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

by

Jack Reid

Submitted to the Program in Media Arts and Sciences
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Media Arts and Sciences

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

December 2022

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Abstract

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, significant improvements in their capabilities, and much greater availability of the data that they produce. This trend has occurred as part of a greater trend of increasing data availability, computational power, and modeling ability. Unfortunately, up until now, this earth observation (EO) data has been largely used only by governments and academics for scientific purposes, typically to understand and predict environmental phenomena. Large corporations and non-governmental organizations (NGOs) have recently been conducting their own analyses, but these have required significant expertise and resources, and the results have sadly been mostly unavailable to the broader public.

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

This work aims to demonstrate the viability of a particular methodology for achieving (a) and (b), while laying the groundwork for a more detailed consideration of (c). To that end, this work centers on exploring the efficacy and difficulties of ***collaboratively developing*** a ***systems-architecture-informed***, multidisciplinary ***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 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, Vulerability, 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. As the name suggests, EVDT integrates four models into one tool: the Environment (data including Landsat, Sentinel, VIIRs, Planet Lab's PlanetScope, etc.; Human Vulnerability and Societal Impact (data including census and survey-based demographic data, NASA's Socioeconomic Data and Applications Center, etc.); Human Behavior and Decision-Making (data including policy histories, mobility data, and urban nightlight data); and Technology Design for earth observation systems including satellites, airborne platforms and in-situ sensors (data including design parameter vectors for such systems). The data from each of these domains is used by established models in each domain, which are adapted to work in concert to address the needs identified during the stakeholder analysis. This framework is currently being used by several researchers in the Space Enabled Research Group and elsewhere. The capabilities provided by this framework will improve the management of earth observation and socioeconomic data in a format usable by non-experts, while harnessing cloud computing, machine learning, economic analysis, complex systems modeling, and model-based systems engineering.

Thesis Supervisor: Danielle R. Wood
Title: Assistant Professor of Media Arts and Sciences

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

Acknowledgments

Before proceeding onto this work, I would like to thank several individuals and communities. First and foremost is my wife, Rebecca, who has been unfailingly supportive of me throughout the endeavor that has been multiple MIT graduate programs. First in a long-distance relationship and then in person, she has consistently buoyed my hopes and sense of self-worth when I needed it most.

Next I would like to thank the continuing expertiment in cooperative living that is pika. It is there that I truly learned what a home is. Thanks for (almost) always having dinner ready at the end of the day and for filling the house with laughter. Similarly, I must thank the forbidden zone (tfz). This rotating cast of genuine characters kept me sane and happy throughout the pandemic even as we moved through three different houses. I do not know what else to say except that I genuinelly miss those of who you have left already and will geninuelly miss the rest of y'all whenever we spend more than a week apart.

I would of course be highly remiss without thanking my advisor, Prof. Danielle Wood. Thank you for building such a wonderful research community and allowing me to take part in it. You have provided a space for morally important work to be done, for those who are interested in space for more than military or scientific purposes to find a research home, and for neglected perspectives to find voice. I wish you the best of fortune in your career to come.

Similarly, I need to thank my other committee members, Prof. Sarah Williams and Prof. David Lagomasino, for mentoring me in the various fields that I needed to complete this work (and become a better person). Be it teaching me how to use Google Earth Engine one summer in Goddard or piling me why with critical GIS books, I appreciate the time and attention given to my education.

I also need to thank Dr. Donna Rhodes, my masters thesis advisor. She taught me a great deal about how to think critically about my research work and how to present it to an audience. Her level of engagement and enthusiasm for my work has been much appreciated. These lessons and encouragment have stuck with me as I have pursued other fields of study.

In a very direct and literal sense, this thesis could not have been completed without many, many hours of involvement and support from my various international collaborators. this includes (among others): Prof Joga Setiawan (Diponegoro University) and Dr. Hanifa Denny (Diponegoro University) lead coordination for the Indonesia Vida work; Prof Joaquin Salas (Centro de Investigación en Ciencia Aplicada y Tecnología Avanzada, Universidad Querétaro) and Mr. Alejandro Monsivais (Mexican Space Agency) led coordination for the Mexico Vida work; Jose Guiridi (Ministerio de Ciencia, Tecnología, Conocimiento e Innovación) led coordination for the Chile Vida effort; and Zolana Joao, Gilson Santos, Eduina Teodoro, and Joana Caetano (Management Office of the National Space Program) led coordination for the Angola Vida work. In particular, however, I must extend my gratitude and affection towards Mr. Felipe Mandarino of the Pereira Passos Municipal Institute of Urbanism (IPP) in Rio de Janeiro, Brazil. Felipe has remained actively engaged with my work for several years now, amid multiple changes in reesarch direction, a pandemic, changes

in governments (both here in the US and there in Brazil). He gave me a place to work in Rio de Janeiro, showed me around, and introduced me to the various folks that I need to speak to for this research work. I doubt that I will ever be able to repay him sufficiently for this.

Finally, I wish to state the following:

> MIT and this author acknowledge Indigenous Peoples as the traditional stewards of the land, and the enduring relationship that exists between them and their traditional territories. The land on which this work was performed and these words were written is the traditional unceded territory of the Wampanoag Nation, Massachusett, and Nipmuc peoples. We acknowledge the painful history of genocide and forced occupation of their territory, and we honor and respect the many diverse indigenous people connected to this land on which we gather from time immemorial.

The above statement is adapted from the Massachusetts Institute of Technology (MIT) Indigenous Peoples Advocacy Committee (IPAC) statement in partnership with MIT's American Indian Science and Engineering Society (AISES), the Native American Students Association (NASA)[1], and other Native American MIT students. This statement is particularly important for my work and for Space Enabled, because, while we pursue various forms of equity, justice, and sustainable development, including with other indigenous groups, such work does not allow us to absolve ourselves of our sins and responsiblities, both past and ongoing. As of this writing, we have not worked directly with the Wampanoag or Nipmuc peoples (nor do I know if they wish to work with us). Until genuine actions and not mere words are taken to address these atrocities, more work is required.

[1] To avoid confusion with the National Aeronautics and Space Administration (NASA), the Native American Students Association will always be written out fully in this work.

Contents

List of Figures

List of Tables

List of Acronyms

AIAA	American Institute of Aeronautics and Astronautics
AISES	American Indian Science and Engineering Society
CAS	complex adaptive system
CBERS	China-Brazil Earth Resources Satellite Program
CEOS	Committee on Earth Observation Satellites
CPR	common-pool resources
DEM	Digital Elevation Model
DSM	Digital Surface Model
DSS	Decision Support System
DTM	Digital Terrain Model
EO	earth observation
EOC	Earth Observation Center
EOS	earth observation system
EPA	Environmental Protection Agency
ESA	European Space Agency
EVDT	Environment, Vulerability, Decision-Making, Technology
FEMA	Federal Emergency Management Agency
GEO	Group of Earth Observations
FEWS NET	Famine Early Warning Systems Network
GIS	geographic information system
GISc	geographic information science
GPM	Global Precipitation Measurement
GRACE	Gravity Recovery and Climate Experiment
ICESat-2	Ice, Cloud, and land Elevation Satellite 2
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ILUTE	Integrated Land Use, Transportation, Environment
INCOSE	International Council on Systems Engineering
IPAC	Indigenous Peoples Advocacy Committee
IPP	the Pereira Passos Municipal Institute of Urbanism
ISO	international standards organization
JAXA	Japan Aerospace Exploration Agency
LEED	Leadership in Energy and Environmental Design
LIDAR	light detection and ranging
LUNR	Land Use and Natural Resources Inventory

MIT	Massachusetts Institute of Technology
MDG	Millenium Development Goal
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NGO	non-governmental organization
OSTP	Office of Science and Technology Policy
OTA	Office of Technology Assessment
PGIS	participatory geographic information system
PPGIS	public participation geographic information system
PPBS	Planning-Programming-Budgeting System
PSS	Planning Support System
SDG	Sustainable Development Goal
SEBoK	Systems Engineering Body of Knowledge
SERVIR	Sistema Regional De Visualización Y Monitoreo De Mesoamérica
SETS	socio-environmental- technical system
SWOT	Surface Water Ocean Topography
UN	United Nations
USAID	United States Agency for International Development
USGS	United States Geological Survey
VIIRS	Visible Infrared Imaging Radiometer Suite

Chapter 1

Introduction

Over the past two decades satellite-based remote observation has blossomed. We have seen a rapid increase in the number of EOSs in orbit [1], significant improvements in their capabilities [2], and much greater availability of the data that they produce [3]. This trend has occurred as part of greater technological and societal trends of increasing data availability, computational power, and modeling ability. Unfortunately, despite some efforts in previous decades [4], this 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 NGOs have recently been conducting their own analyses (as seen in the growing industry of climate consultants [5]), but these have required significant expertise and resources, and the results have sadly been mostly unavailable to the broader public.

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

A quick note on the user of first person pronouns in this piece. The word 'I' will obviously refer to the author, Jack Reid, and will be commonly used when describing work that I have done, arguments that I am asserting, etc. That said, the EVDT Framework and its various implementations, including the Vida DSS, were not solo projects but instead involved multiple contributors, both inside the Space Enabled Research Group and outside of it. Thus when I use 'we' when talking about EVDT I will be referring to this collection of individuals. Additionally, sometimes I will use 'we' to refer to the Space Enabled Research Group, particularly when discussing our group's set of methodologies and principles. Finally, on occassion, I may use 'we' in the general humanistic sense. I will strive to make in which sense I am using 'we' clear in context.

1.1 Research Questions

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

1. Is systems architecture (and systems engineering in general) a relevant and useful approach to sustainability in such complex socio-environmental- technical system (SETS)? In particular, can collaboarative planning theory and other critical approaches enable such an approach to avoid the technocratic excesses of the past?
   - *a*) A critical analysis of systems engineering, GIS, and the other technical fields relied upon in this work
   - *b*) A proposed framework for applying systems engineering for sustainable development in an anticolonialist manner
   - *c*) System architecture analyses of each of the case studies
2. Is collaborative development of DSSs using the EVDT Modeling Framework in particular relevant and useful sustainability in such complex SETS?
   - *a*) Development of an EVDT-based DSS for each of the case studies
   - *b*) An interview-based assessment of the development process and usefulness of each DSS
3. What are further challenges and opportunities for future applications of EVDT?
   - *a*) An assessment of lessons learned from these DSS development processes
   - *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.

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.

To this end, this paper expands and codifies a previously proposed EVDT Modeling Framework for combining EO and other types of data to inform decision-making in complex socio-environmental systems, particularly those pertaining to sustainable development [6]. Such a framework could also inform the development of future EO systems that are better designed for particular application contexts. In the beginning of the following section, this framework will be explained.

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 outself 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 becaues we have chose a certain approach, it is the only or the best possible approach.

