. Complex Adaptive Systems of Systems (CASoS) Engineering: Mapping Aspirations to Problem Solutions. Technical report, Sandia National Laboratories, Albuquerque, NM, 2011.

[238] INCOSE Complex Systems Working Group. A Complexity Primer for Systems Engineers. (July), 2016.

[239] Charles B Keating and Polinpapilinho F Katina. Systems of systems engineering: Prospects and challenges for the emerging field. *International Journal of System of Systems Engineering*, 2(2):234–256, 2011.

[240] Saurabh Mittal, Margery J Doyle, and Antoinette M Portrey. Human in the Loop in system of Systems (SoS) Modeling and Simulation: Applications to Live, Virtual and Constructive (LVC) Distributed Mission Operations (DMO) Training. In Larry B Rainey and Andreas Tolk, editors, *Modeling and Simulation Support for System of Systems Engineering Applications*, pages 415–451. John Wiley & Sons, 2015.

[241] Sarah A. Sheard. Practical Applications of Complexity Theory for Systems Engineers. *INCOSE International Symposium*, 15(1):923–939, 2005.

[242] Andreas Tolk and Larry B Rainey. Toward a Research Agenda for M&S Support of System of Systems Engineering. In Larry B Rainey and Andreas Tolk, editors, *Modeling and Simulation Support for System of Systems Engineering Applications*, pages 583–592. John Wiley & Sons, 2015.

[243] Cynthia F Kurtz and David J Snowden. The New Dynamics of Strategy: Sense-making in a Complex-Complicated World. *IBM Systems Journal*, 42(3):462–483, 2003.

[244] Pierre-alain J Y Martin. *A Framework for Quantifying Complexity and Understanding Its Sources: Application to Two Large-Scale Systems*. PhD thesis, 2004.

[245] Sarah Sheard. A Complexity Typology for Systems Engineering. In *INCOSE International Symposium*, 2010.

[246] Angela Weber Righi, Priscila Wachs, and Tarcísio Abreu Saurin. Characterizing complexity in socio-technical systems: A case study of a SAMU Medical Regulation Center. *Work*, 2012.

[247] Florian Schöttl and Udo Lindemann. Quantifying the Complexity of Socio-Technical Systems – A Generic , Interdisciplinary Approach. *Procedia - Procedia Computer Science*, 2015.

[248] Lucie Reymondet. A Framework for Sense-Making of Complex Sociotechnical Systems. Master's thesis, Massachusetts Institute of Technology, 2016.

[249] Xiaodong Zhang, Guo H. Huang, and Xianghui Nie. Robust stochastic fuzzy possibilistic programming for environmental decision making under uncertainty. *Science of The Total Environment*, 408(2):192–201, December 2009.

[250] Zhengping Liu, Guohe Huang, and Wei Li. An inexact stochastic–fuzzy jointed chance-constrained programming for regional energy system management under uncertainty. *Engineering Optimization*, 47(6):788–804, June 2015.

[251] Hillary Sillitto, James Martin, Dorothy McKinney, Regina Griego, Dov Dori, Daniel Krob, Patrick Godfrey, Eileen Arnold, and Scott Jackson. Systems Engineering and System Definitions. Technical Report INCOSE-TP-2020-002-06, INCOSE, July 2019.

[252] INCOSE. *INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*. Wiley, Hoboken, New Jersey, 4 edition edition, July 2015.

[253] Wen Feng, Edward F. Crawley, Olivier L. de Weck, Rene Keller, and Bob Robinson. Dependency structure matrix modelling for stakeholder value networks. In *Proceedings of the 12th International DSM Conference*, Cambridge, UK, 2010. Design Society.

[254] George M. Samaras and Richard L. Horst. A systems engineering perspective on the human-centered design of health information systems. *Journal of Biomedical Informatics*, 38(1):61–74, February 2005.

[255] Francesco Longo, Antonio Padovano, and Steven Umbrello. Value-Oriented and Ethical Technology Engineering in Industry 5.0: A Human-Centric Perspective for the Design of the Factory of the Future. *Applied Sciences*, 10(12):4182, June 2020.

[256] So Young Kim, David Wagner, and Alejandro Jimenez. Challenges in applying model-based systems engineering: Human-centered design perspective. September 2019.

[257] Frank E. Ritter, Gordon D. Baxter, and Elizabeth F. Churchill. *Foundations for Designing User-Centered Systems*. Springer London, London, 2014.

[258] Magnus Sparrevik, David N Barton, Amy MP Oen, Nagothu Udaya Sehkar, and Igor Linkov. Use of multicriteria involvement processes to enhance transparency and stakeholder participation at Bergen Harbor, Norway. *Integrated Environmental Assessment and Management*, 7(3):414–425, 2011.

[259] Robert Goodspeed. The Death and Life of Collaborative Planning Theory. *Urban Planning*, 1(4):1–5, November 2016.

[260] Petina L. Pert, Scott N. Lieske, and Rosemary Hill. Participatory development of a new interactive tool for capturing social and ecological dynamism in conservation prioritization. *Landscape and Urban Planning*, 114:80–91, June 2013.

[261] Paul Waddell. UrbanSim: Modeling Urban Development for Land Use, Transportation, and Environmental Planning. *Journal of the American Planning Association*, 68(3):297–314, September 2002.

[262] John P. Wilson and A. Stewart Fotheringham, editors. *The Handbook of Geographic Information Science*. Wiley-Blackwell, Malden, MA, 1st edition edition, August 2007.

[263] Dov Dori. *Object-Process Methodology: A Holistic Systems Paradigm ; with CD-ROM*. Springer Science & Business Media, July 2002.

[264] Ana Luísa Ramos, José Vasconcelos Ferreira, and Jaume Barceló. Model-Based Systems Engineering: An Emerging Approach for Modern Systems. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 42(1):101–111, January 2012.

[265] Claudia Yamu, Gert de Roo, and Pierre Frankhauser. Assuming it is all about conditions. Framing a simulation model for complex, adaptive urban space. *Environment and Planning B: Planning and Design*, 43(6):1019–1039, November 2016.

[266] Marian R. Chertow. Industrial Ecology in a Developing Context. In Corrado Clini, Ignazio Musu, and Maria Lodovica Gullino, editors, *Sustainable Development and Environmental Management: Experiences and Case Studies*, pages 335–349. Springer Netherlands, Dordrecht, 2008.

[267] David Bristow and Christopher Kennedy. Why Do Cities Grow? Insights from Nonequilibrium Thermodynamics at the Urban and Global Scales. *Journal of Industrial Ecology*, 19(2):211–221, 2015.

[268] Ben Purvis, Yong Mao, and Darren Robinson. Thermodynamic Entropy as an Indicator for Urban Sustainability? *Procedia Engineering*, 198:802–812, January 2017.

