AN EXAMINATION OF THE APPLICATION OF EXPERT ELICITATION AND VALUE TREE ANALYSIS AS A NOVEL DECISION SUPPORT APPROACH TO AN EARTH OBSERVING ENTERPRISE

by

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Abstract

AN EXAMINATION OF THE APPLICATION OF EXPERT ELICITATION AND VALUE TREE ANALYSIS AS A NOVEL DECISION SUPPORT APPROACH TO AN EARTH OBSERVING ENTERPRISE

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This paper analyzes a newly implemented multi-objective decision analysis (MODA) approach to assess Earth observing (EO) capabilities relied upon across the federal government. The approach develops an enterprise portfolio through value tree development with strategic and managerial input, coupled with expert elicitation at a practitioner level. The study investigates the principles of the analytic method, documents the application of the approach across federal agencies, and examines the utility and extent of the decision support analyses created from the collected data to determine the approach's ability to support analysis and inform the decision-making of the EO enterprise. The process is found to obtain a unique breadth and depth of information in a timely manner to facilitate portfolio management from high level, multi-billion dollar budget management decisions. In addition, it provides detailed analyses of communities of use at a product level. It is underpinned by the use of proven expert

elicitation techniques and subject matter expert judgment. It transparently translates a previously disconnected, vast set of knowledge into an aggregated and actionable quantitative assessment and has evolved to influence various levels of policy. It assists the National Oceanic and Atmospheric Administration (NOAA) and the United States Geological Survey's (USGS) decision-making processes and informed the White House Office of Science and Technology Policy's (OSTP) 2014 National Plan on Civil Earth Observations. Though expert analysts, multiple tools, and many subject matter experts are needed to create analyses for decision makers, this approach offers an effective process to define, portray, and visualize the complexity and connectedness of a large-scale technological sector, such as EO capabilities.

Chapter 1

Introduction

The United States federal government invests over three billion dollars annually in Earth observing (EO) data sources to measure, monitor, and expand understanding of the condition of the planet[1]. From calculating land use changes through decades of satellite imagery, to documenting extreme flooding events with streamgage networks, to assessing air quality with a variety of remote and ground sensors, EO data provides essential information for countless management and policy decisions. These decisions range across a broad spectrum of inter-disciplinary research and operational applications including real-time emergency response to millennia-long climate pattern investigations. The technologies, though complex and costly, offer an estimated annual $30 billion return on investment[1,2]. Can this wide-ranging portfolio be integrated and synthesized in a method to aid data-driven decision-making?

Given the criticality of the portfolio of instruments and data used by the United States, understanding how to best manage needed capabilities, inform future investments, recognize redundancies, and assist in multi-year planning quickly transforms into a complex system of interdependencies, priorities, and alternatives. To maintain the integrity of the intricacy of knowledge and provide high level insight, multi-objective decision analysis (MODA) techniques have developed and expanded to facilitate nuanced and multi-dimensional decision-making processes. MODA is a set of practices intended to aid decision makers when the decisions contain complicated, sometimes contradicting, requirements, with multi-faceted attributes. There is a growing set of literature illustrating MODA methods distilling and modeling diverse types of problems. Over the last twenty years, use of MODA has expanded and weaved into fields ranging from nuclear energy to environmental sustainability to public health initiatives[3–12]. With the expansion of data analytics, increased computing capacity, and the rise of sophisticated algorithms, not only can additional and higher resolution EO data products be processed, but different data types can easily be combined to create powerful models and analyses. A weather model can ingest tens of data sources derived from a variety of EO systems including satellites, ground stations, radars, and human observers. In this increasingly complex system of observations, many data sources are used not only for their primary use or by their primary funding entity, but also in innovative products in unintended fields of application, such as using weather radar to track and identify migratory birds[13].

For the purposes of analysis, an EO data source includes "one or more sensing elements that directly or indirectly collect observations of the Earth, measure environmental parameters, or survey biological or other Earth resources (land surface, biosphere, solid Earth, atmosphere, and oceans). Sensing elements may be deployed as individual sensors or in constellations of networks, and may include instrumentation or human elements. Observing system platforms may be mobile or fixed and are space-based, airborne, terrestrial, freshwater, or marine-based"[14] (4). Sources encompass point data to global coverage fields and span varying measures of temporal frequency.

In this research, each section will address a specific objective, described below. Section 1 will analyze the strengths and weaknesses of the expert elicitation, framework of the value tree, modeling tools, and verification procedures. Section 2 will examine the progression and extent of this application. Section 3 will assess the utility of the analyses available to decision makers using this technique in the EO domain. Section 4 will review future considerations and next steps, and Section 5 will provide concluding remarks. The results and discussion within each of the objectives are contained in each section.

Hypothesis

Does this newly applied approach have the ability to integrate and synthesize the EO enterprise to support data-driven analyses and inform decision-making? This study expected to find the approach a fundamentally sound and analytically beneficial technique for decision makers with a capacity to influence policy, not only in the EO realm, but also in other, unexplored fields.

Objectives

To assess the effectiveness of this approach, the following objectives will be accomplished in this research:

- Compare the data collection methods to the well-established, foundational decision analysis tenets. This will highlight the benefits and limitations of this MODA technique in representing the utility of individual EO sources across an enterprise.

- Document how the information has been leveraged in current applications and policy.
- Evaluate the effectiveness of analyses and tools to disseminate results and answer business intelligence questions.
- Identify potential growth areas for the process.

Methods

This study is the first to comprehensively investigate the impact of this technique on current policy, the value of the approach in EO decision-making analyses, and its extensibility to other application areas. To achieve this, the study contrasted literature documenting best practices of expert elicitation and value trees to the process execution. The author also aggregated hundreds of subject matter expert (SME) interviews of experts using EO data in their respective fields to understand the scope of use, along with strengths, areas of improvement, and future developments. The author gathered published and unpublished federal reports to establish a full timeline, a record of agency participation, and the policy contribution. The author's participation in the implementation of this technique with federal agencies provided insight into the utilization of data by decision makers. In addition, the author executed the end-to-end approach to create examples of data analysis. The resulting analyses provided a method to evaluate the technique's ability to answer common business intelligence questions. The author used all tools identified in the process, including Portfolio Analysis Machine (PALMA™), developed for the U.S. Government by The MITRE Corporation[15], Microsoft Excel, and Tableau to implement the studied technique. After reviewing current policy impacts, the author also addressed potential new domains of expansion.

Section 1: Value Tree and Expert Elicitation Information

The examined MODA approach uses a combination of expert elicitation and structured value tree development to create an enterprise portfolio. The information is then modeled into a quantitative impact assessment. Here, the study evaluates if the value tree structure provides meaning to decision makers and if the approach incorporates expert elicitation tenets.