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

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

> Consider, for example the orthodox planning reaction to a district called the North End in Boston. This is an old, low-rent area merging into the heavy indsutry of the waterfront, and it is officially considered Boston's wost slum and civic shame... When I saw the North End again in 1959, I was amazed at the change. Dozens and dozens of buildings had been rehabilitated... The general street atmosphere of buoyancy, friendliness, and good health was so infectious that I began asking directions of people just for the fun of getting in on some talk. I had seen a lot of Boston in

> the past couple of days, most of it sorely distressing, and this struck me, with relief, as the healthiest place in the city... I called a Boston planner I know.
>
> "Why in the world are you down in the North End?" he said, "That's a slum!... It has among the lowest delinquency, disease, and infant mortality rates in the city. It has has the lowest ratio of rent to income in the city... the child population is just above average for the city, on the nose. The death rate is low, 8.8 per thousand, against the average city rate of 11.2. The TB death rate is very low, less than 1 per ten thousand, [I] can't understand it, it's lower even than Brookline's. In the old days the North End used to be the city's worst spot for tuberculosis, but all that has changed. Well, they must be strong people. Of course it's a terrible slum."
>
> "You should have more slums like this," I said.

1.3 Space Enabled Principles

The mission of the Space Enabled research group is *to advance justice in Earth's complex systems using designs enabled by space.* By "designs enabled by space," we mean primarily six types of space technology that support societal needs: satellite earth observation, satellite communication, satellite positioning, microgravity research, technology transfer, and the inspiration we derive from space research and education. By "advance justice in Earth's complex systems," we mean a combination of social justice (e.g. antiracism and anticolonialism) and sustainable development[1]. Fulfilling this mission is not just an issue of research topics but also of methodology, the master's tools will never dismantle the master's house [11]. Our methods are thus of necessity multidisciplinary, drawing from at least six disciplines: design thinking, art, social science, complex systems, satellite engineering and data science. Our work, unlike the long, problematic history of systems engineering and development (see Section 2.4), 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 improvment.

[1] Space Enabled usually refers to the United Nations (UN) Sustainable Development Goals (SDGs) to explain sustainable development, but a more detailed discussion of that term is provided in Section 2.1.2.

1.4 Methodology Summary

The first two research deliverables, 1a and 1b, are based on literature reviews and the development of written arguments. The former (the critical analysis) is presented in Section 2.4. Deliverable 1b, the development of a framework is laid out primarily in Section 2.2 and indirectly through most of the thesis. The centerpiece of this work, however, are in response to Research Questions 2: the development and evaluation of EVDT DSSs for two primary applications: (1) mangrove forest management and conservation in the state of Rio de Janeiro, Brazil; and (2) coronavirus response in six metropolitan areas across Angola, Brazil, Chile, Indonesia, Mexico, and the United States. In both cases, the methodology involves the application the system architecture framework [12, 13] an approach that has been previously adapted from the aerospace engineering discipline by Prof. Wood for use in sociotechnical systems [14]. This includes using stakeholder mapping and network analysis to inform the design of the DSS in question as well as fulfilling Deliverable 1c. Other components of the methodology taken in this work are developing the DSS through an iterative and collaborative process with specific stakeholders; pursuing targeted, related analyses, such as on the value of certain ecosystem services, the value of remote sensing information, and human responses to various policies; and evaluating the usefulness of both the DSS and the development process through interviews, workshops, and other feedback mechanisms. Finally, to address Research Question 3, lessons learned will be identified and a future development path for EVDT will be laid out. Chapter 3 goes into more detail on each step of this methodology.

1.5 Structure of Thesis

Chapter 2 lays out the EVDT framework used through this work along with its theoretical underpinnings, motivation for its pursuit, and various critiques. Chapter 3 provides more detail on the methodology used in this work. Chapter 4 contains the results from the Rio de Janeiro mangrove application. Chapter 5 contains the results from the coronavirus response application. Chapter 6 contains discussion on both applications and lessons learned. Chapter 7 provides a short conclusion summarizing this thesis.

Chapter 2

Motivation, Theory, and Frameworks

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

2.1 Motivation

The question of motivation includes several elements. Why sustainable development? Why remote observation data? Why systems architecture and engineering? Why these particular case studies? Why me? This section will address these questions as well as lay the groundwork for the discussion of several critiques of the chosen approach that takes place in Section 2.4.

2.1.1 Personal Motiviation

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

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

studying management, engineering and control. RAND and MIT stood at the forefront of this trend. With their heritage of mathematical innovation and ties to the armed forces... these and cognate institutions offered ideal laboratories to transform cybernetic principles into management practices." [4]

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

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

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

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

2.1.2 Why Sustainable Development?

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

What is Sustainable Development?

The term *sustainable development* is simultaneously one that invites immediate, intuitive understanding, and one that reminds 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 refers to something more specific, commonly associated with the natural environment: "pertaining to a system that maintains its own viability by using techniques that allow for continual reuse" [16]. As to what "system" we are talking about here, the "development" half of sustainable development, we mean generally, human society and wellbeing. This is of course still much too vague, so let us turn to the first official use of the term, which was in the 1987 report by the UN World Commission on Environment and Development, commonly known as the Brundtland Report, after the name of the chair of the commission. This report defined sustainable development as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [17]. We have now helpfully clarified the time scale under which this system needs to "maintain its own viability" but still have done little to clarify what aspects of human society are included within "development."

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

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

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

We now have three linked components along with a set of potential actions for implementation. This is the definition that would stick and become commonplace. From here has built intellectual fields and massive multi-governmental interventions.

Jeffery Sachs describes this further, "As an intellectual pursuit, sustainable development tries to make sense of the interactions of three complex systems: the world economy, the global society, and the Earth's physical environment... Sustainable development is also a normative outlook of the world, meaning that it recommends a set of goals to which the world should aspire... SDGs call for socially inclusive and environmentally sustainable growth." [20]

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

Why is Sustainable Development Important?

As former UN Secretary-General Ban Ki-moon put it:"Sustainable development is the central challenge of our times" [20]. Despite significant progress in certain domains and certain regions, many individuals and communities are still suffering from severe privations of food, water, healthcare, and more. This is no mere issue of production, but is also connected with issues of allocation (economic inequality is swiftly rising in many parts of the world, including in the author's own country), political mismanagement and oppression, and environmental changes. This work will not detail these numerous concerns (instead I recommend Jeffrey Sach's *The Age of Sustainable Development* for an accessible survey), but it is worth point out that the last of these issues, that of environmental changes, is particularly important as it shapes how we can seek to rectify the others. Historical means of economic development (particularly 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, as seen in Figure 2-1, particularly those of climate change, biodiversity loss, ocean acidification, and the nitrogen cycle.

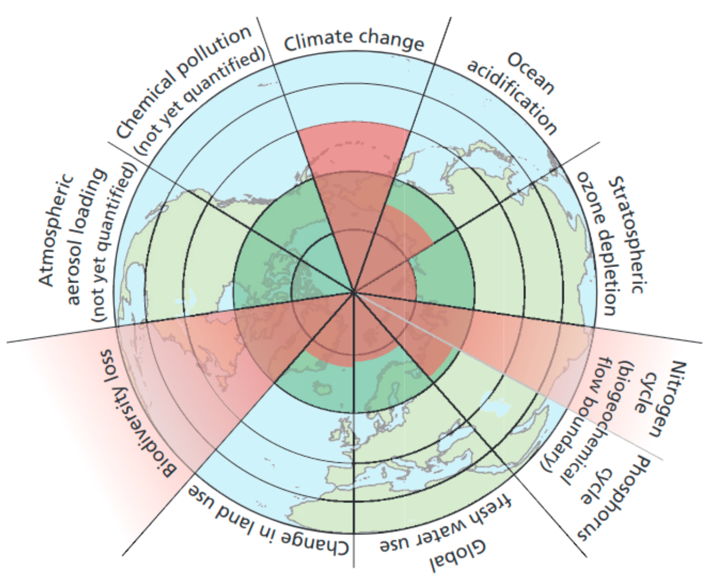

Figure 2-1: Planetary Boundaries. From [21]

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

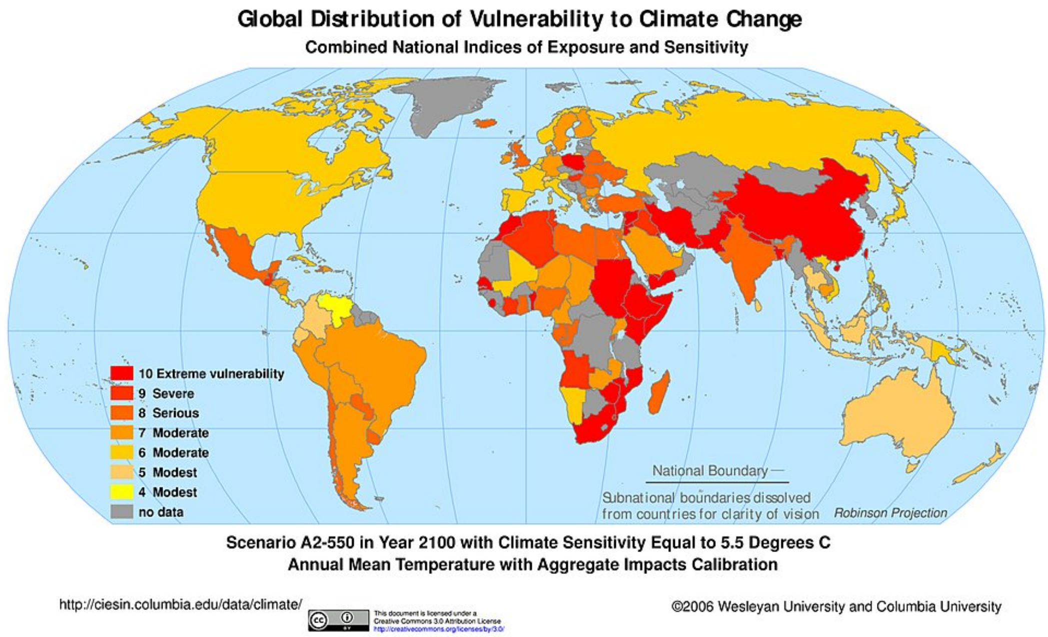

Figure 2-2: Assessment of global distribution of vulnerability to climate change. From [22]

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 iff major, international corrective efforts are not undertaken immediately. The numerous connections between these domains is a key motivation for this work and for the methods chosen, as will be seen later.

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

[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.

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

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

have been useful to the population but whose value could not be converted into fiscal receipts" [24]. Just as these factors were missing from accountings of the natural environment, so were they missing form accounts of human society. "Non-human animals are rarely considered within the realms of social theory, and yet... animals can be regarded as a ‘marginal social group’ that is ‘subjected to all manner of socio-spatial inclusions and exclusions.’" ([25, 26, 27]as paraphrased in [28]). While these authors were referring primarily to animals, it is also I would argue that this includes plants too, as is particularly evident in the common definition of a weed as a plant growing where it is not wanted.

Fortunately, economists and earth scientists in recent decades have embarked on an effort to better understand and catalog such *ecosystem services*, that is to say, the various benefits that humans are provided by the natural environment and healthy ecosystems in particular. Figure 2-3 illustrates these connections between the environment and human wellbeing, along with the degree to which these connections are mediated by socioeconomic factors. 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 (though it should be noted that the database overrepresents valuations involving the United Kingdom, inland wetlands, and coastal systems) [29]. 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.