[269] C. Kennedy, S. Pincetl, and P. Bunje. The study of urban metabolism and its applications to urban planning and design. *Environmental Pollution*, 159(8):1965–1973, August 2011.

[270] José Lobo, Luís M. A. Bettencourt, Deborah Strumsky, and Geoffrey B. West. Urban Scaling and the Production Function for Cities. *PLOS ONE*, 8(3):e58407, March 2013.

[271] Peter Checkland. Soft systems methodology: A thirty year retrospective. *Systems Research and Behavioral Science*, 17(S1):S11–S58, 2000.

[272] William Donaldson. In Praise of the “Ologies”: A Discussion of and Framework for Using Soft Skills to Sense and Influence Emergent Behaviors in Sociotechnical Systems. *Systems Engineering*, 20(5):467–478, 2017.

[273] Nicola Ulibarri. Collaborative model development increases trust in and use of scientific information in environmental decision-making. *Environmental Science & Policy*, 82:136–142, April 2018.

[274] Scott Campbell. Green Cities, Growing Cities, Just Cities? Urban Planning and the Contradictions of Sustainable Development. In Susan Fainstein and James DeFilippis, editors, *Readings in Planning Theory*. Wiley-Blackwell, Hoboken, NJ, fourth edition, January 2016.

[275] Sakiko Fukuda-Parr, Alicia Ely Yamin, and Joshua Greenstein. The Power of Numbers: A Critical Review of Millennium Development Goal Targets for Human Development and Human Rights. *Journal of Human Development and Capabilities*, 15(2-3):105–117, July 2014.

[276] Philip Alston. Ships Passing in the Night: The Current State of the Human Rights and Development Debate Seen through the Lens of the Millennium Development Goals. *Human Rights Quarterly*, 27(3):755–829, 2005.

[277] Office of the United Nations High Commissioner for Human Rights and Center for Economics and Social Rights. Who Will Be Accountable? Human Rights and the Post-2015 Development Agenda. Technical Report HR/PUB/13/1, United Nations, Geneva, Switzerland, 2013.

[278] Sanjay Reddy and Antoine Heuty. Global Development Goals: The Folly of Technocratic Pretensions. *Development Policy Review*, 26(1):5–28, 2008.

[279] Robert W. Snow, Carlos A. Guerra, Abdisalan M. Noor, Hla Y. Myint, and Simon I. Hay. The global distribution of clinical episodes of Plasmodium falciparum malaria. *Nature*, 434(7030):214–217, March 2005.

[280] Data deprivation : Another deprivation to end. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/700611468172787967/Data-deprivation-another-deprivation-to-end.

[281] Group on Earth Observations. Strategic Implementation Plan 2020-2024. Technical report.

[282] Peter J Taylor. Full circle, or new meaning for the global. *The challenge for geography: a changing world: a changing discipline Blackwell, Oxford*, pages 181–97, 1993.

[283] Tibor Vegh, Megan Jungwiwattanaporn, Linwood Pendleton, and Brian Murray. Mangrove Ecosystem Services Valuation: State of the Literature. Technical Report NI WP 14-06, Nicholas Institute for Environmental Policy Solutions, Duke University, Durham, NC, July 2014.

[284] Piotr Jankowski. Integrating geographical information systems and multiple criteria decision-making methods. *International Journal of Geographical Information Systems*, 9(3):251–273, May 1995.

[285] Bottlenecks Blocking Widespread Usage of Planning Support Systems - Guido Vonk, Stan Geertman, Paul Schot, 2005. https://journals.sagepub.com/doi/abs/10.1068/a3712.

[286] Dr Thorsten Wiechmann. Errors Expected — Aligning Urban Strategy with Demographic Uncertainty in Shrinking Cities. *International Planning Studies*, 13(4):431–446, November 2008.

[287] Charles R. Nelson and Stephen C. Peck. The NERC Fan: A Retrospective Analysis of the NERC Summary Forecasts. *Journal of Business & Economic Statistics*, 3(3):179–187, July 1985.

[288] Steve Bankes. Exploratory Modeling for Policy Analysis. *Operations Research*, 41(3):435–449, June 1993.

[289] Pierre Wack. Scenarios: Shooting the Rapids. *Harvard Business Review*, November 1985.

[290] Guido Vonk and Arend Ligtenberg. Socio-technical PSS development to improve functionality and usability—Sketch planning using a Maptable. *Landscape and Urban Planning*, 94(3):166–174, March 2010.

[291] John Dewey. *Human Nature and Conduct: An Introduction to Social Psychology*. Cosimo Classics, New York, N.Y, March 2007.

[292] Ashis BaNandynuri and Shiv Visvanathan. Modern Medicine and Its Non-Modern Critics: A Study in Discourse. In Frédérique Apffel Marglin and Stephen A. Marglin, editors, *Dominating Knowledge: Development, Culture, and Resistance*, pages 145–184. Clarendon Press, Oxford : New York, 1 edition edition, October 1990.

[293] Mark Gahegan. Multivariate Geovisualization. In *The Handbook of Geographic Information Science*, chapter 16, pages 292–316. John Wiley & Sons, Ltd, 2007.

[294] Eric J. Miller, Bilal Farooq, Franco Chingcuanco, and David Wang. Historical Validation of Integrated Transport–Land Use Model System. *Transportation Research Record*, 2255(1):91–99, January 2011.

[295] Zachary A Needell and Jessika E Trancik. Efficiently simulating personal vehicle energy consumption in mesoscopic transport models. In *Transportation Research Board 97th Annual Meeting*, Washington D.C., 2018.

[296] Carlos Lima Azevedo, Ravi Seshadri, Song Gao, Bilge Atasoy, Arun Prakash Akkinepally, Eleni Christofa, Fang Zhao, Jessika Trancik, and Moshe Ben-Akiva. Tripod: Sustainable travel incentives with prediction, optimization, and personalization. In *Transportation Research Board 97th Annual Meeting*, Washington D.C., 2018. Transportation Research Board.

[297] Michiko Masutani, Thomas W. Schlatter, Ronald M. Errico, Ad Stoffelen, Erik Andersson, William Lahoz, John S. Woollen, G. David Emmitt, Lars-Peter Riishojgaard, and Stephen J. Lord. Observing System Simulation Experiments. In *Data Assimilation: Making Sense of Observations*, pages 647–679. Springer, New York City, NY, 2010.

[298] Ronald M. Errico, Runhua Yang, Nikki C. Privé, King Sheng Tai, Ricardo Todling, Meta E. Sienkiewicz, and Jing Guo. Development and validation of observing-system simulation experiments at NASA's global modeling and assimilation office. *Quarterly Journal of the Royal Meteorological Society*, 139(674):1162–1178, 2013.

[299] Sujay V Kumar, Christa D Peters-lidard, Dalia Kirschbaum, Ken Harrison, Joseph Santanello, and Soni Yatheendradas. A mission simulation and evaluation platform for terrestrial hydrology using the NASA Land Information System, 2015.

