[KE-04-019] Managing GIS&T Operations and Infrastructure

Abstract

This article discusses the key role of effective management practices to derive expected benefits from the infrastructure and operations of enterprise GIS, including needs assessment, data evaluation and management, and stakeholder involvement. It outlines management factors related to an emerging application of enterprise GIS. How to configure GIS infrastructure and operations to support enterprise business needs is the focus. When appropriate, additional information is provided for programs, projects, and activities specifically relevant for equity and social justice.

Keywords: enterprise GIS, infrastructure, management, operations

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Explanation

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1. Definitions (see also Albrecht & Obermeyer et al., 2014).

GIS&T infrastructure: the technology, data, resources, and related infrastructure that can be bought, developed, or otherwise acquired to support typical enterprise GIS operations. GIS&T infrastructure represents the enabling capability of an entity's GIS operation and includes GIS management and professional staff

GIS&T operations: the utilization of an entity's GIS&T infrastructure by GIS management and staff responsible to operate the GIS. GIS&T operations are successful when they meet

the needs identified in the entity's needs assessment and support the overall enterprise goals of the entity.

Enterprise GIS: A GIS that is configured to meet the current and future business needs of the entire entity. Enterprise GIS requires GIS&T infrastructure with GIS&T management and operational practices that are configured, developed, and implemented to maximize cost-effective service delivery.

Needs assessment: A part of GIS strategic planning and ongoing operations and management planning for enterprise GIS. Early in the GIS&T development life cycle the business needs assessment provides a foundation for GIS project and program planning. Each infrastructure and operational component of an enterprise GIS should trace back to a requirement identified in a business needs assessment.

2. The Value of Effective Management of GIS Infrastructure and Operations

A GIS is a complex combination of infrastructure components with focused operational practices to deliver the expected value for the agency, office, department, or program charged with its implementation. Typically and especially at the enterprise scale, customization of both infrastructure and operations will be optimal to achieve desired outcomes. Infrastructure components, including software, hardware, data, network infrastructure, and human resources, obviously have costs associated to acquire, develop, and maintain them. Operational practices determine how GIS components are used and deployed to achieve goals.

Effective management is necessary to meet the goals of the enterprise and deliver value that exceeds the cost to design, develop, and operate the GIS. Effective geospatial technology management assumes ongoing awareness of new and emerging business opportunities to leverage the benefits from GIS and to derive additional value. First published in 2012, the Geospatial Management Competency Model (GMCM, https://www.urisa.org/resources/geospatial-management-competency-model/) outlines 18 competency clusters for an effective manager or management team responsible for enterprise geographic information and technology resources. Key management competencies include geospatial technology competency, relationship management, business development, strategic planning and action, and geospatial project management (GIS Management Institute 2012).

A GIS is expensive to design and develop and requires considerable financial and human resources to operate effectively, especially at a large or extensive scale. This article focuses on enterprise GIS – a geographic information system that supports the various needs of an enterprise for geospatial information and technology (see Enterprise GIS). There are a range of models of an "enterprise." It might be a single department in a municipality, the entire municipality, a university, a large department within a state or provincial government, or an entire national government. However it is defined, a key assumption by enterprise stakeholders is that "…GIS data and infrastructure are investments with value and benefits." Value and benefits from GIS can only be achieved with "…a focus on organization-wide business needs and strategic goals." (Croswell 2018). The GIS Capability Maturity Model provides a high-level structure to assess the suitability of the infrastructure components and the effectiveness of the operational practices of the GIS (Babinski 2018).

The benefits of GIS for the enterprise can be both financial and non-financial in nature. These include "...increases in productivity, cost avoidance, information security, better decision-making, improved customer service, savings on personnel, improved modeling and planning, easier inter-office coordination, and increased citizen participation" (Gillespie 2000). Significant financial benefits from GIS infrastructure and operation can also benefit the enterprise (Zerbe 2016).