What about the Sustainable Development Goals?

At the end of Section 2.1.2, 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 acpsdg are a key part of how sustainable development is currently thought about around the world, to the extent that Sachs wrote that, "Our new era will son be described by new global goals, the SDGs" [20]. In order to understand the SDGs, however, we must first go back fifteen years prior to their creation, when the nations of the world sought to proactively face the new millenium. In 2000, the UN established eight Millenium

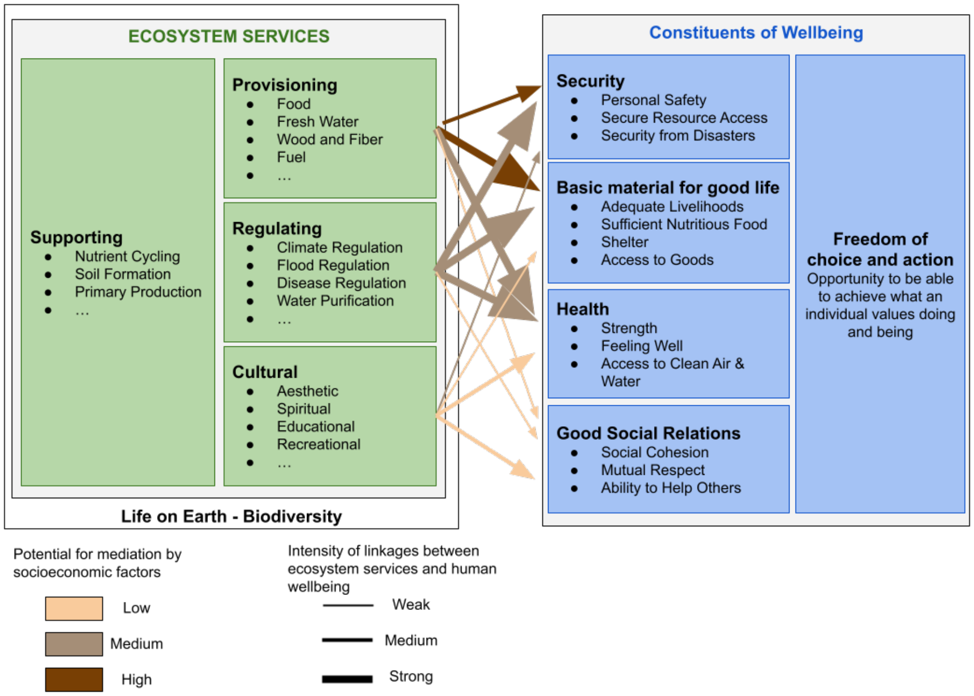

Figure 2-3: Linkages between categories of ecosystem services and compotents of human wellbeing. Adapted from [30]

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 [31]. 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 [32]. Some of the original MDGs were split into multiple, more specific goals (e.g. #1 became #2 and #3) while other SDGs are wholly novel. The abbreviated forms of these new goals can be seen in Figure 2-4.

Figure 2-4: 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 [33], 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 [34]. In short, they require either the creation or the improvement of complex sociotechnical systems. 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" [34]. 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 sociotechnical systems created to reach the target.

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

2.1.3 Why Remote Observation Data

While many of the initial efforts at remote observation from air and space were done with military objectives in mind, scientific, commercial, and social applications soon became abundant. Since much of space-based remote observation in the past several decades has been primarily driven by large governmental scientific organizations, much of that data has been made publicly accessible. An enormous amount of EO satellite data is freely available to the public through 20+ NASA earth science satellites [35], 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 [36, 37]. Even when the data was available to the public, it was not always freely available, as various countries have made attempts to monitize 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 transfered to a private entity and prices were increased by more than an order of magnitude and significant copyright restrictions were put in place [38]. Currently the data is once again made free after the monitization efforts met with limited success [39], but this may not remain the case moving forward [40].

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

Furthermore, despite espousing these five rationales, NASA "did not go a long way toward incorporating remote sensing into day-to-day practices in city planning agencies. This was compounded by the fact that far more academics than local government officials participated in these experiments, providng 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 [41], Digital Global’s WorldView satellites, and Astro Digital’s recent launch of their first two satellites [42], 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. 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 [43]], agricultural monitoring [via Global Precipitation Measurement (GPM) for rainfall [44] and GRACE for soil moisture [45]], climate change vulnerability assessments [via Ice, Cloud, and land Elevation Satellite 2 (ICESat-2) for vegetation and ice monitoring [46]], and many other applications, such as the upcoming Surface Water Ocean Topography (SWOT) [47].

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 Group of Earth Observations (GEO) and 60 agencies with active earth observation satellites have formed the Committee on Earth Observation Satellites (CEOS). In the US, the primary source of such applications is the NASA Applied Science 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). The Applied Science 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 [48]. In keeping with this new mentality, the Applied Science 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 and Asia. In a similar collaborative effort, NASA and USAID have also integrated remote sensing data into the Famine Early Warning Systems Network (FEWS NET).

Such efforts have been quite successful in their goals, but have required significant 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 [49] and maps of damaged areas of Puerto Rico to the Federal Emergency Management Agency (FEMA) following Hurricane Maria [50] (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 [51].

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" ([52] as paraphrased by [53]). Remote observation has the potential to help upend this, by providing at least some base level of data globally, with no distinctions for 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 [43], aquatic bacterial growths [54], or deforestation [55], with only limited excursions into assessing the connections between such phenomena and human wellbeing.

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

2.1.4 Why GIS and Decision Support?

The term GIS refers to any digital system for storing, visualizing, and analyzing geospatial data, that is data that has some geographic component. It can be used to discuss specific systems, a method that uses such systems, a field of studying focusing on or involving such systems, or even the set of insitutions and social practices that make use of such a system [56]. 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 [57, 58, 59, 60]. One perspective, however, is to view GIS to the underlying computer systems enabling the middle three components of the broader geographic information science (GISc) methodology, as shown in Figure 2-1. In that sense, the work related in this thesis can be seen as an exercise in GISc spanning all five components, while the specific software produced for this work are instances of GIS. It should be noted that this distinction is not commonly made outside of academia, with GIS commonly being used generically to encompass both GISc and GIS. Along these lines, there being some debate about whether GIS is best viewed as a scientific field in its own right, or as a mere tool for use in various other fields of science (such as environmental science, economics, etc.) [61, 62]. One important aspect of the acgisc perspective that is not included in Figure 2-1, is that includes "institutional, managerial, and ethical issues [61], something that is naturally core to this work.

The term GIS and the associated field of study originated in the 1960s and 70s with experimental efforts of the Canda Geographic Information System and the US Bureau of the Census to digitize their demographic and land cover data [63]. It should be noted that these early instances were primarily application, rather than technology driven [61]. 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" ([64] as paraphrased in [65]).

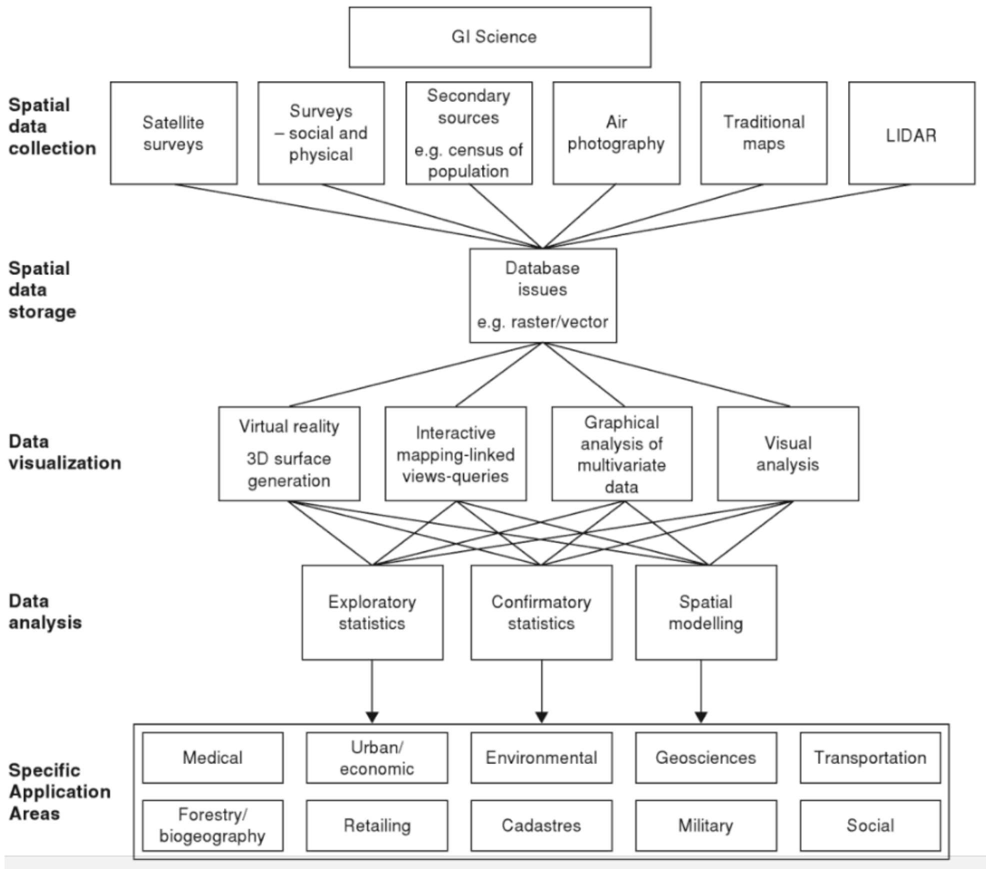

Figure 2-5: Overview of Geographical Information Science. From [66]

Even with the relatively limited computing capabilities of the era, interest in GIS grew quickly with local governments quickly adopting it for planning purposes, as was mentioned in Section 2.1.3. One key moment in the development of GIS as we know it, was ESRI's creation of the shapefile format (which links geometries with data in a standardized, if somewhat limited, fashion) in the late 1980s, and, more importantly, their open publishing of the format, allowing others to create and manipulate such files [67]. In 1990, Tomlin defined the sub-discipline of GIS known as cartographic modeling, which attemps to generalize and standardize the analytic and synthetic capabilities of geopgrahical information systems. It does so by decomposing data, data-processing tasks, and data-processing control notation into elementary components that can be recomposed with relative ease and great flexibility" [68]. This theory would come to underly much of research and development work done with GIS. including that of this thesis.

By 1991, Maguire et al. felt that "it is not fanciful to suggest that by the end of the century GIS will be used every day by everyone in the developed world for routine operations" [69]. 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 [70]. Since the turn of the millenium, spatial data has become deeply ingrained economics, urban studies, private industry, social networks, environmental science, public health, criminal justice, and more [71].

There is now a well established marketplace for geographic data (as shown in 2-6) and thus for GISs to handle that data. It should be noted that the institution that I am associated with, a university, is classified here as a "value-added intermediary" which serves an important connective role between suppliers, infrastructure, and users. This positioning is crucial to the nature of this work, as will be discussed further in Chapter 3. For now it is enough to understand that, whether one is interested in remote observation data or local economics, the question is not whether one should use GIS, but how. To this end, the next two sections will go into more detail about two different veins of GIS: collaborative systems and decision support systems.