[300] Evelyn Honoré-Livermore, Roger Birkeland, and Cecilia Haskins. Addressing the Sustainable Development Goals with a System-of-Systems for Monitoring Arctic Coastal Regions. *INCOSE International Symposium*, 30(1):604–619, 2020.

[301] Cecilia Haskins. *Systems Engineering Analyzed, Synthesized, and Applied to Sustainable Industrial Park Development*. PhD thesis, Norweigen University of Science and Technology, Trondheim, Norway, 2008.

[302] Sean Esbjörn-Hargens. An Overview of Integral Theory. In *Integral Theory in Action: Applied, Theoretical, and Constructive Perspectives on the AQAL Model*. SUNY Press, Albany, NY, August 2010.

[303] Henk van Zyl and Jan Hendrik Roodt. A Transdisciplinary Design and Implementation of Sustainable Agricultural Principles in the Waikato Region of New Zealand. *INCOSE International Symposium*, 30(1):637–650, 2020.

[304] Philipp Geyer, Jochen Stopper, Werner Lang, and Maximilian Thumfart. A Systems Engineering Methodology for Designing and Planning the Built Environment—Results from the Urban Research Laboratory Nuremberg and Their Integration in Education. *Systems*, 2(2):137–158, June 2014.

[305] Pepe Puchol-Salort, Jimmy O'Keeffe, Maarten van Reeuwijk, and Ana Mijic. An urban planning sustainability framework: Systems approach to blue green urban design. *Sustainable Cities and Society*, 66:102677, March 2021.

[306] Dina Margrethe Aspen and Andreas Amundsen. Developing a Participatory Planning Support System for Sustainable Regional Planning—A Problem Structuring Case Study. *Sustainability*, 13(10):5723, January 2021.

[307] Jenna L. Mueller, Mary Elizabeth Dotson, Jennifer Dietzel, Jenna Peters, Gabriela Asturias, Amelia Cheatham, Marlee Krieger, Baishakhi Taylor, Sherryl Broverman, and Nirmala Ramanujam. Using Human-Centered Design to Connect Engineering Concepts to Sustainable Development Goals. *Advances in Engineering Education*, 8(2), 2020.

[308] Lan Yang and Kathryn Cormican. The Crossovers and Connectivity between Systems Engineering and the Sustainable Development Goals: A Scoping Study. *Sustainability*, 13(6):3176, January 2021.

[309] Cecilia Haskins. Systems Engineering for Sustainable Development Goals. *Sustainability*, 13(18):10293, January 2021.

[310] Ufuoma Ovienmhada, Fohla Mouftaou, and Danielle Wood. Inclusive Design of Earth Observation Decision Support Systems for Environmental Governance: A Case Study of Lake Nokoué. *Frontiers in Climate*, 3:105, 2021.

[311] Seamus Lombardo, Steven Israel, and Danielle Wood. The Environment-Vulnerability-Decision-Technology Framework for Decision Support in Indonesia. In *2022 IEEE Aerospace Conference (AERO)*, pages 1–15, March 2022.

[312] Seamus Lombardo, Javier Kinney, Steven Israel, and Danielle Wood. Utilizing Satellite Earth Observation Analyses and the Environment-Vulnerability-Decision-Technology Modelling Framework to Support the Yurok Tribe in Mit-

igating Climate Change Impacts through Natural Resource Management. In *International Astronautical Congress*, Paris, France, September 2022.

[313] Danielle R. Wood. Analysis of Technology Transfer within Satellite Programs in Developing Countries using Systems Architecture. In *AIAA SPACE 2013 Conference and Exposition*, San Diego, CA, 2013. American Institute of Aeronautics and Astronautics.

[314] Danielle Wood. 5.1.1 Applying Systems Architecture to Technology Policy Research: Models of Space Activity in Developing Countries. *INCOSE International Symposium*, 23(1):1368–1384, 2014.

[315] Yaniv Kazansky, Danielle Wood, and Jacob Sutherlun. The current and potential role of satellite remote sensing in the campaign against malaria. *Acta Astronautica*, 121:292–305, April 2016.

[316] Edward Crawley, Olivier De Weck, Christopher Magee, Joel Moses, Warren Seering, Joel Schindall, David Wallace, Daniel Whitney (chair, Edward Crawley, Olivier De Weck, Christopher Magee, Joel Moses, Warren Seering, Joel Schindall, David Wallace, and Daniel Whitney (chair. *The Influence of Architecture in Engineering Systems (Monograph*. 2004.

[317] NASA Office of the Chief Engineer. *NASA Systems Engineering Handbook*. National Aeronautics and Space Administration, Washington DC, first edition, 2004.

[318] Caroline Jaffe. *An Environmental and Economic Systems Analysis of Land Use Decisions in the Massachusetts Cranberry Industry*. PhD thesis, Massachusetts Institute of Technology, Cambridge, MA, 2022.

[319] George A. Hazelrigg. *Fundamentals of Decision Making for Engineering Design and Systems Engineering*. Neils Corp, 2012.

[320] W. Kip Viscusi, Joseph E. Harrington Jr, and David E. M. Sappington. *Economics of Regulation and Antitrust, Fifth Edition*. The MIT Press, Cambridge, Massachusetts; London, England, fifth edition edition, August 2018.

[321] Frank Ackerman and Lisa Heinzerling. Pricing the Priceless: Cost-Benefit Analysis of Environmental Protection. *University of Pennsylvania Law Review*, 150(5):1553–1584, 2001.

[322] Hamid Motieyan and Mohammad Saadi Mesgari. Towards Sustainable Urban Planning Through Transit-Oriented Development (A Case Study: Tehran). *ISPRS International Journal of Geo-Information*, 6(12):402, December 2017.

[323] David R. Morgan, John P. Pelissero, and Robert E. England. Urban Planning: Using a Delphi as a Decision-Making Aid. *Public Administration Review*, 39(4):380–384, 1979.

[324] Seamus Lombardo, Javier Kinney, Steven Israel, and Danielle Wood. Development of Decision Support Systems Utilizing Earth Observation and the Environment-Vulnerability-Decision-Technology modeling framework Towards Natural Resource Management for the Yurok Tribe. In *American Geophysical Union Fall Meeting*, volume 2021, pages GC44A–03, New Orleans, LA, December 2021.

[325] Danielle Renee Wood. *Building Technological Capability within Satellite Programs in Developing Countries*. Doctoral, Massachusetts Institute of Technology, 2012.

[326] Ufuoma Ovienmhada. *Earth Observation Technology Applied to Environmental Management : A Case Study in Benin*. Thesis, Massachusetts Institute of Technology, 2020.

[327] Zoë Slattery. *Quantitative Assessment in Sustainable Digital Urban Planning Using Multi-Criteria Decision Analysis*. PhD thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2019.