3. GIS Needs Assessment, Stakeholder Involvement, and Community Participation

Effective management of enterprise GIS requires ongoing awareness of the evolving needs of the agency. Just as the infrastructure of an enterprise GIS is custom in its configuration, new and emerging business needs require that the infrastructure and operational practices are subject to frequent modifications.

Within government agencies and non-profit entities, there are two communities of users targeted by this document: GIS practitioners and GIS tool users. How the GIS is configured (the infrastructure) and operated (management and operational practices) should directly support the business needs of the enterprise.

GIS practitioners can be grouped within three key categories (Ricker et al. 2020). GIS Tool Users include technicians and analysts who are competent to develop and administer spatial data and to perform analysis and mapping using standard geospatial technology tools. GIS Toolmakers are competent to create custom solutions to develop, extract, or manage spatial data, perform geospatial analysis, or produce spatial visualization. GIS Scientists are competent to go further, in pursuing the fundamental concepts and theoretical application of geospatial technology beyond the limits of GIS tools.

A GIS needs assessment is a process by which the enterprise discovers and documents the business needs of the agency for potential GIS data and applications. A GIS needs assessment is a key component of GIS strategic planning (see Strategic Planning for GIS Design), but the GIS strategic plan and/or GIS needs assessment is a snapshot in time. As the direction of the enterprise changes and new business conditions and objectives emerge, how does the GIS respond to changing conditions to ensure it is appropriately configured and operated? The process of continually assessing the infrastructure and operational practices of the GIS is a key priority for GIS management. One best practice is to conduct a periodic operational planning process to revisit business needs within the enterprise IT/GIS governance structure. This process will typically result in a GIS operations and maintenance plan that revisits existing business needs and explores emerging business requirements. A GIS operations and maintenance plan will document business needs and detail the priority activity for both the enterprise GIS management and end-user business units (King County GIS 2017).

4. The Role of Data in GIS Infrastructure and Operational Management Best Practices

This section details how the GIS infrastructure and operational management practices of an

enterprise might be configured to achieve both existing and emerging management goals. These include spatial data management, spatial data sources, and data quality and validation.

When relevant, particular practices that support and cultivate equity and social justice (ESJ) in the context of GIS infrastructure and operational management will be referenced and highlighted. Public agencies and non-profit organizations may expect to formulate policies and resource allocation practices based on equity and social justice principles, but their offices and agencies will also have many ESJ-practitioners, typically trained in demographics, public health, public administration, sociology, etc., who know little or nothing about GIS and its potential for misuse. GIS and the effective use of spatial data, analysis, and visualization can leverage insights of individual disciplines to ensure that issue-based research is more closely focused on the community (Ricker et al. 2020). The topic of equity and social justice within the context of GIS is also pursued further in its own stand-alone topic here within the GIS&T Body of Knowledge (see GIS&T for Equity and Social Justice) (Babinski 2021).

4.1 Spatial Data Management

A key responsibility of an enterprise GIS is the acquisition, management, and curation of framework and mission-focused spatial data. Careful data management is critical for efficient work that will stand scrutiny and enable the testing and replication of the results of analyses throughout the entire GIS or project lifecycle. Be familiar with the resources provided by the Open Geospatial Consortium (OGC, https://www.ogc.org/) with regards to standards and Best Practices.

4.1.1 Consistent database schemas

An agency initiating the use of GIS&T should architect its database schema carefully. Considerations should include the entire data lifecycle, as well as the geographic scope of the communities of concern, likely partners, and stakeholders.

Data schemas are constrained by the underlying data model that the GIS technology utilizes. A conceptual GIS data model specifies the entity classes, their characteristics, and interrelationships (see Conceptual Data Models). The data model should support understanding of the data use case for spatial analysis and visualization (Nyerges 2017) and be easy for even non-GIS stakeholders to understand. From the conceptual data model, logical and physical data models are derived that utilize the specific database schema within the GIS. Database schema consistency is important to ensure the repeatability of analysis over time and across geographies.