Value Tree Structure

A value tree is a hierarchical design that establishes a linkage from a top objective or priority down through individual capabilities **(**Figure 1**)**. The structure demonstrates the incremental benefit of an individual capability, in this study an EO data source, by tracing its impact on each node of the value tree and aggregating the value at the top node of the tree. A value tree structure introduces flexibility, reusability, and connectivity for policy makers. The top of the tree can be defined in many frameworks (Figure 2). From an organizational perspective, this may be an entire agency broken down by department or program. A value tree may also be constructed from an integrated, cross-cutting strategic perspective. The USGS has utilized both views. Flexibility extends outside of organization constructs into trees developed around communities of interest and the Earth Observations Assessment (EOA) framework of societal benefit areas (SBAs)[16] (Figure 3). With each of these frameworks, the same set of expert elicitation data can be reused because the collection method is divided into two facets. This increases the utility and types of analyses possible and minimizes the engagement time needed with SMEs.

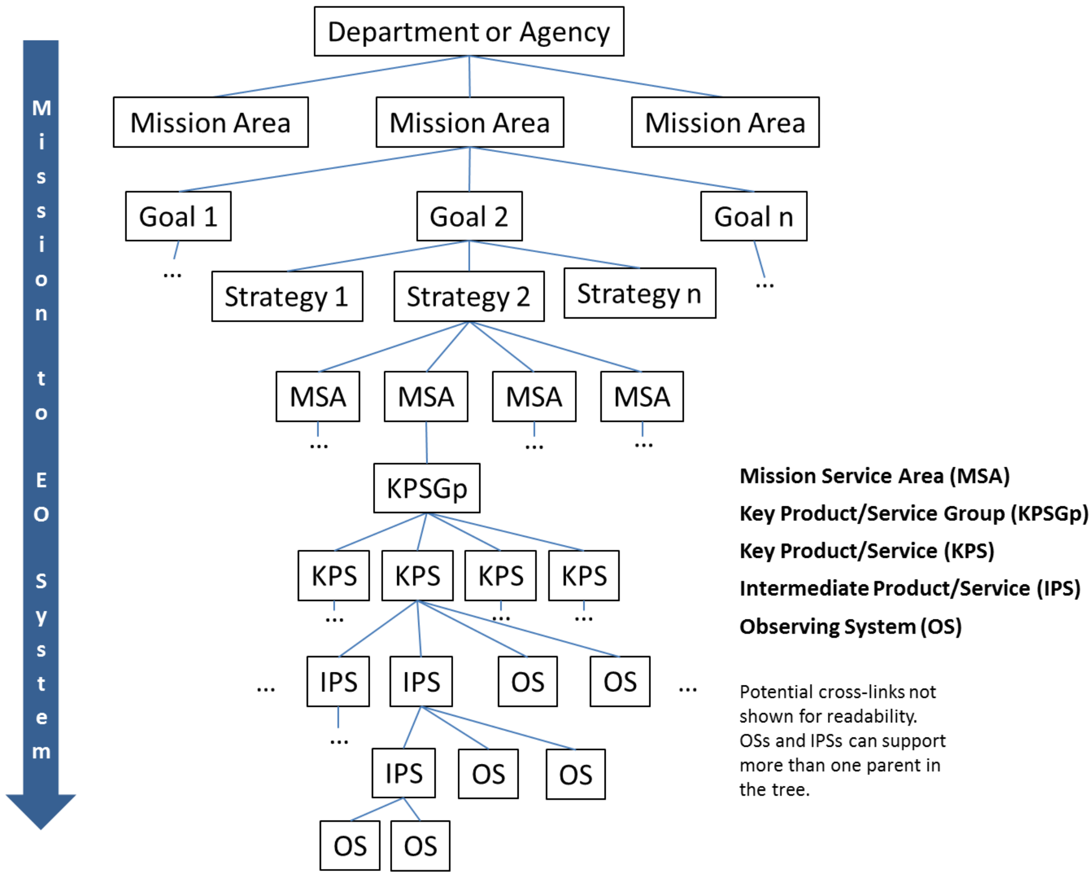


Figure 1. Example value tree demonstrating connectivity from strategic top of tree down to Earth observing systems

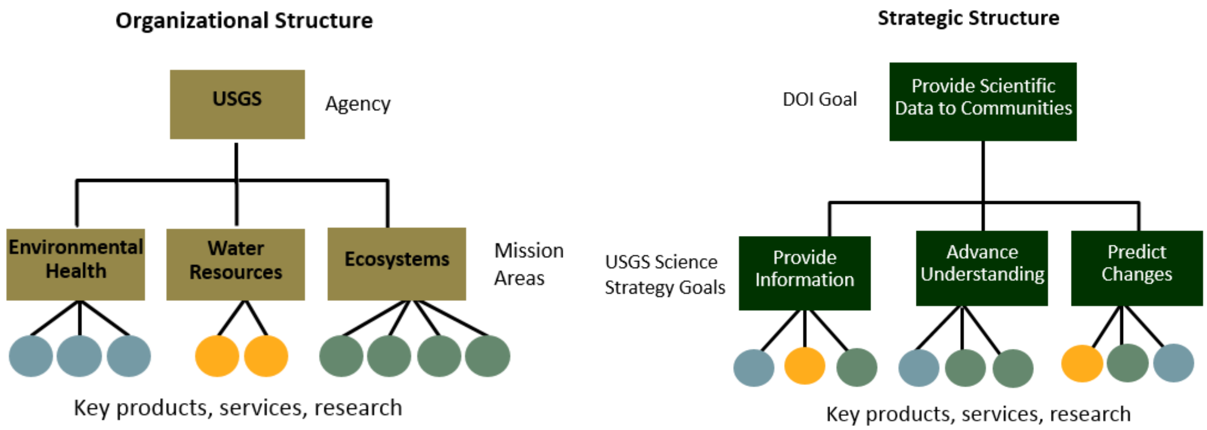


Figure 2. Organizational and strategic value tree framework flexibility using the same key products using the U.S. Geological Survey (USGS) and the Department of Interior (DOI) as examples[17]

Figure 3. Thirteen Societal Benefit Areas from Earth Observation Assessment (EOA)[16]

Distinct from other decision support techniques where the same set of SMEs are used throughout the data collection process, this approach divides the development of the top of the value tree from the EO data collection. For the top of the value tree structure, senior leadership and upper management focus on strategic objectives to determine which framework and levels to build. They identify the key products that contribute to achieve the programmatic or strategic objectives outlined in the tree. Management also establishes priorities through the common multi-attribute utility theory practice of weighted averages across each level of the tree[18,19]. One technique used to obtain a weighted average consensus with anonymity is the Simple Multi-Attribute Rating Technique Exploiting Ranks (SMARTER) technique, where individual surveys are filled out and review for final adjustments occurs as a group[20]. Once fully defined and weighted, the elicitors contact the SME practitioners directly creating the identified key products. The limitation of this approach is the requirement of a broad number of SMEs to complete a full value tree model. In addition, potential missing priorities may not be recognized if not in the purview of the identified SMEs. The study finds much time and support from SMEs and correct identification of the appropriate personnel at all levels of an organization is needed for a robust and accurate value tree. If such endorsement is possible, this separated top-down development and bottom-up data collection minimizes potential biases and elicits expert judgment from the most applicable communities; technical SMEs are not expected to evaluate their work in the context of management significance and managers are not expected to appraise the technical utility of a data source in a specific product.