[328] Darren M. Scott and Mark W. Horner. The role of urban form in shaping access to opportunities: An exploratory spatial data analysis. *Journal of Transport and Land Use*, 1(2):89–119, 2008.

[329] Adam M. Ross, Matthew E. Fitzgerald, and Donna H. Rhodes. Game-based Learning for Systems Engineering Concepts. In Azad M. Madni and Michael Sievers, editors, *Conference on Systems Engineering Research*, volume 28, pages 430–440, Redondo Beach, CA, 2014. Elsevier.

[330] Matthew E Hanson. *Improving Operational Wargaming : It's All Fun and Games Until Someone Loses a War*. Monograph, United States Army Command and General Staff College, For Leavenworth, Kansas, 2016.

[331] Paul Selva. Revitalizing Wargaming is Necessary to be Prepared for Future Wars. *War On The Rocks2*, December 15.

[332] David A Shlapak and Michael W Johnson. *Reinforcing Deterrence on NATO's Eastern Flank: Wargaming the Defence of the Baltics.* RAND Corporation, Washington D.C., 2016.

[333] Paul T. Grogan and Olivier L. de Weck. Strategic Engineering Gaming for Improved Design and Interoperation of Infrastructure Systems. Working Paper, Massachusetts Institute of Technology. Engineering Systems Division, March 2012.

[334] P. T. Grogan and O. L. de Weck. Federated Simulation and Gaming Framework for a Decentralized Space-Based Resource Economy. In *Thirteenth ASCE Aerospace Division Conference on Engineering, Science, Construction, and Operations in Challenging Environments, and the 5th NASA/ASCE Workshop On Granular Materials in Space Exploration*, pages 1468–1477, Pasadena, California, July 2012. American Society of Civil Engineers.

[335] Jeremy W. Crampton. Maps as social constructions: Power, communication and visualization. *Progress in Human Geography*, 25(2):235–252, June 2001.

[336] M J Shifter. Interactive Multimedia Planning Support: Moving from Stand-Alone Systems to the World Wide Web. *Environment and Planning B: Planning and Design*, 22(6):649–664, December 1995.

[337] Jeremy Crampton. Rethinking maps and identity. In Martin Dodge, Rob Kitchin, and Chris Perkins, editors, *Rethinking Maps: New Frontiers in Cartographic Theory*, pages 26–49. Routledge, June 2011.

[338] Michael Batty, David Chapman, Steve Evans, Mordechai Haklay, Stefan Kueppers, Naru Shiode, Andy Smith, and Paul Torrens. Visualizing the City: Communication urban Design to Planners and Decision-Makers. Technical report, University College London, London, UK, 2000.

[339] Shaohui Sun and Carl Salvaggio. Aerial 3D Building Detection and Modeling From Airborne LiDAR Point Clouds. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 6(3):1440–1449, June 2013.

[340] Jack B. Reid and Danielle Wood. Interactive Model for Assessing Mangrove Health, Ecosystem Services, Policy Consequences, and Satellite Design in Rio de Janeiro Using Earth Observation Data. In *Jack Reid*, 2020, October 2020. International Astronautical Federation.

[341] Blue Raster. Blue Raster Vida Repository. https://github.com/blueraster/mit-vida, August 2021.

[342] Jack Reid. EVDT Repository. https://github.com/mitmedialab/evdt, June 2020.

[343] Jack Reid, Seamus Lombardo, and Danielle Wood. MIT Vida Repository. https://github.com/mitmedialab/Vida_Modeling, August 2021.

[344] Alfred Z. Spector, Peter Norvig, Chris Wiggins, and Jeannette M. Wing. *Data Science in Context: Foundations, Challenges, Opportunities*. Cambridge University Press, Erscheinungsort nicht ermittelbar, new edition edition, October 2022.

[345] Afreen Siddiqi, Eric Magliarditi, and Olivier de Week. Valuing New Earth Observation Missions for System Architecture Trade-Studies. In *IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium*, pages 5297–5300, July 2019.

[346] Taylor Umlauf and Youjin Shin. Rio: A City Transformed. *The Wall Street Journal*, August 2016.

[347] Pilar Olivares, Vanderlei Almeida, Silvia Izquierdo, Nacho Doce, and Yasuyoshi Chiba. Rio's Olympic venues, six months on – in pictures. *The Guardian*, February 2017.

[348] Fernanda Sánchez and Anne Marie Broudehoux. Mega-events and urban regeneration in Rio de Janeiro: Planning in a state of emergency. *International Journal of Urban Sustainable Development*, 5(2):132–153, November 2013.

[349] Adam Talbot and Thomas F. Carter. Human rights abuses at the Rio 2016 Olympics: Activism and the media. *Leisure Studies*, 37(1):77–88, January 2018.

[350] Valerie Viehoff, Gavin Poynter, and Gavin Poynter. The Politics of Mega-event Planning in Rio de Janeiro: Contesting the Olympic City of Exception. pages 129–140, March 2016.

[351] Instituto Pereira Passos| Data Rio. Regiões de Planejamento - Indicadores 2018. http://www.data.rio/datasets/regi%C3%B5es-de-planejamento-indicadores-2018, 2018.

[352] L Goldberg, D Lagomasino, and T Fatoyinbo. EcoMap: A decision-support tool to monitor global mangrove vulnerability and its drivers. *AGU Fall Meeting Abstracts*, December 2018.

[353] Lunalva Moura Schwenk and Carla Bernadete Madureira Cruz. The research environmental and socio-economical conflicts relative to the advance of the soybean growth in areas of influence of the integration and development axis in the state of Mato Grosso. *Acta Scientiarum. Agronomy*, 30(4):501–511, December 2008.

[354] Ricardo Matheus, José Carlos Vaz, and Manuella Maia Ribeiro. Open government data and the data usage for improvement of public services in the Rio de Janeiro City. In *Proceedings of the 8th International Conference on Theory and Practice of Electronic Governance*, ICEGOV '14, pages 338–341, New York, NY, USA, October 2014. Association for Computing Machinery.

[355] Carla Bernadete Madureira Cruz, Raúl Sánchez Vicens Seabra, V da S, Rafael Balbi REIS, Otto Alvarenga FABER, Monika Richter, Pedro Kopke Eis Arnaut, and Marcelo Araújo. Classificação orientada a objetos no mapeamento dos remanescentes da cobertura vegetal do bioma Mata Atlântica, na escala 1: 250.000. In *Anais XIII Simpósio Brasileiro de Sensoriamento Remoto*, pages 5691–5698, Florianópolis, Brazil, April 2007.

[356] Vinicius da Silva Seabra and Carla Madureira Cruz. Mapeamento da dinâmica da cobertura e uso da terra na bacia hidrográfica do Rio São João, RJ. *Sociedade & Natureza*, 25(2):411–426, August 2013.