4.1.2 Metadata

Metadata is simply descriptive data about data. Accurate metadata allows for the selection of appropriate data for a given need. Within GIS, the Federal Geographic Data Committee (FGDC) provides rigorous standards for metadata that should be utilized by any GIS organization. Good metadata describes the limitations of the data and captures the preserved institutional knowledge of the stewards of the data.

4.1.3 Managing data across geographic scales

Within the context of enterprise GIS, a business or organization is likely to capture, use, and maintain data for its own particular needs in geographic scope and extent. Sometimes, however, it be necessary or prudent to gather and manage data at a range of geographic scales. For example, a regional approach to managing GIS data may be helpful because of the inherent disconnect between how space is organized by institutions versus how space is experienced by members of society. Any entity utilizing GIS for ESJ should consider the broadest possible universe of geography that impacts the lives of those within its community, especially when its community may traditionally be a more narrowly defined one. GIS&T Infrastructure to support sharing of these regional data may be beneficial too. Analysis of new pro-equity policies or programs should consider all resource opportunities and constraints from every organization that impacts the lives of members of the community. For example, analysis of the optimum location of a new childhood health clinic should consider other existing and planned clinics or related services provided by governments, non-profits, companies, churches, etc. Likewise, analysis of the long-term effectiveness of any single policy or program should analyze all the other resources that might impact or have impacted the original goals.

4.1.4 Managing and preserving temporal data

Managing the temporal component of GIS data is notoriously challenging and always important. Data can be added or replaced readily within a GIS, but time-related changes are not always documented or maintained. Three states of spatio-temporal data have been identified (Song 2019): "…valid-time (when an event occurs/is observed), transaction-time (when an event is recorded), and user-time (when an additional event is perceived and registered by users)."

Two particularly important temporal practices within data management are to use consistent data schemas across sources to support future year to year comparisons, and to preserve historical data in "year series" format to support recreating analysis.

For data within the ESJ lifecycle, understanding, managing, and preserving the temporal dimension of spatial data is equally critical. For one reason, the ultimate effectiveness of an ESJ-based approach or practice can be measured only after many years have passed, even lifetimes. Effective GIS for ESJ must support long-term preservation of data to support analysis of the effectiveness of past actions taken.

4.2 Spatial data sources

The abundance and diversity of GIS data sources is incredibly large and growing greater every day. Understanding and accurately documenting data sources is critical for GIS operations. This includes proper and complete usage of metadata, including information about the limitations and confidence levels of the sources, and effective usage and integration of data in different formats. Significant technical expertise may be required to navigate map services and GIS application programming interface (GIS API)-based access.

4.2.1 Evaluating Data Sources

Spatial data is available from a diverse set of sources, and those in charge of GIS&T operations and infrastructure should make deliberate choices, rather than default ones,

when selecting data. The best sources of data for a given activity may be outside the default ones that the typical municipal GIS office maintains. For example, an analysis of equity issues related to the arts and culture economy in the Seattle area combined both local and state agency demographic and arts infrastructure data, as well as specialized data related to the arts economy from the National Arts Index of the Vitality of the Arts and Culture in the United States (Moch 2020).

The concept of authoritative data is an information technology term "…to identify a system process that assures the veracity of data sources. These IT processes should be followed by all geospatial data providers. The data may be original, or it may come from one or more external sources all of which are validated for quality and accuracy" (FGDC Subcommittee for Cadastral Data 2008). The authoritative nature of the data should be documented in the related metadata.

At the national level, primary authoritative spatial data in the United States is built upon the National Spatial Data Infrastructure framework, which includes data standards, support of a national geospatial data clearinghouse, and a collection of authoritative base layers commonly used in many GIS projects and operations (see US National Spatial Data Infrastructure). Another key authoritative data collection is the decennial United States Census and the American Community Survey, representing foundational social and economic data (see US Census Data). State, regional, municipal and local governments are also reliable sources of authoritative data for their respective geographies. Outside of the United States, free or open access to authoritative spatial data varies widely and would have to be pursued on a case-by-case basis.