Expert Elicitation

The structured process of expert elicitation emerged after World War II as a way to leverage expert opinion for decision and policy makers[21]. In recent years, there is amplified interest in expert elicitation as the complexity of environmental interactions, technological advancements, and socioeconomic development leads to exigent issues filled with uncertainty. This resurgence parallels the growing MODA field. Since the 1990s, the process increased prevalence in literature six-fold in environmental applications alone[22]. Expert elicitation is defined as

> "*a systematic process of formalizing and quantifying, typically in probabilistic terms, expert judgments about uncertain quantities. The expert elicitation process may involve integrating empirical data with scientific judgment, and identifying a range of possible outcomes and likelihoods. An important part of the EE process includes documentation of the underlying thought processes of the experts. Expert elicitation is a multi-disciplinary process that can inform decision-making by characterizing uncertainty and filling data gaps where traditional scientific research is not feasible or data are not yet available. If performed using appropriate methods and quality standards, including peer review and transparency, EE can be a reliable component of sound science* [23]" (1).

It is primarily used in situations where objective, full-scale analyses are not feasible or not reasonable in the expected timeframe. This includes estimating parameters of rare and complicated phenomena and forecasting future events[24]. In the case of constructing an EO portfolio, expert elicitation is used to integrate large amounts of previously undocumented qualitative and quantitative data from SMEs. While this approach leverages expert judgment, it should be noted this analysis could theoretically be completed through a fully objective evaluation. However, the trade-off to complete an assessment of the desired scope is time intensive and cost prohibitive. To gather all the required data and specifications on hundreds of EO data sources, along with their individual impact on thousands of key products would yield costly, ineffective, and out-of-date results for decision makers. For the purposes of EO analysis, relying on expert elicitation best practices is an appropriate method of data collection.

This research finds caution must be applied as many attributes of an elicitation may affect a SME's answer, even though it is an accepted form of collecting subjective expert judgment. Motivational and cognitive biases such as group think, overconfidence, wishful thinking, and anchoring can creep into expert elicitation interviews[21,25]. The examined process does attempt to mitigate these biases from entering a data collection session. SMEs in their particular area of expertise are identified by program managers, ensuring the proper individuals are included in the interview process. Elicitors interview more than one expert about a specific key product whenever possible. This is beneficial to gain a more representative view of the subject as it collects multiple views, reaches a consensus perspective, and eliminates the need to formulate an algorithm to merge multiple individual judgments on a single key product. However, group dynamics can introduce other biases depending on the relationships between members of the group. Elicitors must act as mediators to confirm every participant in the room can voice their opinion for an effective data collection. This can be difficult if one person is more vocal than others or there are individuals of varying levels of authority on the same interview. One strength of this approach is that each meeting begins with an explicit explanation of how to avoid potential biases during the session. Rather than written or survey form data collection, all SME interviews used in this study were conducted via face to face meetings or teleconference with audio and visual technology. This format leads to less process and misunderstanding errors in the data; however, it is more time consuming when gathering large amounts of data. Also, because of the desire for multiple individual's inputs, this procedure is known to facilitate discussion best[25]. Outside of SME implicit bias, bias from the within elicitation team can occur. To minimize this, the process trains a small group of elicitors familiar with EO data sources to conduct interviews with similar explanations and terminology to facilitate consistent data collection and interpretation. In addition, multiple members of the elicitation team attend each interview, to capture notes and reinforce consistency.

Performance / Satisfaction Scale		
100	Ideal	Meets all requirements and exceeds some
90	Fully Satisfied	Meets all requirements
80	Good	Meets all major requirements with minor limitations
70		
60	Fair	Meets most major requirements, with significant limitations
50		
40	Poor	Fails to meet many major requirements, but provides some value
30		
20	Very Poor	Fails to meet most major requirements, but provides minor value
10		
1	No Capability	Provides no value

Figure 4. Standardized Performance Satisfaction Scale used throughout expert elicitation

The focus of the SME interview concentrates on translating subjective knowledge into a quantitative score using the standardized numerical scale (Figure 4**)**. Using this scale, SMEs issue three primary scores. First, they rate the current status of their overall product, known as the Status Quo Score. Minimum and maximum scoring is offered to avoid anchoring of this initial mark. Secondly, the elicitors use a swing weighting technique to evaluate the relative impact of all EO data sources used to produce the key product. This exhibits awareness of Miller's demonstration of the human mind to be able only to compare seven attributes, plus or minus two[26]. Swing weighting is a proven MODA expert elicitation technique[27,28]. Rather than focusing solely on importance, swing weighting generates quantitative estimates of both criticality and variability of each EO data source to the product. Swing weighting for the impact of EO data involves asking the SME for an alternative product performance score if all data sources except one source are available. The difference in the newly assigned performance score from the original score is an indication of relative impact. Swing weighting only occurs for data sources the SME interacts with directly to prevent speculation about data products and EO systems. If a SME uses a derived dataset, such as a land cover map, they evaluate the impact of the land cover map only, not the components of the land cover map. The elicitors then contact the producer of the land cover map and initiate the same data collection technique to gather an accurate appraisal of the data sources used in the land cover map. This method of decomposition continues until all branches reach direct EO data sources, such as satellites sensors. Thirdly, a satisfaction score of each data source based on its role in the product is recorded. This differs from the swing weight score because it is independent of impact. A data source with low impact may perform well for its needed function. Thus, it receives a small swing weighted difference, but high satisfaction score. Unlike the Delphi Technique[29], where judgments are often intended for forecasting, all judgments measured are based on a current snapshot of use to minimize uncertainty. A detailed description of the data collection approach applied is documented in the NOSIA Methodology Report[30].