[357] Prefeitura da Cidade do Rio de Janeiro. PLANO ESTRATÉGICO DA CIDADE DO RIO DE JANEIRO, 2017.

[358] Jr Acioly C. Reviewing urban revitalisation strategies in Rio de Janeiro: From urban project to urban management approaches. *Geoforum*, 2001.

[359] BOAVENTURA de SOUSA SANTOS. Participatory Budgeting in Porto Alegre: Toward a Redistributive Democracy. *Politics & Society*, 26(4):461–510, December 1998.

[360] Prefeitura da Cidade do Rio de Janeiro. Climate Change Adaption Strategy for the City of Rio de Janeiro, 2016.

[361] 100 Resilient Cities. Resilience Strategy of the City of Rio de Janeiro. Technical report, Rio de Janeiro, Brazil, 2017.

[362] United Nations Brazil. ONU convida cariocas a utilizar plataforma para plano de desenvolvimento sustentável. https://nacoesunidas.org/onu-convida-cariocas-a-utilizar-plataforma-para-plano-de-desenvolvimento-sustentavel/, 2019.

[363] Will Connors. Local Golfers Test Rio's Olympic Course. *The Wall Street Journal*, March 2016.

[364] Luc Nadal and Clarisse Linka. Minha Casa Minha Vida (MCMV), Access and Mobility: A Case for Transit-Oriented Low-Income Housing in Rio de Janeiro. Technical report, Lincoln Institute of Land Policy, Cambridge, MA, 2018.

[365] Lucas Faulhaber. *Rio Maravilha, Projetos Políticos e Intervenção No Território No Início Do Século XXI*. PhD thesis, Universidade Federal Fluminense, Rio de Janeiro, Brazil, 2012.

[366] Eva Kassens-Noor, Christopher Gaffney, Joe Messina, and Eric Phillips. Olympic Transport Legacies: Rio de Janeiro's Bus Rapid Transit System. *Journal of Planning Education and Research*, 38(1):13–24, March 2018.

[367] Jonathan Watts. Fury and frustration in Brazil as fares rise and transport projects flounder. *The Guardian*, February 2014.

[368] Cerianne Robertson. The Results Are In: Costly Mega-Event Transport Projects Did Not Expand Mobility, Address Inequalities. https://www.rioonwatch.org/?p=40085, 2017.

[369] Cláudio Gonçalves Couto and Gabriel Luan Absher-Bellon. Imitation or coercion? State constitutions and federative centralization in Brazil. *Revista de Administracao Publica*, 52(2):321–344, March 2018.

[370] Instituto Chico Mendes de Conservação da Biodiversidade. Lista Nacional Oficial de Espécies da Fauna Ameaçadas de Extinção. 2014.

[371] Instituto Estadual do Ambiente. Lista das Espécies da Fauna Ameaçadas de Extinção no Estado do Rio de Janeiro.

[372] Izabella Teixeira. PORTARIA Nº 245 DE 11.07.2011 - DOU 12.07.2011, 2011.

[373] Cecilia Polacow Herzog. *Guaratiba Verde: Subsídios Para o Projeto de Uma Infra-Estrutura Verde Em Área de Expansão Urbana Na Cidade Do Rio de Janeiro*. PhD thesis, Universidade Federal do Rio de Janeiro, 2009.

[374] Anna Jean Kaiser. Rio governor confirms plans for shoot-to-kill policing policy. *The Guardian*, January 2019.

[375] Mariana Simões. Brazil's Bolsonaro on the Environment, in His Own Words - The New York Times. 2019-20-27.

[376] Jennifer Chisholm. Who's invading whom? The complex battle for Rio de Janeiro's informal settlements on federal land. https://blogs.lse.ac.uk/latamcaribbean/2017/11/14/whos-invading-whom-the-complex-battle-for-rio-de-janeiros-informal-settlements-on-federal-land/, 2017.

[377] Tyler Strobl. SOS Araçatiba Community in Guaratiba Faces Imminent Evictions. https://www.rioonwatch.org/?p=43965, 2018.

[378] Tyler Strobl. Four Core Criticisms at the Public Hearing on 'Settlements Occupying Federal Land' | RioOnWatch. https://www.rioonwatch.org/?p=47434, 2018.

[379] R. N. L. Costa. *Pensar o Mar Para Poder Pescar: O Espaço Da Pesca de Litoral Na Baía de Sepetiba, RJ.* PhD thesis, Universidade Federal do Rio de Janeiro, 1992.

[380] Ecologus. ESTUDO DE IMPACTO AMBIENTAL-E I A DO TERMINAL PORTUÁRIO CENTRO ATLÂNTICO. Technical report, CSA Companhia Siderúrgica do Atlântico, Rio de Janeiro, Brazil, 2005.

[381] Alissandra Pinheiro Lopes. *Territorialidades Em Conflitos Na Baía de Sepetiba Estudo de Caso Dos Pescadores Atingidos Pelas Zonas de Exclusão de Pesca Do Porto Da Companhia Siderúrgica Do Atlântico.* PhD thesis, Universidade de São Paulo, 2013.

[382] A. O. C. CASTRO, A. A GOMES, G. V. C. P. BATISTA, and J. T. GONÇALVES. OS DESAFIOS DO PLANEJAMENTO E CONSERVAÇÃO AMBIENTAL DA RESERVA BIOLÓGICA DE GUARATIBA (RJ) de Geoecologia e Planejamento Territorial e do 4º Seminário do. (79):69–76, 2012.

[383] Jenesca Florencio Vicente, Maria Geralda De Carvalho, and Giselle Ramalho Barbosa. Avaliação Hidrogeológica Das Regiões Administrativas De Campo Grande E Guaratiba / Rj. *XVI Congresso Brasileiro de Águas Subterrâneas*, (21):1–18, 2010.

[384] Marcio Luis Fernandes. *Decodificando Geografias Pretéritas e Hodiernas de Ilha de Guaratiba.* PhD thesis, Universidade do Estado do Rio de Janeiro, 2010.

[385] Maria Alice A. Cabrera, Adelzon A. Paula, Luis Antonio B. Camacho, Mauro Célio A. Marzochi, Samanta C. Xavier, Alba Valéria M. Da Silva, and Ana Maria Jansen. Canine visceral Leishmaniasis in Barra de Guaratiba, Rio de Janeiro, Brazil: Assessment of risk factors. *Revista do Instituto de Medicina Tropical de Sao Paulo*, 45(2):79–83, 2003.

[386] Nelio Domingues Pizzolato and Rafael Menezes. LOCALIZAÇÃO DE ESCOLAS PÚBLICAS EM GUARATIBA, RIO DE JANEIRO, USANDO CRITÉRIOS DE ACESSIBILIDADE. *Pesquisa Operacional para o Desenvolvimento*, 5(1):71–83, 2013.