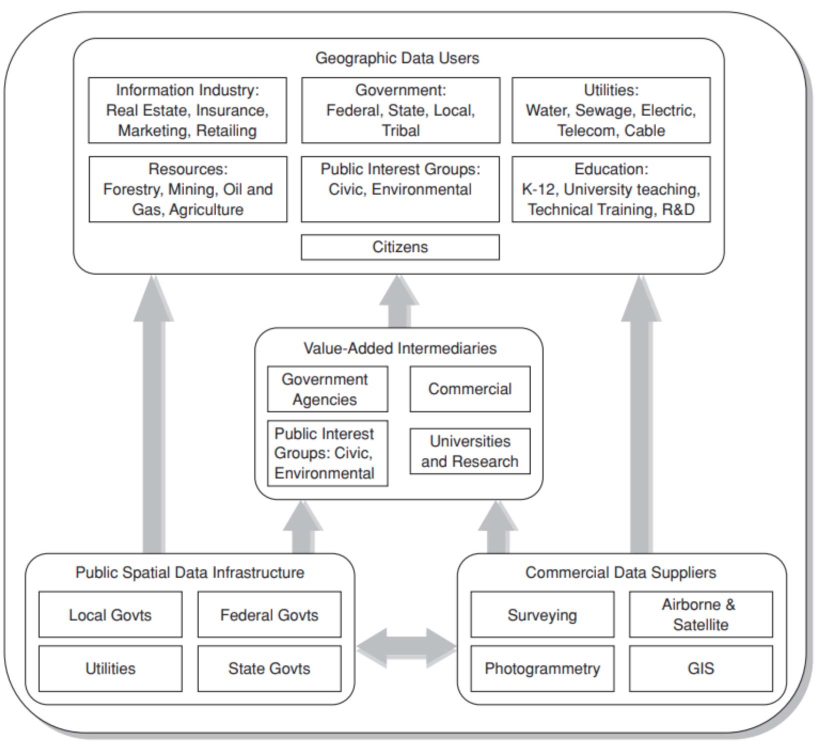

Figure 2-6: The marketplace for geographic data. From [72]

Why Collaborative and Open Source?

As was mentioned in Section 2.1.3, many of the early applications of remote observation data was technology, rather than need, driven. So it was with the closely related field of GIS as well, leading to powerful critiques by Pickles and others [73]. 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" [63]. 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 [74]. The dynamics at play in such collaborations can be seen in Figure 2-7. This is certainly a more complicated situation than the traditional, straightforward, academic implementation of a GIS project.

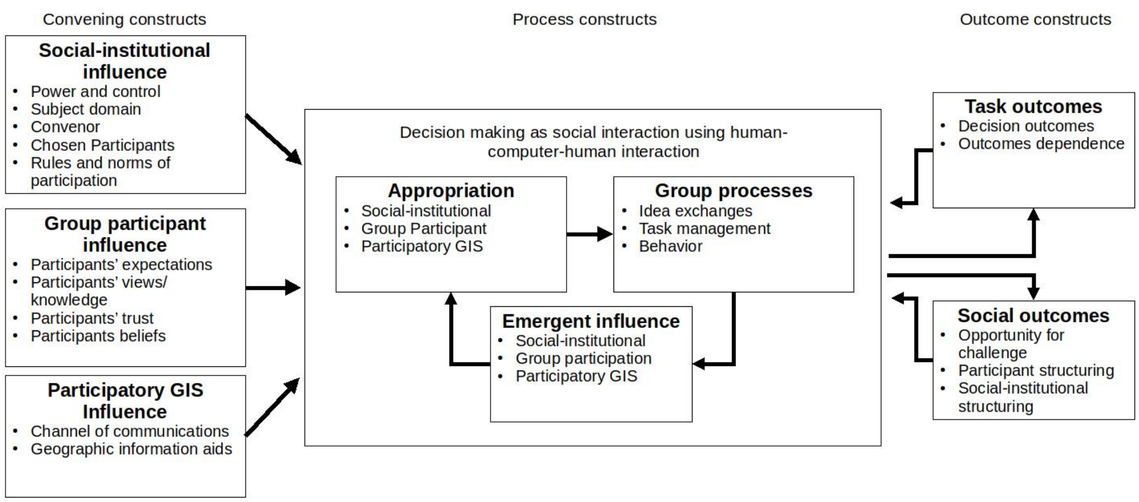

Figure 2-7: Enhanced Adaptive Structuration Theory 2 (EAST2). Adapted from [75]

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 [76]. 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" [77]. 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" ([78] as paraphrased in [79]).

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" [38].

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 [76], critical cartography [80, 81], GIS and Society [82], 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) [82], which also included other stakeholders, including government officials, NGOs, private corporations, etc. 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 [83, 76]. For example, in Washington state in 2002, several American Indian tribes were using GIS technology to "inventory, analyze, map, and make descisions regarding tribal resources... includ[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" [84]. And in 1999, the 'What If?' Planning Support System (PSS) was created to use "GIS data sets that commnities have already developed to support community-based efforts to evaluate the likely implications of alternative public-policy choices" [85].

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") [86]. Having only the former forces the user to rely upon blind trust, instilling a sense of complacency or alieanation 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 [87].

PGIS has thus naturally been strongly advocated and widely adopted over the past three decades [88], with numerous frameworks being proposed for how to implement it [89]. A relatively early project in this vein, for example, sought to try and overcome issues of inequal access and use of GIS technology in South Africa in the early 1990s through the pursuit of five specific objectives [79]:

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 knoweledge.
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 bureaucractic constraints, allowing real time combination of data from different souces; (2) construct a loop between government and the community in which cooperation builds respect continuously; (3) enable two-way communication, promotiving collaboration [70]. That said, some of these implementations have been criticized for being participative in name only, particularly within the research domain [90].

Civic technology [91]

Many PGIS implementations still rely upon closed source, proprietary code for the underlying software [60]. 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 [80]. 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 [92],

> 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" [93].

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 [94]. 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.

2.1.5 Why Systems Engineering?

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

Systems engineering, perhaps due to its inherently interdisciplinary nature coupled with its roots in several different fields (aerospace engineering, civil engineering, mechanical engineering, etc.), has had numerous definitions proposed over the course of the past century. Some of these have been by individual authors, such as Maier and Rechtin's "*A multidisciplinary engineering discipline in which decisions and designs are based on their effect on the system as a whole*" [12], and some by international standards organizations, such as the international standards organization (ISO)/International Electrotechnical Commission (IEC)/Institute of Electrical and Electronics Engineers (IEEE) definition "*Interdisciplinary approach governing the total technical and managerial effort required to transform a set of customer needs, expectations, and constraints into a solution and to support that solution throughout its life*" [95] . For the purposes of this discusion, 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" [96]. 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 tendancy 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 [97].

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

Other subfields that will be relevant later in the EVDT lifecycle include multi-stakeholder negotiation and decision-making, which contains numerous lessons on how structure communications to avoid deadlock or domination [98, 99, 100]; tradespace visualization and exploration [98, 99, 101, 102, 103], 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 [104, 105]. Sachs stated that "Sustainable development is also a science of complex systems" and argued that two specific tools are important for implementing the SDGs: backcasting and technology road-mapping [20]. Systems engineering is well equiped 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 paralled by the (rightfully) expanded number of stakeholders involved in decision-making processes and a increased recognition of linkages across differing geographic scales [89]. This increase in complexity is something that systems engineering is well posed to address.

2.2 EVDT Framework

Computational models have been closely linked to the pursuit of sustainable development and with its definition, stemming from the World3 system dynamics model underlying the Club of Rome's *The Limits to Growth* report in 1972 [106].

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

We are far from the first to argue that such integration is necessary, nor to recognize that it is easier said than done [107].

There have been many land use and transportation models. The open source UrbanSim, for example, combines land use, transportation, and certain environmental factors in a dynamic, area-based simulation system that, similar to EVDT, is a collection multiple models [108].

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 [109].

Existing PSS have often been criticized for being lacking with regard to "visioning, storytelling sketching, and developing strategies," as well as being "too generic, too complex, inflexible, incompatible..., oriented towards technology rather than problems" [89]" This leads to what some have called the "implementation gap" of PSSs [110].

For the past couple of decades, there has been a recognition that DSSs and PSSs must include more than purely spatial analysis components [111].

The closest attempt to what we are proposing is probably that of Shahumyan and Moeckel, though their approach focused on linking together existing models in a loose manner using ArcGIS Model Builder, to avoid having to gain access to proprietary source code. While their example focused on combinging transportation, land use, mobile emissions, building emissions, and land cover, with only limited feedbacks, their approach could be extended to capture the full feedback loops proposed by EVDT. Their example is also proof that the kind of loose integration of library of models that EVDT envisions is possible [107].

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 [112]

Pert et al. combined environmental and decision-making in a participatory model to improve conservation outcomes [113].

Miller argues that, despite the historical dificulties that integrated urban models have had, there is reason to be optimistic about the state of the art moving forward, particularly for integrating transportation and land-use models in particular [114]. <—important to discuss at more length

Is not itself a means of planning and implementing projects. It is not a full life-cycle tool such as Planning-Programming-Budgeting System (PPBS) [115]

Clifton et al. breaks down the various ways of modeling the urban form into five categories (though they do not assert that these are comprehensive or mutually exclusive), as seen in Table 2.2 [116]. 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 [117].

The motivation for combining so many variables from different disciplines stems from both push and pull factors. The push factors are the simple increase in availability of data, as has already been described, along with the increase in the interoperability of the variables (which the work described in this thesis is trying to help contribute to). The primary pull factor is our increased understanding of - and appreciation for - the complex relationships between these domains, relationships that were previously ignored in analyses [118].

Position EVDT using the different dimensions of models proposed in [119]:

1. descriptive vs. analytic

Table 2.2: Five categories of urban form models. Adapted from [116]

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

2. holistic vs. partial
3. macro vs. micro
4. static vs. dynamic
5. deterministic vs. probabilistic
6. simultaneous vs. sequential (directly calculate the output or go through intermediate phases)

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

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

In the mid 90s, GIS had several limitations [63]:

- 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 [62].

Yamu et al. argue that urban modeling should treat the urban form as a complex adaptive system (CAS) and use fractal metrics to develop scenarios for planning purposes [120].

In order for cost-benefit analysis to maximize economic welfare, the following conditions must be met [121]:

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

More details modeling, as well as breaking down specific costs and benefits (as opposed to converting them to monetary terms and summing them) and attributing them to specific goals, can circumvent these constraints, though at the cost of increased complexity [122].

The Law of requisite variety from the field of cybernetics says that the variety (the number of elements or states) of the control device must be at least equal to that of the disturbances [123]. 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. [124]

2.3 Intended Use Cases / Applications

While EVDT does not include any concrete spatial scale requirements, it is often the most straightforward to apply to it at a a relatively local scale, like much of the early history of GIS applications [74]. Most of the applications to date have been at the area of a metropolitan area or that of a small province.