Value Tree Model and Verification

To integrate the top of the value tree with all the dimensions of the expert elicitation data, value tree modeling occurs with the multi-attribute decision support software tool, Portfolio Analysis Machine (PALMA™), developed for the U.S. Government by The MITRE Corporation[15]. PALMA has been used in multiple fields including Department of Defense (DoD) agencies, but this is the first application specifically for EO portfolio analysis[31]. PALMA can model traditional weighting and aggregation techniques, as seen in Analytic Hierarchy Process (AHP) and the top of the tree structure. Also, it exhibits the capacity to incorporate non-linear response curves into analyses[7,10,32]. The software employs an exponentially-based function to appropriately demonstrate the range of functionality needed. This fits the non-linearity and nuanced dependencies of the SMEs' scores. However, the graphical user interface of the software is unwieldy and does not have the functionality needed to succinctly navigate through large datasets. Trained modelers or analysts are needed to create and synthesize the data into easily digestible, decision-ready analyses. Alternative tools used to overcome these limitations will be discussed in Section 4. To ensure the model correctly represents the needs of the SMEs, the elicitation team generates an individual impact assessment for each product. The results are presented back to the SMEs for verification that the numerical outputs of the model embody their judgment and match the information they explained during the data collection.

Overall, the value tree structure and implementation lead to a strong top-down directed, but bottom-up collected dataset. Previously fragmented, unsynthesized, and unstandardized data becomes structured with traceable branches of EO incremental impact. Gathering data and verifying results through a controlled feedback process at the bottom levels of the tree, while employing the correct SMEs at each level, leads to confident estimates of impact when aggregated together[33]. Given the restriction of timely information, the choice of expert elicitation is suitable and the process relies on many best practices of the field. The team trades the anonymity and large group consensus of the Delphi technique and written questionnaires for mediated interviews and structured data collections. Although the weakness of lack of anonymity introduces similar biases to expert elicitation, the choice minimizes interpretation errors and allows for the addition of qualitative data through notes. These recorded notes add significant depth to the portfolio by demonstrating the rationale for scoring, such as data limitations or ideal improvement, and are frequently used to augment analyses.

Section 2: Evolution of the Process

The decentralized role of research and development across many federal agencies and many federal discretionary spending appropriations bills adds to the complexity of large-scale science and technology policy and planning in the U.S. Individual agency funding and allocations vary in each appropriation bill, though budget bills pass through mission-oriented channels[34]. Setting national science and technology priorities in a cross-cutting, multi-agency way presents a challenge with limited coordinating mechanisms. This is relevant to EO systems as many involve long-term mission planning and funding to ensure continuity of measurements, advancements in sensors, and sufficient funding for the entire life cycle of the technology. Adopting a process to consistently and accurately characterize the dynamics of the EO portfolio provides policy makers with data-driven analyses to remove typical funding silos and display the integrated nature of technology. This section explores if the value tree and expert elicitation approach has garnered the needed support over its evolution (Figure 5) to impact policy planning.

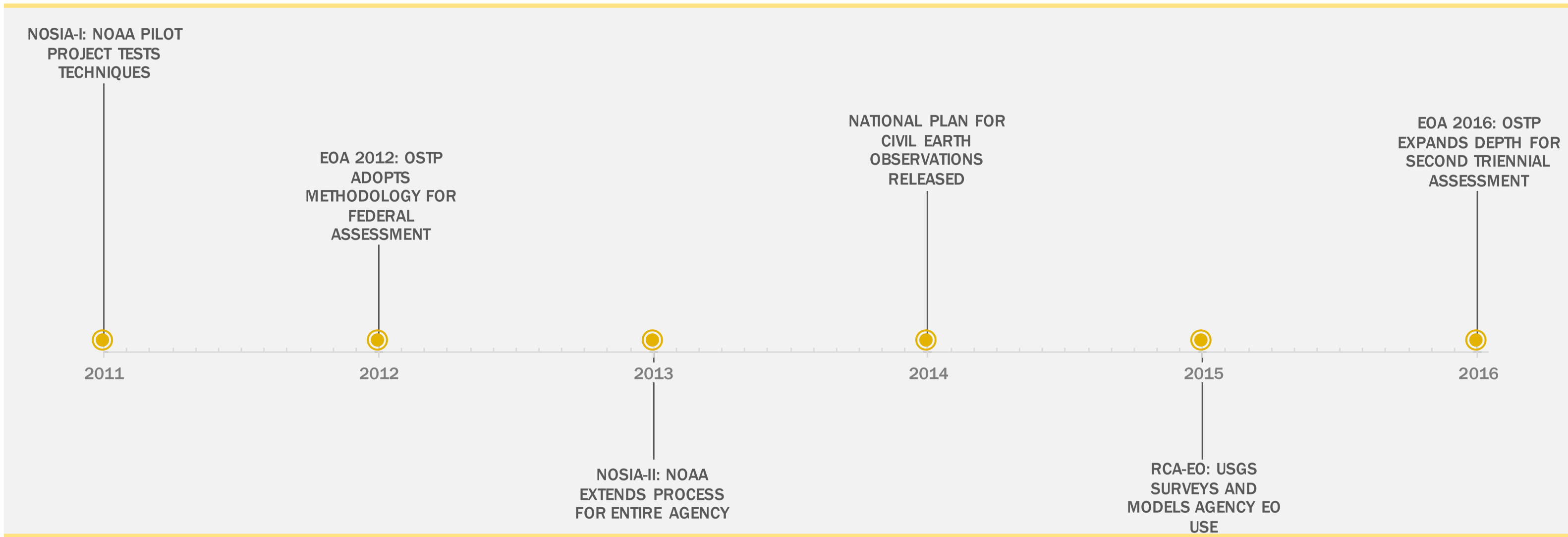


Figure 5. Timeline displaying use of the examined approach across government agencies over time

Over the past six years, this decision support technique evolved in scope, as well as visibility. Applied to the novel field of EO capabilities, it initiated in 2011 as a proof of concept project within NOAA. The outcomes possessed little decision-making influence, but exhibited the managerial prospects to analyze a dynamic, multi-billion dollar technology enterprise. It resulted in the NOAA Observing System Council (NOSC) directing the funding of a full assessment for the entire agency, called NOAA's Observing System Integrated Analysis (NOSIA-II)[35]. By engaging hundreds of scientists and involving multiple levels of management to construct the agency value tree, this technique built credibility within NOAA and is now creating analyses to inform internal decisions through a formalized process in the Technology, Planning and Integration for Observation (TPIO) Office. This support ranges from budget proposals, return on investment portfolio analyses, the satisfaction of observing systems, analysis of alternatives, and future architectures studies. As stated on their website,

> *"NOAA Observing System Integrated Analysis (NOSIA-II) is a capability used to document the relationship between available observing systems and their impact on NOAA's diverse services and scientific objectives. Understanding the relationship between the cost of available data sources and their impact on mission outcomes is fundamental to informing current and future observing system investments and managing NOAA's observing system architecture* [35]*."*

Prior to NOSIA-II, no single NOAA capability existed to assess the integrated impact of individual EO data sources to the diversity of NOAA missions and mandates.