[387] Elaine Cavalcante Peixoto Borin and Frederico Guilherme Ferreira Lima. UMA ABORDAGEM DO ASSOCIATIVISMO : O ESTUDO DE CASO DA RANICULTURA EM GUARATIBA/RJ. *Revista Pomlêm!ca*, 12(4):740–749, 2013.

[388] A. Begossi. Mapping spots: Fishing areas or territories among islanders of the Atlantic Forest (Brazil). *Regional Environmental Change*, 2(1):1–12, August 2001.

[389] Tyler Strobl. Following Recent Eviction Threats, Araçatiba Unites and Pushes Forward. https://www.rioonwatch.org/?p=46329, 2018.

[390] Cecilia P Herzog and Ricardo Finotti. Local assessment of Rio de Janeiro city: Two case studies of urbanization trends and ecological impacts. In *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities*, pages 609–628. Springer, 2013.

[391] Elmo da Silva Amador. *Baía de Guanabara. Ocupação Histórica e Avalição Ambiental.* Interciência, Rio de Janeiro, January 2013.

[392] Daniel A. Friess. Ecosystem Services and Disservices of Mangrove Forests: Insights from Historical Colonial Observations. *Forests*, 7(9):183, September 2016.

[393] Claudia Gutterres Vilela, Brígida Orioli Figueira, Mariana Cardoso Macedo, and José Antonio Baptista Neto. Late Holocene evolution and increasing pollution in Guanabara Bay, Rio de Janeiro, SE Brazil. *Marine Pollution Bulletin*, 79(1):175–187, February 2014.

[394] Lacerda, Luiz and Menezes, Marcelo and Mussi Molisani, Maurício. Changes in mangrove extension at the Pacoti River estuary, CE, NE Brazil due to regional environmental changes between 1958 and 2004. *Biota Neotropica*, 7:1–7, 2007.

[395] F Fromard, C Vega, and C Proisy. Half a century of dynamic coastal change affecting mangrove shorelines of French Guiana. A case study based on remote sensing data analyses and field surveys. *Marine Geology*, 208(2):265–280, August 2004.

[396] Mark Spalding, Mami Kainuma, and Lorna Collins. *World Atlas of Mangroves*. Routledge Taylor & Francis Group, New York, NY, first edition, 2010.

[397] Daniel C. Donato, J. Boone Kauffman, Daniel Murdiyarso, Sofyan Kurnianto, Melanie Stidham, and Markku Kanninen. Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, 4(5):293–297, May 2011.

[398] Jonathan Sanderman, Tomislav Hengl, Greg Fiske, Kylen Solvik, Maria Fernanda Adame, Lisa Benson, Jacob J. Bukoski, Paul Carnell, Miguel Cifuentes-Jara, Daniel Donato, Clare Duncan, Ebrahem M. Eid, Philine zu Ermgassen, Carolyn J. Ewers Lewis, Peter I. Macreadie, Leah Glass, Selena Gress, Sunny L. Jardine, Trevor G. Jones, Eugéne Ndemem Nsombo, Md Mizanur Rahman, Christian J. Sanders, Mark Spalding, and Emily Landis. A global map of mangrove forest soil carbon at 30 m spatial resolution. *Environmental Research Letters*, 13(5):055002, April 2018.

[399] Marc Simard, Lola Fatoyinbo, Charlotte Smetanka, Victor H. Rivera-Monroy, Edward Castañeda-Moya, Nathan Thomas, and Tom Van der Stocken. Mangrove canopy height globally related to precipitation, temperature and cyclone frequency. *Nature Geoscience*, 12(1):40–45, January 2019.

[400] Liza Goldberg, David Lagomasino, Nathan Thomas, and Temilola Fatoyinbo. Global declines in human-driven mangrove loss. *Global Change Biology*, 26(10):5844–5855, July 2020.

[401] C. Giri, E. Ochieng, L. L. Tieszen, Z. Zhu, A. Singh, T. Loveland, J. Masek, and N. Duke. Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography*, 20(1):154–159, 2011.

[402] Pete Bunting, Ake Rosenqvist, Richard M. Lucas, Lisa-Maria Rebelo, Lammert Hilarides, Nathan Thomas, Andy Hardy, Takuya Itoh, Masanobu Shimada, and

C. Max Finlayson. The Global Mangrove Watch—A New 2010 Global Baseline of Mangrove Extent. *Remote Sensing*, 10(10):1669, October 2018.

[403] C. Vancutsem, F. Achard, J.-F. Pekel, G. Vieilledent, S. Carboni, D. Simonetti, J. Gallego, L. E. O. C. Aragão, and R. Nasi. Long-term (1990–2019) monitoring of forest cover changes in the humid tropics. *Science Advances*, March 2021.

[404] Masanobu Shimada, Takuya Itoh, Takeshi Motooka, Manabu Watanabe, Tomohiro Shiraishi, Rajesh Thapa, and Richard Lucas. New global forest/non-forest maps from ALOS PALSAR data (2007–2010). *Remote Sensing of Environment*, 155:13–31, December 2014.

[405] Stanley C. Freden, Enrico P. Mercanti, and Margaret A. Becker. Monitoring vegetation systems in the Great Plans with ERTS. In *Hird Earth Resources Technology Satellite-1 Symposium: The Proceedings of a Symposium Held by Goddard Space Flight Center at Washington, D.C. on December 10-14, 1973*, pages 309–329, Washington D.C., 1974. Scientific and Technical Information Office, National Aeronautics and Space Administration.

[406] Driss Haboudane, John R Miller, Elizabeth Pattey, Pablo J Zarco-Tejada, and Ian B Strachan. Hyperspectral vegetation indices and novel algorithms for predicting green LAI of crop canopies: Modeling and validation in the context of precision agriculture. *Remote Sensing of Environment*, 90(3):337–352, April 2004.

[407] Nathalie Pettorelli, Jon Olav Vik, Atle Mysterud, Jean-Michel Gaillard, Compton J. Tucker, and Nils Chr. Stenseth. Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution*, 20(9):503–510, September 2005.

[408] Tiezhu Shi, Jue Liu, Zhongwen Hu, Huizeng Liu, Junjie Wang, and Guofeng Wu. New spectral metrics for mangrove forest identification. *Remote Sensing Letters*, 7(9):885–894, September 2016.

[409] Hanqiu Xu. Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. *International Journal of Remote Sensing*, 27(14):3025–3033, July 2006.

[410] Carl F. Jordan. Derivation of Leaf-Area Index from Quality of Light on the Forest Floor. *Ecology*, 50(4):663–666, 1969.

[411] Dinh Ngo Thi, Nguyen Thi Thu Ha, Quy Tran Dang, Katsuaki Koike, and Nhuan Mai Trong. Effective Band Ratio of Landsat 8 Images Based on VNIR-SWIR Reflectance Spectra of Topsoils for Soil Moisture Mapping in a Tropical Region. *Remote Sensing*, 11(6):716, January 2019.