Tends to be at intersections of rural and urban areas. Urban areas often depend on an area significantly larger than the built-up area for basic resources and ecosystem services, particularly for water, bulky materials, and waste disposal. I will not attempt to strictly define rural and urban here, as the "distinctions are often arbitrary" [125]. Instead this work will rely upon local definitions of urban, rural, and peri-urban, similarly to the UN [20].

Commonly has to do with common-pool resourcess (CPRs). Talk about the three common ways of managing CPRs: Central management, privatization, self-management. Bring in Table 2.3 showing design principles of long-enduring self-management institutions. Refer to successful aspects of the water basin in California (incremental and sequential process to reduce the costs of local institutional supply, shared information at each step, intermediate benefits from initial investments were realized prior to larger investments, transformed structure of incentives within which fuure strategic decisions can be made) (pg. 137. [7]

Table 2.3: Design principles illustrated by long-lasting CPR institutions. Adapted from [7]

1.	Clearly defined boundaries
2.	Congruence between appropriation and provision rules and local conditions
3.	Collective-choice arrangements
4.	Monitoring
5.	Graduated sanctions
6.	Conflict-resolution mechanisms
7.	Minimal recognition of rights to organize
For CPRs that are parts of larger systems:	
8.	Nested enterprises

We also

Harris et al. have pointed out that reliance on mapping products to designate certain geographic areas for conservation has several negative consequences, including:

- solidifying a notion that humans and non-human others are, and should be, separate.
- privileging those voices and perspectives that have access and expertise related to Western cartographic approaches and GIScience in conservation debates.
- favoring those spaces, ecosystems, and natures that may be "more mappable" for protection over other areas.
- cementing an overly-limited territorial approach to conservation, in ways that potentially sideline non-territorial approaches.
- consolidating an overly-fixed and static approach to sonservation, rather than enabling approaches that may be more seasonal, fluid, or appropriate for shifting and evolving ecological conditions and needs.

2.4 Critiques

- 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. If you truly want to save the Earth and stop oppression, you should abandon technology rather than doubling down on it.
- Western-run technocratic planning and international development perpetuates colonialism, typically fails in its own goals, and merely destroys traditional communities.
- 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.
- The effectiveness of scenario planning and most other forms of decision support is ambiguous at best, despite their long history. Another research project in this vein is thus fundamentally flawed and is not real science.
- Systems engineering is an inherently elitist methodology whose primary use is to defend the oppressive status quo and eke out greater "efficiencies" with little regard for societal consequences.

2.4.1 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 pessism 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 persistant, particularly among the scientists and engineers who were most directly involved with the development of technology[126], as is currently seen with the proponents of Big Data and machine learning [127]. 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, explicity 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" [128].

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." [129]. John Pickles was one of the more articulate purveyors of such an argument [73]:

> 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 diference 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 satisfication 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 severly 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" [130]. 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, hte other democratic, the first system-centered, immensely powerful, but inherently unstable, athe other [hu]man-centered, relatively weak, but resourceful and durable" [131].

For examples of these two types, Hayes suggested the inherently bulky and centralized nuclear power with inherently decentralized solar power [132] (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 creater 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" [133].

The ideas of Mumford and Winner have become commonplace. Even self-admitted technological optimists like Jeffrey Sachs [134] feel it necessary to qualify their optimism: "*Choosing the right technologies*, we can achieve continued economic growth and also honor the planetary boundaries" [emphasis mine] [20]. Similarly, the largest developers of new technologies, such as Google, find it necessary to put effort into studying the ethics of their systems (though there is some evidence that this is mere lip-service [135]).

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

GIS and 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 explicity of means for resource exploitation and control [38]. 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" [136], 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 intenions, and the powerful forces being them, were understood only too well" [38]. 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 [137].

A more specific, early critique, also by Pickles, was that of privacy and control over one's own information [58]:

":"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 [138], and big data in general [127].

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 [56].

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" [136]. Meanwhile Tulloch argued that GIS is naturally developing through phases, seen in Figure 2-8, while the problematically simplistic outcomes of efficiency and effectiveness were the primary reseult of earlier stages, future states, including democratization of GIS will instead produce equity.

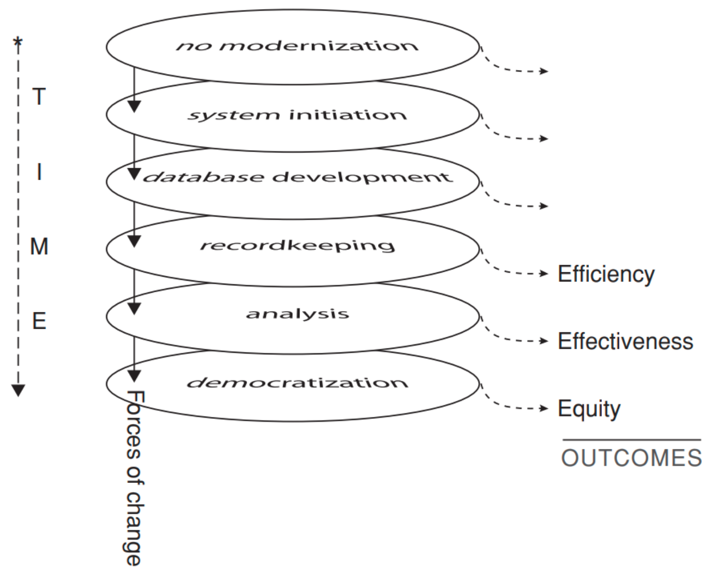

Figure 2-8: Development of GIS development and associated outcomes. From [139] as reprinted in [74]

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 responsibility is highly problematic. Many designers of digital tools seek to reject the former and commit themselves to a sort of tehnological determinism [56]. 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) [70]. 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 judgements about what issues matter enough to be analyzed. Becaues 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," [140] thereby aligning it with the democractic, human-centered type of technology.

We must recognize that, as Krygier and Wood so playfully illustrated, maps (and all GISs) are, fundamentally, propositions about that world that are asserting a fact and promoting an action. Because of this "you must accept responsibility for the realities you create with maps" [141]. 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" ([142] as paraphrased in [143]).

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 [144]. 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 [145]. 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 [144]. Florence Nightingale's famous rose diagrams famously shifted policy on hte handling of sanitation in warzones [146], even if these diagrams were, in fact, misleading (cite).

Additionally, in some ways, we want to avoid making a seemless tool, as "the most significant impacts of technology tend to occur when the technology becomes indistringuishable from the fabric of every day life" ([147] as paraphrased in [65]). 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 [148].

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" [136]. 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.'

As we proceed, we must keep in mind that "the very notion that technologies are neutral must be directly challenged as a misnomer," [143] 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" [149].

Technocratic Planning and 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 [150]), but instead to focus in on the narrower question of whether *technocratic planning*, particularly in an international context, can be helpful and ethical.

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

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

These individuals are what Easterly calls "Planners," to be distinguished by "Searchers," those who seek for bottom-up solution to specific, addressable needs

[151]. The Planners, meanwhile, fashion themselves into benevolent dictators (though they would eskew being called as such) focused on implementing their solution [152]. Beyond outright failure, such endeavours 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 [153].

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

1. The "administrative ordering of nature and society." This includes items like cadastral maps, surnames, census records, and a standardized legal system. As Theodore Porter put it, "Society must be remade before it can be the object of quantification." [154]
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 uman 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 inact the high-modernist ideology.
4. A vulnerable civil society that "lacks the capacity to resist" the plans of that authoritarian state.

In essence what is "truly dangerous to us and our environment... is the *combination* of the universalist pretensions of epistemic knowledge and authoritarian social engineering" [24]. Such a combination often takes the form of undue focus being places on specific metrics, with little interest in underlying causes and dynamics. "Many studies involve ranking places on one or more criteria, and allocating policy benefits accordingly. At its crudest this applied geography merely provides a list of winner and losers with no understanding of why the differences occur" [53].

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 legitmacy of sciency and technology." In fact, it was more an aesthetic prediliction than anything scientific. Furthermore, the underlying ideas were in fact quite sympathetic. "Doctors and public-health engineers who did possess new knowledge that could save millions of lives were often thwarted by popular prejudices and entrenched political interests" [24]. The dangers were when an authoritarian state adopted the aesthetic veilings of such ideas to justify actions, in the way that Social Darwinism used evolutionary theory to justify horrid actions. In this way "the classism and racism of elites are mathwashed, neutralized by technological mystification and data-based hocus-pocus." [148] 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" [148] (something that we are currently seeing repeated with discussions about Big Data and machine learning [155]).

The details lost in the necessary simplifications that the technocrat must make often turn out to not be so neglibible after all. In the USSR, "a set of informal practices lying outside of the formal command economy - and often outside Soviet law as well - [arose] to circumvent some of the colossal waste and inefficiencies built into the system. Collectivized agriculture, in other words, never quite operated according to the hierarchical grid of production plans and procurements." [24] The technocratic leaders were often aware of this but so committed to their ideology that they had no alternative but to maintain a sort of pretense, which anthropologist Alexi Yurchak called 'hypernormalization' [156], that served to compound problems until the Soviet Union eventually collapsed. Such a phenomena is particularly visible in strictly planned capital cities that have, "as the inevitable accompaniment of [their] official structures, given rise to another, far more 'disorderly' and complex city *that makes the official city work* - that is virtually a condition of its existence" [24].

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

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

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

And the unfortunate matter is, even if we assume that Scott is correct in that his conditions are the necessary and sufficient conditions, what are they conditions for? "The *most tragic* episodes of state-initiated engineering" (emphasis mine) [24]. The egregiously racist influence that Robert Moses had the design of New York City [133] 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" [157]. It is certainly true that many of the tools have changed over the past few decades. Systems engineering, for instance, is a substantionally different field than it was in the middle of the 20th century, as is discussed in Sections 2.1.5 and 2.4.1. Sachs meanwhile proposes that prescreptive economics should be modeled on clinical medicine and should not seek to attribute all negative outcomes to the same cause nor to prescribe the same solution to all problems, but instead to "make a differential diagnosis for the economic case at hand." He lays out several different conditions of poverty, for example, and proposes different solutions to each. Foreign aid is effective at treating the "poverty trap" condition (wherein "the country is too poor to make the basic investments it needs to escape from extreme material deprivation and get on the ladder of economic growth"), but less so for other conditions [20]. In this way, he seeks to distance himself from the high modernist ideology, with its affinity for singular, simple solutions, while still doubling down on the technocratic approach in general.

It should be noted, however, that Sachs has been a senior advisor to numerous states and the UN dating back to the mid 1980s and thus has had ample time to demonstrate his ideas. Nonetheless, many of the critiques referred to already are addressing this time period and some, such as Easterly [151], were specifically aimed at Sach's efforts, with some arguing that many of his projects have left people worse off than before [158].

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

The third argument we may make that planning still has a positive role to play involves collaborative and participatory forms of planning, similarly to what was done for GIS DSSs in Section 2.1.4. 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" [159]. Even if participation is quite extensive and includes actual political power, "democracies rarely end up expropriating and redistributing capital" [160]. 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'" [153].