The success of the process led to its use in the first National Earth Observations Assessment (EOA 2012), under the direction of the White House Office of Science and Technology Policy (OSTP). EOA 2012 was conducted in response to the NASA Act of Authorization of 2010 by Congress to provide a triennially updated strategic implementation plan to "ensure greater coordination of the research, operations, and activities relating to civilian Earth observation[14](28)." EOA 2012 marked the first use of a value tree model on a multi-agency, federal enterprise level. Uniquely creating a value tree framework outside of agency boundaries, EOA 2012 instead functioned through 13 cross-cutting Societal Benefit Areas[16] comprised of key products supported by multiple federal agencies. The overall assessment demonstrated federal reliance of EO data sources through integrated societal benefit, rather than agency-specific objectives. EOA 2012 was used by OSTP and the Office of Management and Budget (OMB) to inform the federal budget and was a foundational element of the first National Plan for Civil Earth Observations, published in 2014. This report highlighted 145 high impact EO systems[16].

EOA 2012 catalyzed the USGS Land Remote Sensing Program (LRSP) to develop a value tree approach to better understand EO capabilities within their agency. Following a pilot project focused on a small set of key products, LRSP expanded the effort to create an agency-wide value tree covering 24 programs and over 450 research areas in a framework aligned to the DOI Strategic Plan[17]. USGS is currently using this value tree information to broaden its understanding of the users and uses of EO technologies, as will be discussed further in Section 4.

Development of the second National Earth Observation Assessment (EOA 2016) again sought the value tree-based technique to assist in determining the impacts of EO data across the federal enterprise. Spanning a diverse range of societal needs, EOA 2016 integrated the contributions of hundreds of disparate EO data sources, from ships to satellites, to surface networks, to aircraft, culminating in over 1300 data sources, a list over four times more comprehensive than EOA 2012. Technical advancements in data collection and value tree modeling allowed the efficient collection of data on 2400 information products from 36 different federal agencies, 3000 SME interviews with thousands of years of combined experience, and a value tree model of over 53000 nodes, over 10 times the size of EOA 2012[36]. This application of the value tree model is one of the largest uses of the software program PALMA.

This approach started as a small, program-focused endeavor, but its utility in the EO arena led to much larger applications. A strength of the approach allows decision support analysts to view utility of systems, missions, and products outside of typical funding hierarchies. EOA 2012 embraced this capability and brought the value tree decision support technique to a multi-agency, national policy level. Such exposure and insight into its utility continued to cement the approach's role in other federal agencies. The technique has yet to be applied to international interests, though such extension is plausible and will be discussed in Section 5.

This approach has successfully obtained increasing acceptance across federal agencies since its inception in EO application. Its ability to deliver information of value provides federal agencies with opportunities to better understand the multi-purpose nature of their EO capabilities and stakeholder communities. It enabled national priorities and actions to be established through the National Plan for Civil Earth Observations. In addition, analysis of this data has resulted in cross-program coordination, a data-driven evidence base for continuation of high priority EO systems, as well as better characterization of users and user needs.

Section 3: Analysis and Decision-Making Utility

On a broad scale, this technique follows the four steps of the analytic process: Data, Analysis, Insight, and Action[37]. It can assist in budget allocation and review, mission or program justification, redundancies and dependencies, the architecture of future systems, and multi-year planning. Data-driven decision making has proven to increase performance and productivity of businesses implementing business intelligence techniques into their decision processes[38]. This multi-dimensional value tree dataset provides many analyses and visualization of information to decision makers regarding gaps, alternatives, strategic investment, societal benefit value, and communities of use. Herein, the utility of the most common analyses are assessed.

Relative Impact Assessments

The primary output of this value tree technique creates a portfolio of the relative impact of all EO capabilities. The results can be displayed in a straightforward 1 to n ranked list of the relative impact of each data source providing benefit to the value tree and has been used by NOAA, USGS, and EOA (Table 1). New insights can be gleaned from cases where data sources appear higher in a ranking than expected. It allows an analyst to not only view the reliance on a data source at the top of the tree, but at any intermediate level, such as specific objective, program, or key product. Because of the standardized data collection, comparative use across programs or objectives is achievable, as seen in a target chart visualization (Figure 6). In addition to expressing impacts across objectives, in depth studies of all impacts on one or two products can be isolated (Figure 7). The strength of the value tree reports the reliance, linkages, and dependencies. Analysts can navigate any size value tree to pinpoint exactly where an impact of interest originated. For example, the ranking of an elevation data source within a weather safety objective may not be intuitive, but the model displays how elevation data supports an operational tropical cyclone warning embedded in many of the key products within the objective.

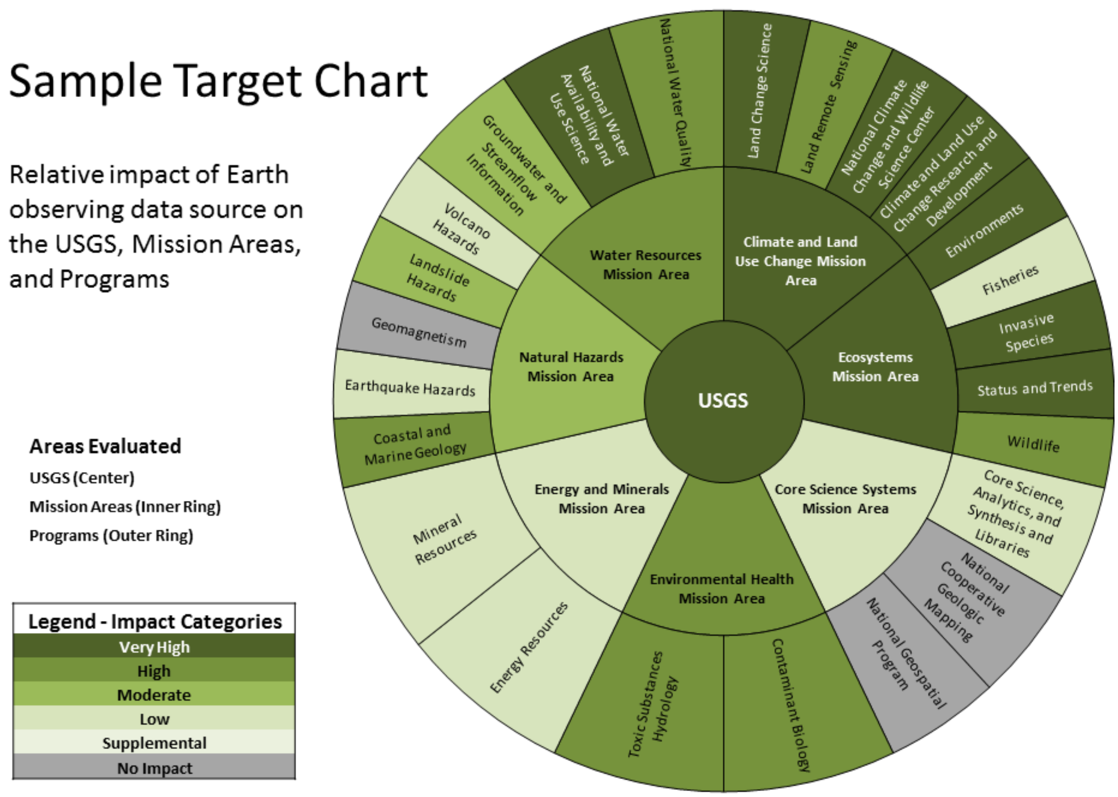


Figure 6. Notional example of visualization of impact of one Earth observing data source across various levels of an organizationally structured value tree