Differentiating between data sets collected and distributed for general purposes versus specific policy ones is an important factor when selecting GIS data. Policy-oriented ones may also still be authoritative. For example, in Washington State the Departments of Labor and Industry, Health, and Office of Public Instruction provides data that is needed for development, management, or administration of programs that have resulted from ESJ-related policies. Non-profits and many foundations may be the source of authoritative data related to health, crime, employment, housing, retail, digital, environmental, and other resources or community conditions. Some private GIS or data visualization companies provide access to libraries of spatial data formatted for easy analysis. Many of these data sets are contributed by end-users and often have incomplete or questionable documentation. In other situations, data that is compiled or distributed may be incomplete or designed and formatted in a way to serve a particular issue of concern.

It behooves the GIS&T manager or practitioner to document the validity of any data used, and decide when the best data for a project may not be the default or authoritative source. For example, crowd-sourced data provides insights into community conditions and involving citizen-scientists in data collection and validation efforts have been shown to increase the quality of data in many types of spatial research (see Volunteered Geographic Information, VGI), though care must be taken in documenting the information and integrating it with all other data sources.

4.2.2 Spatial data uncertainty

All spatial data contain elements of uncertainty that can impact geospatial analysis and cartographic visualization. The very concept of cartographic representation of the real

world requires some abstraction of the world. Types of spatial data uncertainty include location of features, attributes of features, and geo-semantic uncertainty. Geo-semantic uncertainty refers to differing understanding of the precise meaning of a locational term or attribute by members of the community. For example, asking members of a community to draw the boundary of their community's "downtown" or of a specific neighborhood invariably results in disagreement (Li 2017). In all situations, known limitations or uncertainty related to the data being used for analysis or visualization should be documented in the metadata. For additional ideas about spatial data uncertainty, see Conceptual Models of Error and Uncertainty, Spatial Data Uncertainty, Thematic Accuracy and Assessment, and Representing Uncertainty.

4.2.3 Open Data and Data Privacy

Open data can be defined as "…data that can be freely used, re-used and redistributed by anyone - subject only, at most, to the requirement to attribute and sharealike." (Open Knowledge Foundation 2020). Benefits of open data include transparency and democratic control, enabling public participation, impact measurement of policies, and new knowledge from combining data sources. The use of open GIS data sources enables others to reproduce and challenge the original analysis.

The foundation for good GIS work requires transparency, trust, and repeatability of analysis, as well as appropriate respect for the privacy rights of individuals. Both imperatives are incorporated into the GIS Code of Ethics: "Make data and findings widely available" and "Protect individual privacy, especially about sensitive information" (URISA 2003).

The use of sensitive location data may be required for certain types of analyses, and every effort must be undertaken to ensure that any data considered confidential or private is kept that way. This is a regular practice in certain domain sectors, such as public health and emergency management, and those practitioners are likely to working with data whose sensitive or private components have been safeguarded. At other times those safeguards may not have been put in place, and this undermines trust and safety, factors that are critical in ESJ matters. The long-term success of ESJ activities requires positive impact on individuals within unserved and underserved communities. GIS professionals should take the lead within their organizations to defend the privacy rights and consider the reasonable privacy expectations of individuals (Kerski 2016).

4.3 Data Quality and Validation

Deciding what data to use for a given GIS project should prioritize the outcomes of that project, taking into account factors about data uncertainty, authoritative vs. non-authoritative sources, appropriate spatial and temporal scales, etc. Decisions made with data of poor or questionable quality or validity could impact the effectiveness of policies, projects, and programs with consequences for decades or generations.