Not only is participation evidently insufficient on its own, but some argue that neoliberalism in factor prefers to use participation as a means of underming resistance, rather than violence, though this has the risk of providing a structure for coalition building and radicalization [161]. This can occur even unintentionally, as "an inappropriate leve lof participation may disempower individuals... and it also can distract groups from a desired outcome" [82]. In fact, increased community involvement can result in more restrictive, unambitious goals that are not in the interests of certain minorities [162]. A key aspect of participatory planning is that mere participation does not magically eliminate power hierarchies. Such pre-existing hiearchies can wield their power in planning discussions in three primary ways: "by promoting formal decisions, setting the agenda, and influencing the broader ideogical context of the debate" ([163] as paraphrased by [140]). Similarly, merely connecting individuals and enabling the sharing of information does not necessarily promote engaged political deliberation [164].

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 [140]. I discuss further evidence to this effect in Section 2.4.3.

To resolve this confusion, Arnstein proposes an eight-step "ladder of civic participation" [165] [ADD FIGURE AND DISCUSSION] Bekkers and Moody provide some examples of visualization and GIS use that made the citizenry feel manipulated [166].

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 [164].

In line with some of Easterly's arguments, Virginia Eubanks proposees two gut check questions to ensure that a planning tool avoids harmful consequences [148]:

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 ([167] as paraphrased by [143]):

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 eradiction 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 harmful outcomes of the past (and present), Eubank's and Furner's points are worth keeping in mind as we continue.

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. US Vice President Herbert Humphrey said in 1968 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 a multi-year 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 bare on the urban crises of the time [4]. It was a heady time, with engineers themselves 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" [168]. 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. While recounting the full history of this trajectory is beyond the scope of this work, one can get a sense of it in quotations from urban planners of the time and since:

> The systems engineers bring some expertise and substantial pretensions to the problems of the city. Their prinicpal 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 surival and welfare for soceity 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. [169]
>
> 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 2-9 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 nuetrality. In reality, they address their work to those who are in power and see their primary mission as serving the state" [168]. 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 policital order in which its role is to make that order function smoothly." [159]. 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 democractic nature of the US kept these applications from becoming large scale tragedies, but this does not mean they were successes by any means either.

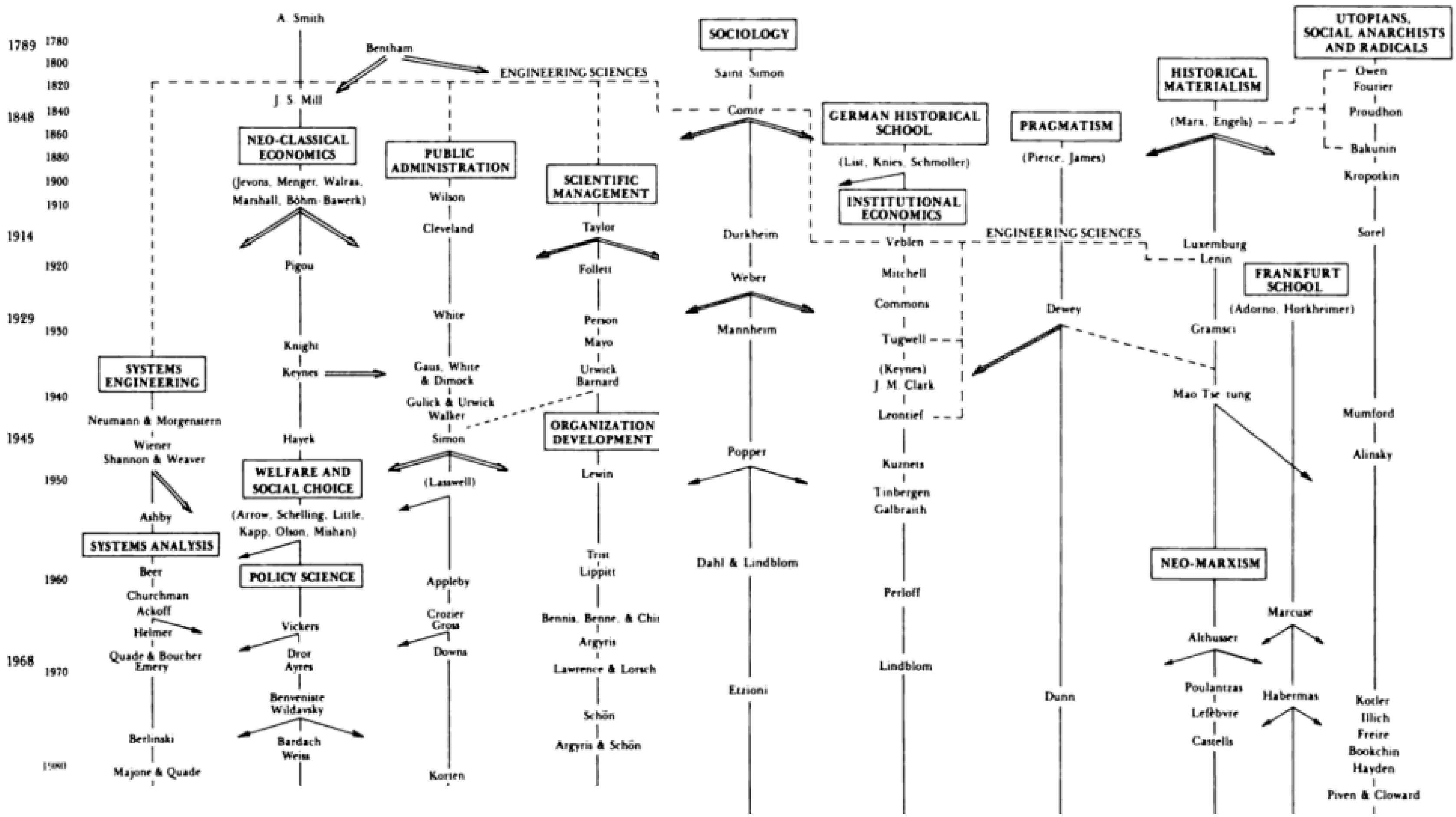

Figure 2-9: Timeline of intellectual influences on American planning theory. From [168]

This leads us to asking why systems engineering did not achieve all that it was promised to. An examination of the literature reveals certain common factors [4, 168, 148, 24, 124, 170]:

- These new techniques, heavily dependent on quantification, suffered from a lack of relevant data, particularly on social wellbeing.
- There was a lack of prior goal setting by decision makers. Technical experts were driven by a desire to use the tools available to them rather than to actually address the specific needs of the community. This resulted in proposed alternatives being unconnected to community goals and thus irrelevant.
- Systems engineers tended to have a sense of certainty about the virtues of designing a society from the ground up and an ignorance of history that blinded them to the lessons learned by previous technocratic and utopian planning endeavors.
- Technocratic systems and defense analysts displaced professional urban planners and others with detailed subject knowledge, rather than seeking to cooperate and learn from them. Some urban planners went so far as to complain that "their work had been hijacked by refugees from aerospace."
- Similarly, engineers tended to ignore and denigrate local practices and local expertise, perhaps because to recognize these as reasonable, to learn from and negotiate with them, would have undermined the institutional powr and status of the technical expert.
- Having been raised on the cultural norms of the military and private industry, development applications of systems engineering were marked by significant secrecy, undermining their legitmacy in the eyes of the public.
- While proponents of social applications of systems engineering argued that it would transform urban planning and decision-making into scientific endeavors, such an espousal tended to be more of an aesthetic argument, grounded in the high modernist ideology rather than fact.
- The Law of requisite variety from the field of cybernetics says that the variety (the number of elements or states) of the control device must be at least equal to that of the disturbances [123]. 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. System engineering tools of the time did not have the capacity to make use of such flexible measures.
- Systems engineering frameworks of the period held that complex controversies could be remedied by simply getting the correct information to the correct place in an efficient manner. They failed to recognize that even if complete and 'correct' information is available to all stakeholders, significant or even irresolvable disputes may remain.

All of these causes led to the gradual rejection and retreat of systems engineering in development planning. As early as 1973, planning scholars were (perhaps preemptively) eulogizing the death of large-scale models and other tools of the systems engineer [171]. The intervening decades have seen the fields of systems engineering and development planning grow largely independently of one another. In particular, the urban planning profession has evolved and adopted computational models on its own terms. Interactive DSS abounds [108, 172]. The use of GIS has become the norm [75, 68, 173]., including more participatory variants [82]. Numerous quantative economic and social indeces have been developed [174, 116, 175, 176, 177] . Mathematical tools such as cellular automata have become popular [178, 112]. Digital models underly the popular subdiscipline of scenario planning [140, 179]. Interdisciplinary, integrated models have even started to re-emerge [114, 180, 107]. Arguably urban planning has adopted many of the tools and methodologies of systems engineering.

At the same time, systems engineering has changed. The belief that systems, even human systems, can be made simple, rational, and controllable has been largely outmoded within the field. Instead, in the guise of theories of complex systems and chaos, they have adopted Jane Jacob's view 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, systems-of-systems, and complex adaptive systems have all become popular fields of study within systems engineering [181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191], with numerous frameworks being proposed for how to classify and handle such systems [192, 193, 194, 195, 196, 197]. Faced with such systems, engineers have had to recognize their own inability to definitively predict the future and have turned to probabalistic methods that instead "manage" complexity over longer time scales, such as epoch-era analysis [104, 105] (which in many ways resembles the aforementioned urban planning method called scenario planning).

Parallel to this, systems engineers have moved away from singlemindedly implementing the directives of an individual client to 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 stakeholder analyses involves both qualitative and quantitative tools, such as the Stakeholder Requirements Definition Process [198], Stakeholder Value Network Analysis [199], and qualitative interviews of representatives from different stakeholder groups (something that would have been anathema to the earlier era of systems engineering. In order to translate these complicated networks of stakeholders into designs, systems engineers have developed methods for handling multi-stakeholder negotiation and [98, 99, 100] tradespace visualization and exploration [98, 99, 101, 102, 103], , the latter of which demonstrates an increased willingness to appreciate the psychology and experience of ther user. The historic preference of the impersonal and 'objective' versus the personal and 'subjective' is by no means unique to systems engineering. It can also be found in economics, jurisprudence, education theory, political science, and even moral philosophy [200]. The development of stakeholder analysis has helped to bridge the gap between these two and thus rectify this traditional deficiency. In fact, the use of stakeholder analysis in contemporary systems engineering is, in a way, a step away from the worldview that sees "human beings as unknowable black boxes and machines as transparent," a viewpoint that "surrenders any attempt at empathy and forecloses the possibility of ethical development" and is a tacit "admission that we have abandoned a social commitment to try and understand each other" [148].