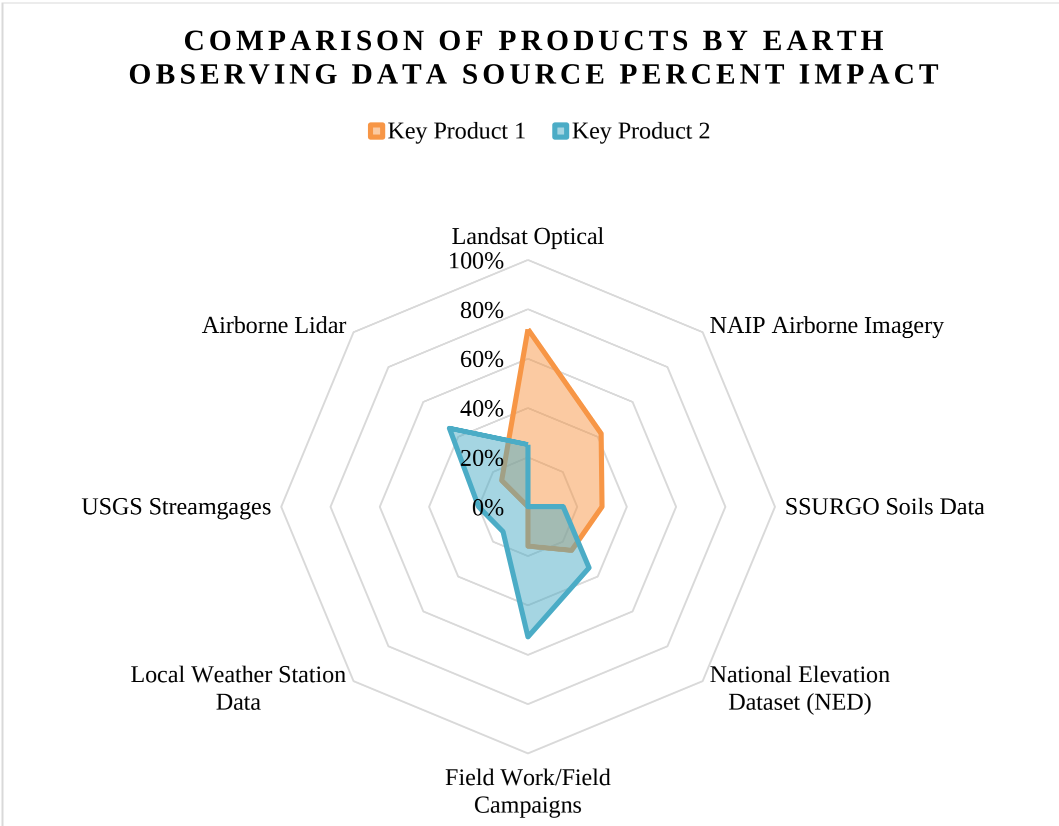


Figure 7. Comparison of the magnitude of the impact of each data source to two key products. Points in the outer rings represent higher impact percentage than the center rings. The graphic also illustrates unique data sources uses in notional key products (NAIP Airborne Imagery in Key Product 1 and USGS Streamgages in Key Product 2) and overlapping data sources with impact in both key products (Landsat Optical)

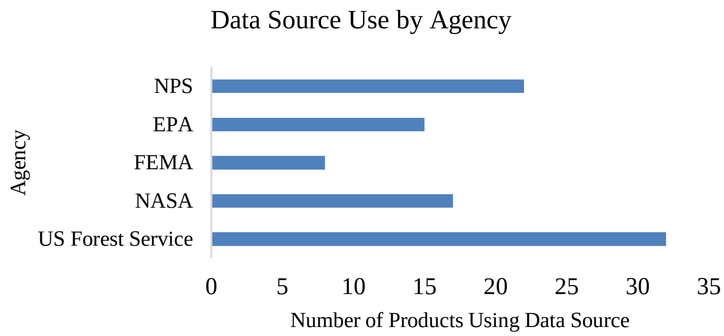
Table 1. Notional sample ranked list displaying relative percent impact of an Earth observing data source to a given value tree node

Notional Sample Value Tree Node of Interest	
Status Quo Score	68
Earth Observing Data Source	Percent Impact
Field Work/Field Campaigns	29%
National Elevation Dataset (NED)	11%
Landsat Optical	10%
National Agricultural Imagery Program (NAIP)	9%
State and Regional Mesonets	8%
USGS Streamgages	6%
USDA NRCS SNOwpack TELemetry (SNOTEL)	6%
Global Positioning System (GPS)	5%
NWS Cooperative Observer Program (COOP)	5%
Commercial Airborne Lidar	5%
Global Climate Observing System (GCOS) Surface Network (GSN)	4%
DMSP Special Sensor Microwave Imager Sounder (SSMIS)	2%
Next Generation Weather Radar (NEXRAD)	2%
Automated Surface Observing System (ASOS)	2%
Community Collaborative Rain, Hail and Snow Network (CoCoRAHS)	1%
Soil Climate Analysis Network (SCAN)	1%
Geostationary Operational Environmental Satellite (GOES) Imager	1%
Census of Agriculture Data	1%
Commercial High-Resolution Satellite Imagery - Quickbird	1%
Tropical Atmosphere Ocean (TAO) Project TAO/TRITON Array	1%

This process also generates capability-based and platform analyses. Scenarios are initiated by removing multiple data sources and measuring the overall impact of the loss of the entire group. This is applied to a group of similar measurements, such as all atmospheric sounders, or an entire satellite platform comprised of multiple sensors. In addition to relative impact, collected EO satisfaction scores present areas of improvement for data sources and are the starting point for gap analyses and analyses of alternatives.