[412] Lei Ji, Li Zhang, Bruce K. Wylie, and Jennifer Rover. On the terminology of the spectral vegetation index (NIR - SWIR)/(NIR + SWIR). *International Journal of Remote Sensing*, 32(21):6901–6909, November 2011.

[413] A. Jarvis, H.I. Reuter, A. Nelson, and E. Guevara. Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database. http://srtm.csi.cgiar.org/, 2008.

[414] Romie Jhonnerie, Vincentius P Siregar, Bisman Nababan, Lilik Budi Prasetyo, and Sam Wouthuyzen. Random forest classification for mangrove land cover mapping using Landsat 5 TM and ALOS PALSAR imageries. *Procedia Environmental Sciences*, page 7, 2015.

[415] D. P. Roy, V. Kovalskyy, H. K. Zhang, E. F. Vermote, L. Yan, S. S. Kumar, and A. Egorov. Characterization of Landsat-7 to Landsat-8 reflective wavelength and normalized difference vegetation index continuity. *Remote Sensing of Environment*, 185:57–70, November 2016.

[416] Alijafar Mousivand, Massimo Menenti, Ben Gorte, and Wout Verhoef. Global sensitivity analysis of the spectral radiance of a soil–vegetation system. *Remote Sensing of Environment*, 145:131–144, April 2014.

[417] Planet Labs PBC. Planet Announces New Details of Hyperspectral Offering. https://www.planet.com/pulse/planet-announces-new-details-of-hyperspectral-offering/, September 2022.

[418] Caiyun Zhang, Sara Denka Durgan, and David Lagomasino. Modeling risk of mangroves to tropical cyclones: A case study of Hurricane Irma. *Estuarine, Coastal and Shelf Science*, 224:108–116, August 2019.

[419] Adewole Olagoke, Christophe Proisy, Jean-Baptiste Féret, Elodie Blanchard, François Fromard, Ulf Mehlig, Moirah Machado de Menezes, Valdenira Ferreira dos Santos, and Uta Berger. Individual mangrove tree measurement using UAV-based LiDAR data: Possibilities and challenges. *Remote Sensing of Environment*, 223:34–49, 19/December/2015.

[420] B. F. Clough and K. Scott. Allometric relationships for estimating above-ground biomass in six mangrove species. *Forest Ecology and Management*, 27(2):117–127, May 1989.

[421] Temilola Fatoyinbo, Emanuelle A. Feliciano, David Lagomasino, Seung Kuk Lee, and Carl Trettin. Estimating mangrove aboveground biomass from airborne LiDAR data: A case study from the Zambezi River delta. *Environmental Research Letters*, 13(2):025012, February 2018.

[422] David Lagomasino, Temilola Fatoyinbo, SeungKuk Lee, Emanuelle Feliciano, Carl Trettin, and Marc Simard. A Comparison of Mangrove Canopy Height Using Multiple Independent Measurements from Land, Air, and Space. *Remote Sensing*, 8(4):327, April 2016.

[423] Tim C. Jennerjahn and Venugopalan Ittekkot. Relevance of mangroves for the production and deposition of organic matter along tropical continental margins. *Naturwissenschaften*, 89(1):23–30, January 2002.

[424] Erik Kristensen, Steven Bouillon, Thorsten Dittmar, and Cyril Marchand. Organic carbon dynamics in mangrove ecosystems: A review. *Aquatic Botany*, 89(2):201–219, August 2008.

[425] Trisha B. Atwood, Rod M. Connolly, Hanan Almahasheer, Paul E. Carnell, Carlos M. Duarte, Carolyn J. Ewers Lewis, Xabier Irigoien, Jeffrey J. Kelleway, Paul S. Lavery, Peter I. Macreadie, Oscar Serrano, Christian J. Sanders, Isaac Santos, Andrew D. L. Steven, and Catherine E. Lovelock. Global patterns in mangrove soil carbon stocks and losses. *Nature Climate Change*, 7(7):523–528, July 2017.

[426] Hiraishi Takahiko, Thelma Krug, Kiyoto Tanabe, Nalin Srivastava, Baasansuren Jamsranjav, Maya Fukuda, and Tiffany Troxler. *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands Methodological Guidance on Lands with Wet and Drained Soils, and Constructed Wetlands for Wastewater Treatment*. IPCC, 2014.

[427] LD Lacerda. Carbon burial in mangrove sediments, a potential source of carbon to the sea during events of sea level change. *Paleoclimatic changes and the carbon cycle*, 1:107–114, 1992.

[428] Oxford Poverty and Human Development Initiative. Charting patheways out of multidimensional poverty: Achieving the SDGs. Technical report, United Nationals Development Programme, 2020.

[429] Andrea Pulici, Danilo Carvalho Moura, and Marcelo Sette Mosaner. Relatório Metodológico: Índice de Progresso Social no Rio de Janeiro. Technical report, Instituto Pereira Passos, Rio de Janeiro, Brazil, 2016.

[430] L.F.G. Rego and B. Koch. Automatic classification of land cover with high resolution data of the Rio de Janeiro City Brazil. In *2003 2nd GRSS/ISPRS Joint Workshop on Remote Sensing and Data Fusion over Urban Areas*, pages 172–176, May 2003.

[431] Roy Haines-Young and Marion Potschin. Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure. Technical report, 2018.

[432] Michael Getzner and Muhammad Shariful Islam. Ecosystem Services of Mangrove Forests: Results of a Meta-Analysis of Economic Values. *International Journal of Environmental Research and Public Health*, 17(16):5830, January 2020.

[433] Luke M. Brander, Raymond J. G. M. Florax, and Jan E. Vermaat. The Empirics of Wetland Valuation: A Comprehensive Summary and a Meta-Analysis of the Literature. *Environmental and Resource Economics*, 33(2):223–250, February 2006.

[434] Luke Brander, Alfred Wagtendonk, Salman Hussain, Alistair McVittie, Peter H. Verburg, Rudolf S. de Groot, and Sander van der Ploeg. Ecosystem service values for mangroves in Southeast Asia: A meta-analysis and value transfer application. *Ecosystem Services*, 1(1):62–69, July 2012.

[435] Marwa E. Salem and D. Evan Mercer. The Economic Value of Mangroves: A Meta-Analysis. *Sustainability*, 4(3):359–383, March 2012.

[436] Quoc Tuan Vo, C. Kuenzer, Quang Minh Vo, F. Moder, and N. Oppelt. Review of valuation methods for mangrove ecosystem services. *Ecological Indicators*, 23:431–446, December 2012.

[437] Amber Himes-Cornell, Susan O. Grose, and Linwood Pendleton. Mangrove Ecosystem Service Values and Methodological Approaches to Valuation: Where Do We Stand? *Frontiers in Marine Science*, 5, 2018.

[438] Edward B. Barbier. The protective service of mangrove ecosystems: A review of valuation methods. *Marine Pollution Bulletin*, 109(2):676–681, August 2016.