4.3.1 Community Participation and Ground-truthing

Having trust in GIS data and the analyses conducted with those data are critical in all projects, and notably in ESJ matters. Often the most disadvantaged segments of society have been harmed by government-sponsored mapping in the past. Community involvement

and ground-truthing are critical components to build trust. The concept of ground-truthing is more typically associated with verifying remotely sensed data, but ground-truthing can also be applied to the ESJ-related process of validating community conditions that have impacts on equity index values, described in more detail in GIS&T for Equity & Social Justice. Intensive oversight and careful scrutiny of data can be a costly process, but to enhance trust in both data sources and analytical processes, a ground-truthing process may be warranted. Sampling-based ground-truthing has been shown to yield satisfactory data validation results at a reduced cost (Caspi & Friebur 2016).

Community participation plans (CPP) are very important for success and sustainability of ESJ projects. Different approaches exist in how to form and support CPPs, but a CPP should achieve community involvement in defining problem statements, data acquisition, analysis methodologies, and decision metrics (URISA 2003). Another structured approach to achieving community involvement is the concept of public participation GIS (PPGIS). PPGIS has been defined as an approach "…to make GIS and other spatial decision-making tools available and accessible to all those with a stake in community decision-making" (George & Ramasubramanian 2014). Sensitivity to cultural concerns and expectations is also important for a well-designed citizen-science based approach to ground-truthing (see Citizen Science with GIS&T).

4.3.2 Data Validation Workflows and Toolkits

GIS professionals are responsible for validating the quality of data used for spatial analysis. This responsibility extends beyond simply accepting the use constraints stated in the metadata. Especially for data that may have been obtained from sources lacking strong GIS data management practices, utilizing appropriate data validation tools and methodologies will ensure that analyses are based on good geospatial data science. For projects involving ESJ matters, the workflow should detail explicit and clear steps for using the community's expertise to validate data.

Leathers (2017, 2018) has described a process for data quality from three perspectives: 1) spatial data maintenance prioritization and data review, 2) validation of spatial data warehouse objects, and 3) quality assessment of metadata completeness and content.

In addition to those perspectives, having a systematic process to assess the quality of any GIS data set is helpful for operations and infrastructure. A spatial data quality assurance (QA) practice should start with a statement of data accuracy acceptance criteria based on what is required for the intended analysis, e.g. what standards, criteria, or thresholds must be met. Examples of data quality attributes to consider include completeness, topological consistency, resolution, thematic accuracy, positional accuracy, temporal accuracy, physical consistency, referential integrity, and attribute validation. To assess if a data set meets the acceptance criteria, QA steps should include defined visual and automated QA routines that sample positional accuracy, data completeness, thematic accuracy, attribute accuracy, and data inconsistencies (Balakrishnan 2019).

Having structured workflows and processes to validate data quality is so important for GIS operations that some software companies are offering toolboxes or extensions that support a systematic process. For example, Esri's Data Reviewer extension offers a Data Validation toolset as one part of a data quality control framework. Some companies, such as Europe's AccuEarth, focus specifically on providing additional data (such as ground control points or

calibration sites) to facilitate an organization's data validation processes, and they will even undertake the data validation process.

5. GIS Analyses and Cartographic Communication in GIS Infrastructure and Operational Management Best Practices

As was noted in Section 3, a GIS needs assessment will also identify other elements or factors necessary for the organization, such as what types of skill sets will be required for the organization, agency, or group to accomplish its desired GIS projects and programs.

5.1 GIS Analyses

Through GIS, practitioners can manipulate, combine, and analyze data. Geospatial analysis is based on geographic theory. Tobler's first law of geography states that '…everything is related to everything else, but near things are more related than distant things' (Waters 2017). The power of geospatial analysis comes from the fundamental data-information-knowledge concept. The basis of this concept is that individual units of attribute data, when arrayed across space, can be analyzed against various scientific geographic processes and classified to provide spatial information. This spatial information can then be further analyzed via geo-statistics to reveal new knowledge about relationships and underlying processes. The Analytics and Modeling section of the GIS&T Body of Knowledge contains many examples and approaches.