Capabilities Usage Summaries

The value tree structure provides an agency the ability to map products and interests, not only in a traditional organizational framework, but also to use the same data in a cross-cutting, integrated strategic framework. The exercise of formatting a department's key products into a clear-cut configuration has been used by program managers in multiple federal agencies. Looking outside primary funding structures, the value tree allows producers to investigate where other users of their data or product may exist (Figure 8). This includes direct use, where SMEs assigned an overall satisfaction score and noted any limitations. Producers apply this information to better understand user needs to facilitate advancements in product design and development. It also identifies user communities that indirectly rely on an EO data source for a key product. This occurs when a downstream model or other derived product used by the key product relies on the EO data source of interest. For example, a habitat assessment ingests a land cover map and the land cover map consists of airborne imagery. In the value tree model, the airborne imagery will exhibit an indirect impact on the habitat assessment. In 2016, USGS utilized this technique to analyze the use of Landsat across the agency and discovered Landsat reliance across all seven of the agency's Mission Areas[1]. It can reveal communities of use and patterns of data reliance, such as the expanding and emerging uses of light detection and ranging (LIDAR) from digital elevation models to biomass estimates to aerosol clusters[39–41]. Often these users are outside of primary or intended application areas, as scientists find ways to incorporate new and available data to augment their work. Synthesizing and summarizing capability information can improve advocacy, bolster budget justification, advise future improvement for specific data types, and improve social capital by inviting groups to collaborate in new ways with a common interest.



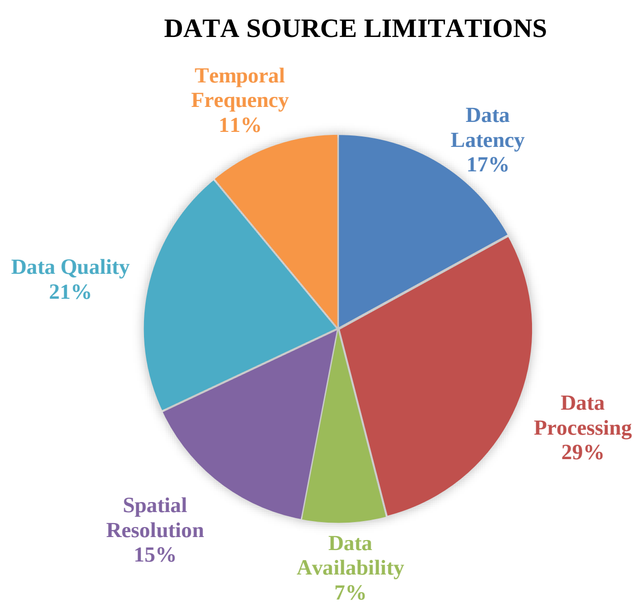


Figure 8. Notional example of summarized satisfaction information of a given Earth observing data source. Here, overall satisfaction scores and data limitations are aggregated and count of products are separated by agency.

Portfolio Management

How much will investment in improvements aid in reaching goal targets and mission outcomes? Where is the best avenue to place investment or identify unneeded redundancies within a system? Looking at a multi-year portfolio or architecture planning, where will the introduction and loss of data sources have the greatest impact? What are priority data sources and products and where are they being utilized? Information to answer these questions is garnered from the collected and modeled dataset and used by federal agencies.

This transparent and repeatable process is the first of its kind in the civil EO portfolio domain to be readily updated and maintained, leading to reliable and current management assistance[16]. Rather than one-time trade studies or anecdotal information to propel decisions, this data format provides a way to analyze alternatives effectively. The value tree allows for scalable data discovery, from delving data source by data source to objective by objective, and also determines the most effective combination of sources in multiple programs or goals in a tradespace. A decision maker can glean business analysis information with the combination of relative impact and overall satisfaction score of an EO data source. High impact scores, but low performance scores indicate a potential area of investment for improvement and gaps in capability, whereas high impact and high performance may point to the need to ensure continuity of a critical data source. From an economic perspective, this data and accompanying analyses provide an effective utility analysis across a range of decision options[42]. Studies to determine where capabilities currently exist and where deficiencies reside are a routine capacity of the data. These impact evaluations have been combined with cost information to perform cost-benefit analyses and portfolio optimization to recommend actionable budget and spending choices. Because the data is reused in multiple value tree structures, agencies map key products into traditional hierarchies and strategic perspectives outside of conventional budget pipelines to gain insight into EO use and connectivity within the portfolio.

Visualization Tools

A variety of visualization methods and tools present this information in a digestible way for analysts and non-analysts. The examples included in this paper are portrayals of the data created using Microsoft Office Excel and PALMA software. A number of other tools, not shown here, have been integrated with the value tree model, including known uses of Tableau, SEMOSS, R Studio, and the collapsible tree tool in D3. Pertinent visualizations are intended to be iterative constructions between decision makers and analysts, as the data can inform many relevant studies depending on a decision maker’s need. While the means of providing a quantitative analyses is the same for each application as described in Section 2, the decision-making challenges of each organization vary. A limitation of this dataset is the nuance of the raw analysis outputs. An analyst familiar with the data is required to craft effective reports.

This data is currently used both on a federal planning level and within agency programs to understand what and where EO data is used along with its strengths and limitations. This approach highlights the integrated nature of EO information and its use across agencies and disciplines, aiding in advocacy within known areas of use and justification for cross-area benefits. It also offers a tangible communication link between data users and data producers.

This multi-step procedure provides unprecedented breadth and depth of information for the U.S. federal government's EO portfolio. The large dataset collected and assembled in a defensible and transparent process can answer pertinent business and policy inquiries. Substantive analyses are used across management levels, from scientists uncovering which established systems and products they may be able to leverage, to program managers advocating for high utilization data sources, to strategic planners informing future investments and system designs. All of this information is a critical element of data-driven federal policy on the civil applications of EO data.

Section 4: Next Steps and Future Applications

In addition to U.S. EO portfolios, this business analytics capability can apply to other sectors, such as international arenas, energy policy, or infrastructure decision-making. While PALMA and MODA techniques have been employed in a variety of studies, this combination of value tree development and expert elicitation has been limited in its topic EO application. Extension from EO system analysis to broader science and technology or research and development strategic investment analysis needs little adaptation. The current technique fuses scientific data with both system performance and user utility. Applying this to a research division or emerging technology field, such as the United Kingdom strategy for data capability[43], would rely on similar expertise and verification methods. Current analysis products generate information useful to such portfolio applications.

To extend into energy policy, this decision support tool could provide a view into the priorities of a diverse energy portfolio mix and link technologies and stakeholders to governmental strategic energy policy goals. The value tree could aid in identifying how a government balances the energy security, environmental issues, and economics of their energy profile at the top of the tree; and from the bottom-up, collect data to understand the impacts of different objectives and technologies in meeting goals.