[439] Edward B. Barbier. Estuarine and Coastal Ecosystems as Defense Against Flood Damages: An Economic Perspective. *Frontiers in Climate*, 2, 2020.

[440] Renan Granado, Luiza C. Pinto Neta, André F. Nunes-Freitas, Carolina M. Voloch, and Catarina F. Lira. Assessing Genetic Diversity after Mangrove Restoration in Brazil: Why Is It So Important? *Diversity*, 10(2):27, June 2018.

[441] Rio Prefeitura. Environmental Recovery of Rodrigo de Freitas Lagoon. http://www.rio.rj.gov.br/web/recuperacao-lagoa/principal-en, 2019.

[442] Mário Soares. Estrutura vegetal e grau de perturbação dos manguezais da Lagoa da Tijuca, Rio de Janeiro, RJ, Brasil. *Revista Brasileira de Biologia*, 59, August 1999.

[443] V. F. Cavalcanti, M. L. G. Soares, G. C. D. Estrada, and F. O. Chaves. Evaluating Mangrove Conservation through the Analysis of Forest Structure Data. *Journal of Coastal Research*, pages 390–394, 2009.

[444] Laís Coutinho Zayas Jimenez, Hermano Melo Queiroz, Gabriel Nuto Nóbrega, Danilo Jefferson Romero, Youjun Deng, Xosé Luis Otero, and Tiago Osório Ferreira. Recovery of Soil Processes in Replanted Mangroves: Implications for Soil Functions. *Forests*, 13(3):422, March 2022.

[445] Suhyun Jung, Laura Vang Rasmussen, Cristy Watkins, Peter Newton, and Arun Agrawal. Brazil's National Environmental Registry of Rural Properties: Implications for Livelihoods. *Ecological Economics*, 136:53–61, June 2017.

[446] Suhyun Jung and Stephen Polasky. Partnerships to prevent deforestation in the Amazon. *Journal of Environmental Economics and Management*, 92:498–516, November 2018.

[447] Olivier de Weck, Daniel Krob, Li Lefei, Pao Chuen Lui, Antoine Rauzy, and Xinguo Zhang. Handling the COVID-19 crisis: Toward an agile model-based systems approach. *Systems Engineering*, page sys.21557, August 2020.

[448] Seamus Lombardo, Jack Reid, Katlyn Turner, Mulan Jiang, David Lagomasino, Mohammad Jalali, Eric Ashcroft, and Danielle Wood. Designing Decision Support Systems with Interdisciplinary, International Teams: A Case Study of the Environment, Vulnerability, Decision, Technology Model. In *American Geophysical Union Fall Meeting*, Virtual, 2020.

[449] Christopher D. Elvidge, Tilottama Ghosh, Feng-Chi Hsu, Mikhail Zhizhin, and Morgan Bazilian. The Dimming of Lights in China during the COVID-19 Pandemic. *Remote Sensing*, 12(17):2851, January 2020.

[450] R. J. Isaifan. The dramatic impact of Coronavirus outbreak on air quality: Has it saved as much as it has killed so far? *Global Journal of Environmental Science and Management*, 6(3):275–288, July 2020.

[451] Shefali Arora, Kanchan Deoli Bhaukhandi, and Pankaj Kumar Mishra. Coronavirus lockdown helped the environment to bounce back. *Science of The Total Environment*, 742:140573, November 2020.

[452] Miguel O. Román, Zhuosen Wang, Qingsong Sun, Virginia Kalb, Steven D. Miller, Andrew Molthan, Lori Schultz, Jordan Bell, Eleanor C. Stokes, Bhartendu Pandey, Karen C. Seto, Dorothy Hall, Tomohiro Oda, Robert E. Wolfe, Gary Lin, Navid Golpayegani, Sadashiva Devadiga, Carol Davidson, Sudipta Sarkar, Cid Praderas, Jeffrey Schmaltz, Ryan Boller, Joshua Stevens, Olga M. Ramos González, Elizabeth Padilla, José Alonso, Yasmín Detrés, Roy Armstrong, Ismael Miranda, Yasmín Conte, Nitza Marrero, Kytt MacManus, Thomas Esch, and Edward J. Masuoka. NASA's Black Marble nighttime lights product suite. *Remote Sensing of Environment*, 210:113–143, June 2018.

[453] Instituto Pereira Passos. Data Rio. https://www.data.rio/, 2017.

[454] Ministerio de Ciencia, Tecnología, Conocimiento, e Innovación. Datos-COVID19, September 2021.

[455] Jack B. Homer and Gary B. Hirsch. System Dynamics Modeling for Public Health: Background and Opportunities. *American Journal of Public Health*, 96(3):452–458, March 2006.

[456] Arielle R Deutsch, Rebecca Lustfield, and Mohammad S Jalali. Community-based System Dynamics Modeling of Sensitive Public Health Issues: Maximizing Diverse Representation of Individuals with Personal Experiences. *Preprint, Submitted for peer review*, page 22, 2020.

[457] Ran Xu, Hazhir Rahmandad, Marichi Gupta, Catherine DiGennaro, Heresh Amini, and Mohammad S Jalali. The Modest Impact of Weather and Air Pollution on COVID-19 Transmission. Technical report, Cambridge, MA, 2020.

[458] Google. COVID-19 Community Mobility Report. https://www.google.com/covid19/mobility?hl=en.

[459] IplanRio. Indicadores do Plano de Retomada. http://inteligencia.rio/plano-de-retomada/, September 2020.

[460] CoronaNet Research Project. https://www.coronanet-project.org/.

[461] xbsd. Scipy 2021: Predicting the economic impact of COVID-19 using real-time images from space, August 2021.

[462] Aslam Ahmed, Julie Greensmith, and Uwe Aickelin. Variance in System Dynamics and Agent Based Modelling Using the SIR Model of Infectious Disease. SSRN Scholarly Paper ID 2829229, Social Science Research Network, Rochester, NY, January 2012.

[463] Blue Raster. MIT-Vida Support - Boston, MA. https://blueraster.maps.arcgis.com/apps/dashboards/2475062b48dc410195ee9955c178b2b0, 2021.

[464] Moya Bailey. More on the origin of Misogynoir.

[465] J Sobieszczanski-Sobieski and R T Haftka. Multidisciplinary aerospace design optimization: Survey of recent developments. *Structural Optimization*, 14(1):1–23, 1997.

[466] Melissa Garber, Shahram Sarkani, and Thomas A. Mazzuchi. Multi-Stakeholder Trade Space Exploration Using Group Decision Making Methodologies. *INCOSE International Symposium*, 25(1):1118–1132, 2015.

[467] Adam M. Ross and Daniel E. Hastings. The Tradespace Exploration Paradigm. *INCOSE International Symposium*, 15(1):1706–1718, 2005.