All of this suggests that the fields of systems engineering and urban planning are perhaps more close to each other than ever before, even showing some elements of convergent evolution (see the use of the term complex adaptive system in both fields [120]). Much benefit could be gained through more direct dialogue and collaboration with one another. Why then, do we not see that occuring? After all, several of the critical comments made about systems engineering cited above were from recent years. Part of this is likely historical memory. While decades have elapsed, we are still within a single professional lifetime of some of the excesses of systems engineering. But some concerns can be found much temporally closer. While urban planning is a deeply historical field, systems engineering is not. What histories do exist tend to focus on the engineered technical systems, such as the Apollo program [201], rather than the planning dalliances of the 50s-70s. This is has not gone unnoticed: “One cannot know about the history of media stereotyping or the nuances of structural oppression in any formal, scholarly way through the traditional engineering curriculum of the large research universities from which technology companies hire across the United States. Ethics course are rare" [143]. This can lead to each new generation of engineers using new tools that are attempts to resolve the mistakes of the past, but while maintaining the same tabula rasa mindset that led their forebearers astray. Can one begrudge the urban planner their skepticism when one of the highest profile contemporary applications of systems engineering to planning is the ‘urban digital twin’ or ‘smart city’ [70, 202, 203, 204, 205] that seems to be a repitions of the belief that “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, systems engineers assume, the correct answers to intractable policy problems like homelessness will be simple, uncontroversial, and widely shared" [148].

So how can we make use of the opportunity for constructive collaboration and avoid falling prey to the same pitfalls as before? I propose three actions:

1. Explicitly grapple with the historical ethical shortcomings of the systems engineering field and related technocratic approaches to societal development.
2. Seek collaborations outside of the engineering disciplines and even outside of technical experts.
3. Select an application domain that can benefit greatly from both systems engineering and urban planning, preferably a relative novel domain.

The first is necessary, as mentioned in earlier sections, to avoid new generations of systems engineers being educated in ignorance of past mistakes. This grappling should take place in classes (either designated ethics courses or as integrated components of other engineering courses), within research groups, and in the scholarly literature. Topics can include the urban planning perspectives of systems engineering, such as Robinson [169], Friedmann [168], and Marcuse [159]; it can include critical histories of systems engineering, such as Light [4]; and specific case studies, such as the Navajo perspective on the lunar burial of Eugene Shoemaker [206] or Nostikasari’s account of how underlying assumptions in a transportation model can perpetuate inequality [207]. In general, systems engineers should take a firm stance of antiracism and anticolonialism and engage in the related fields of literature.

The second approach is an extension of norms already embedded within systems engineering. From its beginnings, systems engineers have depended upon multidisciplinary teams of engineers. After all, systems engineers are largely would unnecessarily for projects that can be accomplished by a single individual. 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. 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 [81, 113, 82, 76, 208]. 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.

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

> The danger of translation is that one language will dominate the debate and thus define the terms of the solution. It is essential to exert equal effort to translate in each direction, to prevent one linguistic culture from dominating the other... Another lesson from the neocolonial inguistic 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 *ingua franca*, by creating equal two-way translations... Translation can thus be a powerful planner's skill, and interdisciplinary planning education already provides some multiculturalism [209].

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." I tend to agree with him.

2.4.2 Sustainable Development and the SDGs

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

"The pessimistic thought is that sustainable development has been stripped of its transformative power and reduced to its lowest common demoninator. 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 manny people without requiring commitment to any specific policies." [209]

"Yet there is also an optimistic interpretation of the broad empbrace given sustainability: the idea has become hegemonic, an accepted meta-narrative, a given. It has shifted from being a variable to being the parameter of hte debate, almost certain to be integrated into any future scenario of development." [209]

"To... critics, the prospect of integrating economic, environmental and equity interests will seem forced and artificial. States will require communities to prepare "Sustinable Development Master Plans," which will prove to be glib wish lists of goals and suspiciously vague implementation steps. To achieve consensus for the plan, language wil lbe reduced to the lowest common demoninator, and the pleasing plans will gather dust." (written in 1996, pre MDGs and SDGs) [209]

"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 inguistic experience is that it is crucial for each social group to express itself in its own language before any translation. The challenge for planners is to write the best translations among the languages of the economic, the ecological, and the social views, and to avoid a quasi-colonial dominance by the economic *lingua franca*, by creating equal two-way translations... Translation can thus be a powerful planner's skill, and interdisciplinary planning education already provides some multiculturalism. Moreover, the idea of sustainability lends itself nicely to the meeting on common ground of competing value systems." [209]

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. [92]

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

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

Goals accomplish several things [20]:

- Global goals are critical for social mobilization and coordinated orientation.
- Global goals provide global peer pressure for adoption, monitoring, and action.

- Global goals mobilizing epistemic communities (experts, researchers, etc. These in turn can help map pathways to acheiving the goals, making them seem more managable and less remote.)
- Global goals mobilize stakeholder networks and thereby leverage capital and other resources.

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

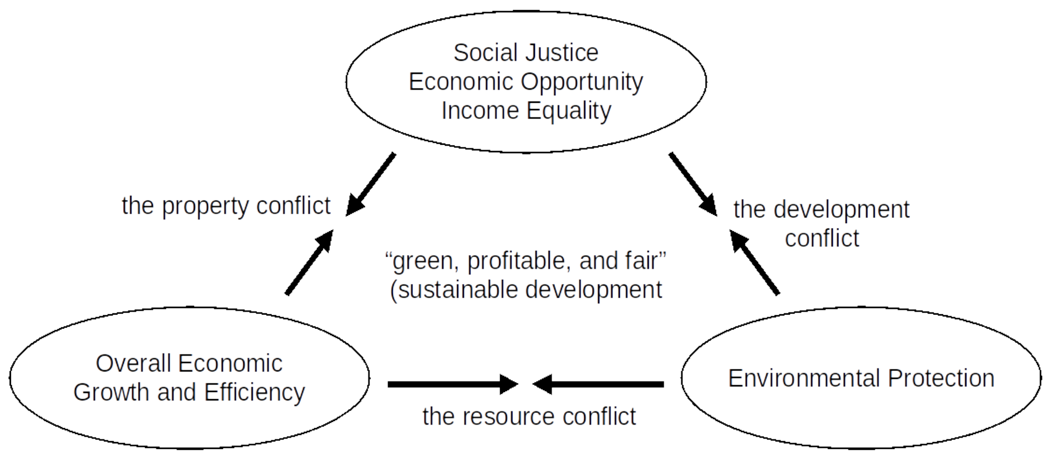

Figure 2-10: The triangle of conflicting goals of sustainable development. Adapted from [209]

Respond to critiques of MDGs/SDGs [210, 211]

Fukuda-Parr et al. argued that the primary strengths of the MDGs - " simplicity, measurability, and concreteness - also proved to be sources of distortion." They also point to evidence that the MDGs did little to raise awareness and motivate action for neglected priorities, but instead merely provided metrics for already popular initiatives [212]. Those issues that did see awareness raised and resources provided produced "ambiguous impacts on complex social issues," particularly because some of the metrics were chosen for ease of implementation rather than importance.

2.4.3 Scenario Planning and Decision-Support is unfounded

As far back as the 1970s, there have been critiques of the use of complicated, multi-domain models to address multiple concerns at the same time. The models of this era were (rightfully) critcized for failing to provide accurate results, requiring too detailed data while outputting uselessly coarse data, mis-applying theory, being black boxes, and expense [171].

Refer to critique made by [171]

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

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

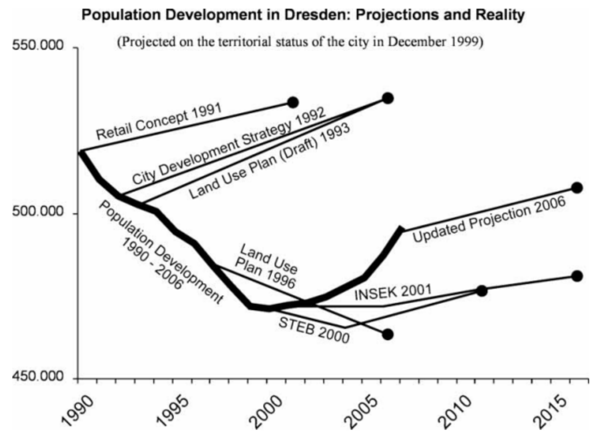

Figure 2-11: Population changes in Dresden compared to various projections. From [213]

Bankes argues that many of these problems can be avoided by clearly differentiating between *consolidative models* that strive to be "a surrogate for the actual system" but are often out of reach, and *exploratory models*, which seek to examine the implications of varying assumptions and hypotheses [214]. 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, explictly "does not attempt to predict future conditions exactly. Instead it... can be used to determine *what* would happen *if* clearly defined policy choices are made and assumptions concerning the future prove to be correct" (emphasis original) [85].

Often, however, so-called "strategic planning" is anything but. "A strategic plan might more closely resemble a project plan, with long lists of specific proposals and policies... many have relatively short time frames. Scenario planning may not make sense for these plans." [140]

While forecasting can be problematic as it constitutes "someone else's understanding and judgement crystallized in a figure that then becomes a substitute for thinking," scenario planning instead allows users to "develop their own feel for the nature of the system, the forces at work within it, the uncertanties that underlies the laternative scenarios, and the concepts useful for interpreting key data." [215]

The evidence for such practices as scenario planning is decidedly mixed. Goodspeed's review of scenario planning use in urban planning and environmental research resulted in only modest benefits, with use in management being more unambiguously positive [140]. His own study of impact of a scenario planning project in Lockhart, Texas, which corrected some of the flaws he identified in many previous studies, confirmed that modest, but real positive changes are the result of scenario planning.

I readily acknowledge and embrace the fact that this work is predominantly a piece of design science, which aims to "design propositions, which inform speciic practices, artifacts, or tools", rather than 'conventional' science, which "primarily aims to describe, explain, or predict the world but not to change it." [140]

In fact, there are significant reasons to avoid practicing "conventional science" in these domains as treating society as a laboratory can lead to significant harms and a "vivisectionaist" mentality [216].

Evidence that collaboration improves DSS functionality and usability [217, 218, 89, 208]

"Dewey famously distinguishes between a *planned* society, which subordinates the present in pursuit of a rigid planned future, and a *planning* society, which is intellectually preoccupied by the future but knows that only the present - and not the future can be controlled." ([219] as paraphrased by [140]

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

Chapter 3

Methodology

3.1 Mapping and Visualization

"A single map is but one of an indefiniteliy large number of maps that might be produced for the same situation or from the same data." [220]

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" [221] though arguably Scheiner's 1626 sunspot visualization qualifies as a data map [146], as perhaps do Polynesian knot maps, which long predates either [CITE]. Graphing data over time, meanwhile dates by to the 14th century [146].

Choropleths are one of the more common types of non-imagery geospatial data that EVDT uses. These are maps that express "quantity in area" (i.e. some statistic tied to a particular geographic area with color, texture, or shading). It should be noted that choropleths have a few well-known limitations, including the ecological fallacy and the modifiable areal unit problem [222, 176]. It is for these reasons that EVDT does not rely entirely on choropleths and why we strive to store data with the finest geospatial resolution available.

Historically, GIS implementations have often struggled to handle temporal data [223].

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 [176].

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 [176]:

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

Initial versions of EVDT and Vida featured quite large graphics. Tufte argues that graphics in general should be significantle shrunk and that "many data graphics can be reduced in area to half their current published size with virtually not loss in legibility and information." [221] Inaccordance with this Shrink Principle, these graphics were greatly reduced in later versions.