For example, though Morocco is a leader in energy policy as a developing nation, it faces obstacles in its long-term economic and process framework for sustained and reliable energy policy optimization[44]. This approach could provide a view to gain insight into Morocco's energy portfolio mix and link technologies and stakeholders to governmental strategic energy policy goals. The value tree can aid in understanding the impacts of different players (e.g. operator requirements compared to consumer needs) and technologies in meeting different goals, as well as identifying how the Moroccan government balances the energy security, environmental issues, and economics of their energy profile. Currently, an unbalanced weight toward energy security and environmental initiatives appears to maintain precedent, but could be quantitatively documented with this process. It could also mitigate against unneeded policy and process complications from the many internal discrepancies of chains of responsibilities arising from the propagation of governmental agencies and international partnerships through the traceability of the value tree. Engaging different stakeholder communities including private and state-owned utilities, industry, local residential consumers, along with governmental and partnership agencies, could provide true awareness, rather than perception, of needs in each area. Integration of all areas could deliver powerful information about shared interests or unique value provisioning. This can assist in policy advocacy or new relationships with previously unconnected stakeholders. In addition, by parsing through stakeholder requirements, including quantitative technical expertise and more qualitative factors, clearer lines for determining roles of authority and budgetary investments may appear. Expert elicitation can also provide benefits by collecting more than survey data and bottom-line economic information. It coherently and systematically recognizes the distinct context and geography of the greatly varying stakeholder needs and can serve as a baseline for future assessments.

An analyst can run different hypothetical scenarios, such as if all three priorities are given equal weight or if one priority is weighted more heavily with the flexibility of the value tree structure. It also provides an explicit manner in which to quantify environmental concerns and other uncertainty costs. Unlike the U.S., where environmental priorities often fall lower than the other two, Morocco faces economic ambiguity, as its natural resources are the more costly renewables[45]. If cost information is available, benefit-cost trade-offs can be examined in detail at every level of the country's energy portfolio. By incorporating known budgets and projected costs, estimates reflecting the impact on stakeholders and strategic goals can be traced through to view situations where a given technology is lost or bolstered. This type of analysis can facilitate discussions of short-term versus long-term investments by recognizing conflicting stakeholder goals and acknowledging potential constraining factors, such as redirecting funds to new technologies like small nuclear or hydro-wind versus increasing grid efficiency.

There are multiple ways to use decision support tools to understand the priorities within an energy profile, and with this information value tree analysis can directly affect the associated politics and policy. It can help tease apart which gaps need to be filled and which agency may be best able to handle responsibilities within the plethora of players in Morocco's list of stakeholders and its current lack of defined regulation[44]. For example, enforcement of safety regulations should fall under the Ministry of Interior or ADEREE (Agence Nationale pour le Développement des Energies Renouvelables et de l'Efficacité Energétique'), as to prevent the conflict of placing both roles of operator and safety manager solely within the commercial utility sector. In addition, when viewing the entire integration of an energy enterprise, recognizing the process of timing of investments may be needed. Understanding the scientific foundation of a technology life cycle and its many attributes is critical to producing comprehensive and relevant policy, especially in Morocco as it diversifies its energy portfolio to novel sources, both in terms of technology and policy[44,45]. Multi-attribute decision-making utilization can aid in the participation and understanding of stakeholder needs, the analysis of alternative scenarios and priorities, and the design of new energy policies and processes moving forward.

Value tree information is focused on current capabilities and technology. Continued maintenance increases its utility as it can be used as baseline data for future evaluations. As new data sources and sensors come online, the model can be updated with new technology options. However, as elicitors ask experts for evaluation of current data sources, the unmet needs and future requirements captured in the qualitative notes have no bearing on the quantitative modeling. As qualitative data can be used as evidence in business intelligence methods[46], finding ways to mine this gathered data is an area of prospective growth. Looking to the future, documentation should move beyond current use to creating truly 'technology agnostic' requirements. Requirements detail which environmental parameter users are trying to measure, rather than the existing capabilities they are using. By remaining independent of specific technology, long-term requirements remain in place, even as the landscape of existing technology changes. Datasets with this type of requirement information can further facilitate strategic planning of future technology advances. For example, the USGS is currently capturing moderate resolution land imaging requirements to inform the development of the Landsat 9 follow-on mission as part of the USGS/NASA Sustainable Land Imaging program. USGS leverages value tree information to identify areas for requirements collection across multiple agencies, including application areas such as agriculture, land cover change, cryosphere, fire hazards, water quality, etc. Searching for appropriate areas of engagement would be more time-consuming and less representative without the value tree information.

Section 5: Conclusion

As technology and innovation are drivers of long term economic growth, the use and advancement of technology will continue in the future[47]. Establishing a method to define, portray, and visualize the complexity and connectedness of a large-scale technological sector, such as EO capabilities, will be an essential tool for policy and investment decisions for years to come.

This study is the first to investigate the value tree and expert elicitation MODA approach from the perspective of its current policy impact, the value of the data in decision-making analyses, and its extensibility to other application areas. Overall, the approach emerged, sustained, and extended acceptance across multiple federal agencies through time. From the proof of concept with limited scope and little decision-making influence, to increases in scope and feeding internal decisions, to cross-agency exposure on a national level, this process continues to expand its applicability and participation. It proved a sound, effective, and useful decision support technique on an enterprise portfolio level. The process obtains an unprecedented breadth and depth of data promptly to facilitate portfolio management from a high level, multi-billion dollar budget management decisions, to a detailed analysis of communities of use at a product level.

Limitations include the need for a broad selection of SMEs across an enterprise. Support at all levels, from senior management to technical researchers, is needed throughout the process to obtain an accurate and useful value tree. It is possible that priority areas could be overlooked and not included in the evaluation if they go unrecognized by the engaged SMEs. In addition, multi-step training in multiple tools is needed to implement this process, as the model is created in PALMA and analyses and visualizations in other programs. Trained analysts are required to create easily digestible visualizations. A decision maker would not likely be able to wade through the raw data and pull out needed answers. Another weakness is the introduction of potential bias throughout the elicitation process by SMEs and elicitors. This weakness is mitigated against throughout the design of the process. When weighed against the time required for a full-scale, objective study or the variance of anonymous survey answers, the benefits of the directed interview structure (timely and verified results, higher response rate, minimized miscommunication, standardized data collection, appropriate SME engagement) result in a robust and effective dataset.

Underpinned by the use of recognized expert elicitation techniques, the approach obtains detailed judgment on the types of data used, the perceived reliance on current systems to achieve research and operational goals, and limitations with the current data. It then integrates the multi-faceted dataset together through a value tree framework. This process allows for continued resilience as the data is easily maintained and updated with future technological advancements or shifting strategic priorities. Management questions can be addressed through flexible value tree forms such as organizational alignment, strategic goals and missions, societal benefit areas, or thematic and functional classes of interest without additional data collection. Analysts have created multiple tools to visualize and communicate the results of these large data analyses in a compelling manner for decision makers. It assists NOAA and USGS's decision-making processes and informed the White House Office of Science and Technology Policy's (OSTP's)

2014 National Plan on Civil Earth Observations. Overall, this process of expert elicitation and a value tree framework possesses a distinct capability to aggregate previously unconnected, unsynthesized, unstandardized information on data requirements into a detailed, representative, and quantitative impact assessment.

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Biography

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