Sometimes, an analysis is conducted by combining data from different sources to form an index or statistic. On their own, the data layers are inadequate to measure, qualify, or quantify the conditions or characteristics on the ground, but once they are combined into one or more indices, they are powerful measures. The creation and use of indices takes place across many disciplines. Within the world of geospatial data, one well-known example is the **normalized difference vegetation index (NDVI),** derived from multi-band color imagery and designed to assess vegetation health, or a Neighborhood Destination Accessibility Index, for measuring infrastructure support for physical activity (Witten et al. 2011). An **equity index** value for a location may combine data from socio-economic, housing, and transportation data, and can be read about more in the GIS&T Equity and Social Justice topic.

Regardless of the analytical method that is chosen, a best practice of GIS operations is to ensure that analytical methods are consistent, transparent, trustworthy, and replicable. The use of a code version control system such as Git allows distributed sharing of code among developers, as well as version documentation. Consistent and transparent analysis methods can be documented as runbooks. Use of Jupyter Notebooks or ArcGIS Notebooks provides for easily documented analytics and preservation of the code set and associated documentation. When multiple and complex spatial analyses are required, they may be more efficiently executed by using open source data analysis tools like SQL queries, Python, and R (Lott 2019). More about these can be learned in the Programming & Development section.

5.2 Cartographic Communication

Cartography and visualization are complex and important topics for communicating with

GIS and spatial data. Poor choices can result in erroneous and misleading maps, and completely undermine projects and programs. The topics of map projections, symbology, color theory, and other decisions that must be made with data-driven maps are beyond the scope of this entry, but anyone needing to manage GIS&T operations and infrastructure would want to be familiar with the range of topics with the Cartography and Visualization Knowledge Area, or have dedicated staff suited for developing this expertise.

6. Data and Deliverable Sharing in GIS Infrastructure and Operational Management Best Practices

The rapid growth of web-based maps and mobile mapping means that GIS operations and infrastructure should leverage the potential of APIs, spatial cloud computing, and Web GIS. For an enterprise GIS, data and deliverable sharing is both an imperative and an opportunity.

Government entities include myriad overlapping jurisdictions. These range from the national level, to states/provinces, and within states and provinces, first order counties/parishes/districts, and down to individual municipalities. There may also be independent public utilities, school districts, transit agencies, and other specific-purpose public entities. However, they all share two typical characteristics: they share citizens/residents and they share geography. Citizens expect their government entities to be prudent with the financial resources provided via taxes and fees. Shared geography provides the opportunity to share GIS&T infrastructure, and in some cases GIS&T operations within local public agencies (Babinski 2019).

For an effective enterprise GIS, a variety of GIS&T infrastructure components are required, along with GIS&T operations and management, that can ensure that the defined business needs of the enterprise are met. The effectiveness of the enterprise GIS is not diminished if the infrastructure and/or operational/management resources are provided from outside the enterprise. This is made clear in the GIS Capability Maturity Model (Babinski 2018). There are many examples of multi-agency collaborative GIS operations in the US and Canada that demonstrate the effectiveness of shared GIS&T infrastructure and operations and management (Croswell 2015).

The potential data and deliverable sharing for enterprise GIS is supported by a variety of geospatial technology. GIS APIs provide a convenient and effective means to consume and share data between jurisdictions on an autonomous basis (Chow & Yuan 2019). Spatial cloud computing enables the management of geographic data for a region as a platform as a service (PaaS). It enables the centralized management of geographic data for a region to high standards of quality and availability, within a regional collaborative GIS environment (Huang 2020). Web GIS further leverages regional collaboration by facilitating cost-effective spatial data compilations. As a platform independent method of GIS data display and analysis, Web Mapping can put GIS tools and data in the hands of agency staff and the public at very low cost (Quinn 2018).

Leveraging APIs, spatial cloud computing, and Web GIS enable more cost-effective GIS&T infrastructure. They facilitate the GIS&T operations and management to meet their existing and emerging enterprise business needs on a sustainable basis.

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