As with most GIS software [60], early verions of EVDT were structured as entirely object-oriented, and later versions remained primarily object-oriented. This has many advantages but also comes at certain costs, the most important of which include (a) difficulty in recording continuous spatial variables and (b) a requirement to pre-identify the different classes (objects) to sort phenomena and relationships into [67].

It is recognized that this desktop version comes with numerous downsides. *theirwork*, an early collaborative, open source GIS platform, specifically "decided at an early stage to make the software Web-based to allow for a process of rapid development and iteration and allow a maximum number of potential participants." [92] It should be noted, however, that *theirwork* was a UK-based project (an area with high internet connectivity penetration) and started in the mid 2000's, a period with significantly diversity of internet browsing methods, which simplified the task of ensuring accessibility. Nonetheless, it is impossible to deny the collaboration and software sustainability benefits of an online platform, particularly in an age when many of the early concerns with the internet (low speeds, lack of knowledge about how to use it, etc.) [224] have been largly alleviated.

the meeting arrangment that EVDT supports, Table 3.1

Does EVDT aimed at *backward visualization*, which is aimed at assisting experts and professoinals, or *forward visualization*, which is aimed at a less informed audience [225].

While three dimensional data exists for both the urban environment [225] and from remote sensing (reference lidar), EVDT focuses primarily on two dimensional symbolic visualizations.

EVDT takes a somewhat Harleian approach to visualization, in which "*presentation* is de-emphasized in favor of *exploration* of data" [226].

Table 3.1: Different types of meeting arrangements. Adapted from [75]

<table>
<tr><td></td><td>Same time</td><td>Different time</td></tr>
<tr><td>Same place</td><td>Conventional Meeting
Advantage:
• face-to-face expressions
• immediate response

Disadvantage:
• scheduling is difficult</td><td>Storyboard meeting
Advantage:
• scheduling is easy
• respond anytime
• leave-behind note

Disadvantage:
• meeting takes longer
• difficult to maintain in the long run</td></tr>
<tr><td>Different place</td><td>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</td><td>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)</td></tr>
</table>

Chapter 4

Rio de Janeiro Mangroves

4.1 Study Area

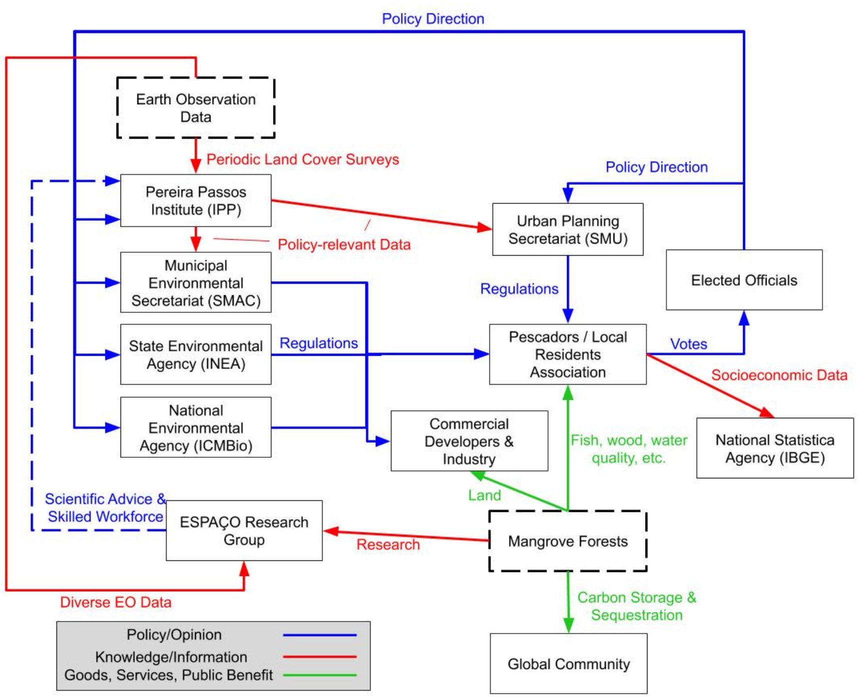

Figure 4-1: Stakeholder Map for the Mangrove Forests of Reio de Janeiro

4.2 EVDT Application

Chapter 5

Vida Decision Support System

5.1 Study Areas

5.2 Vida Variant of EVDT

Chapter 6

Discussion

6.1 Lessons Learned

6.2 The Future of EVDT

Chapter 7

Conclusion

7.1 Research Questions

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] 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.

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

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

[14] 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.

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

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

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

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

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

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

[21] 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.

[22] 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.

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

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

[25] 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.

[26] 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.

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

[28] 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.

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

[30] 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.

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

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

[33] 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.

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

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

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

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

[38] 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.

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

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

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

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

[43] 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.

[44] 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.

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

[46] 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.

[47] Sylvain Biancamaria, Dennis P. Lettenmaier, and Tamlin M. Pavelsky. The SWOT Mission and Its Capabilities for Land Hydrology. *Surveys in Geophysics*, 37(2):307–337, 2016.

[48] 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.

[49] 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.

[50] 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.

[51] 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.

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

[53] 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.

[54] 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.

[55] 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.

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

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

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

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

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

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

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

[63] 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.

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

[65] 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.

[66] 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.

[67] 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.

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

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

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

[71] 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.

[72] 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.

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

[74] 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.

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

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

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

[78] 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.

[79] 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.

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

[81] 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.

[82] 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.

[83] 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.

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

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

[86] 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.

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

[88] 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.

[89] 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.

[90] 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.

[91] Derek Poppert. Navigating the field of civic tech, May 2021.

[92] 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.

[93] 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.

[94] 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.

[95] 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.

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

[97] 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.

[98] 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.

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

[100] 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.

[101] 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.

[102] 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.

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

[104] 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.

[105] 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.

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

[107] 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.

[108] 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.

[109] 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.

[110] Bottlenecks Blocking Widespread Usage of Planning Support Systems - Guido Vonk, Stan Geertman, Paul Schot, 2005. https://journals.sagepub.com/doi/abs/10.1068/a3712.

[111] Stan Geertman and John Stillwell. Planning support systems: An inventory of current practice. *Computers, Environment and Urban Systems*, 28(4):291–310, July 2004.

[112] 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.

[113] 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.

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

[115] Harry P. Hatry. Criteria for Evaluation in Planning State and Local Programs. In Ira Robinson, editor, *Decision-Making in Urban Planning: An Introduction to New Methodologies*. SAGE Publications, Inc, Beverly Hills, CA, first edition, 1972.

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

[117] 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.

[118] Mark Gahegan. Multivariate Geovisualization. In *The Handbook of Geographic Information Science*, chapter 16, pages 292–316. John Wiley & Sons, Ltd, 2007.

[119] Britton Harris. Quantitative Models of Urban Development: Their role in Metropolitan Decision-Making. In Ira Robinson, editor, *Decision-Making in Urban Planning: An Introduction to New Methodologies*. SAGE Publications, Inc, Beverly Hills, CA, first edition, 1972.

[120] 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.

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

[122] 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.

[123] 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.

[124] 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.

[125] Cecilia Tacoli. Rural-urban interactions: A guide to the literature. *Environment and Urbanization*, 10(1):147–166, April 1998.

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

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

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

[129] 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.

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

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

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

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

[134] 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.

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

[136] 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.

[137] 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.

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

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

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

[141] 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.

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

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

[144] 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.

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

[146] 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.

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

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

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

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

[151] 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.

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

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

[154] 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.

[155] 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.

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

[157] 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.

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

[159] 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.

[160] 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.

[161] 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.

[162] 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.

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

[164] 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.

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

[166] 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.

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

[168] Johnn 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.

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

[170] Brian J. McLoughlin. Charting Possible Courses of the System. In Ira Robinson, editor, *Decision-Making in Urban Planning: An Introduction to New Methodologies*, pages 103–114. SAGE Publications, Inc, Beverly Hills, CA, first edition, 1972.

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

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

[173] John P. Wilson and A. Stewart Fotheringham, editors. *The Handbook of Geographic Information Science*. Wiley-Blackwell, Malden, MA, 1st edition edition, August 2007.

[174] 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.

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

[176] 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.

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

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

[179] 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.

[180] 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.

[181] 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.

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

[183] 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.

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

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

[186] 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.

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

[188] 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.

[189] 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.

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

[191] 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.

[192] 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.

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

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

[195] 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.

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

[197] Lucie Reymondet. Complexity&Emergence, 2016.

[198] INCOSE. *INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*. Wiley, Hoboken, New Jersey, 4 edition edition, July 2015.

[199] 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.

[200] Tariq Banuri. Modernatization and its Discontents: A Cultural Perspective on the Theories of Development. In Frédérique Apffel Marglin and Stephen A.

Marglin, editors, *Dominating Knowledge: Development, Culture, and Resistance*, pages 73–101. Clarendon Press, Oxford : New York, 1 edition edition, October 1990.

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

[202] Navin Sregantan. Singapore pips London, NY to top global smart city ranking. *The Strait Times*, March 2018.

[203] Abigail Francisco, Neda Mohammadi, and John E. Taylor. Smart City Digital Twin–Enabled Energy Management: Toward Real-Time Urban Building Energy Benchmarking. *Journal of Management in Engineering*, 36(2):04019045, March 2020.

[204] Timo Ruohomäki, Enni Airaksinen, Petteri Huuska, Outi Kesäniemi, Mikko Martikka, and Jarmo Suomisto. Smart City Platform Enabling Digital Twin. In *2018 International Conference on Intelligent Systems (IS)*, pages 155–161, September 2018.

[205] Gabey Goh. Building Singapore's 'digital twin'. *Digital News Asia*, 2015(September 15), 2015.

[206] Enric Volante. Navajos Upset After Ashes Sent To Moon; Nasa Apologizes | The Spokesman-Review. *The Spokesman-Review*, January 1998.

[207] Dian Nostikasari. Representations of everyday travel experiences: Case study of the Dallas-Fort Worth Metropolitan Area. *Transport Policy*, 44:96–107, November 2015.

[208] 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.

[209] 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.

[210] 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.

[211] Sanjay Reddy and Antoine Heuty. Global Development Goals: The Folly of Technocratic Pretensions. *Development Policy Review*, 26(1):5–28, 2008.

[212] 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.

[213] Dr Thorsten Wiechmann. Errors Expected — Aligning Urban Strategy with Demographic Uncertainty in Shrinking Cities. *International Planning Studies*, 13(4):431–446, November 2008.

[214] Steve Bankes. Exploratory Modeling for Policy Analysis. *Operations Research*, 41(3):435–449, June 1993.

[215] Pierre Wack. Scenarios: Shooting the Rapids. *Harvard Business Review*, November 1985.

[216] 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.

[217] Robert Goodspeed. The Death and Life of Collaborative Planning Theory. *Urban Planning*, 1(4):1–5, November 2016.

[218] 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.

[219] John Dewey. *Human Nature and Conduct: An Introduction to Social Psychology*. Cosimo Classics, New York, N.Y, March 2007.

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

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

[222] 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.

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

[224] 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.

[225] 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.

[226] Jeremy W. Crampton. Maps as social constructions: Power, communication and visualization. *Progress in Human Geography*, 25(2):235–252, June 2001.