Knowledge-Enabled Decision Support System for Routing Urban Utilities

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Abstract: This paper presents a Web-based system for supporting the selection of the most suitable routes for buried urban utilities. The aim of the proposed system is to support (not make) decisions through a collaborative semiautomated environment, in which stakeholders can share information and/or study the impacts of different routing alternatives with respect to decision constraints. First, the knowledge relating to route selection for urban utilities is represented through an ontology. The ontology defines the types and attributes of infrastructure products and the surrounding areas. It also defines the impacts of routing options on surrounding areas through a set of decision criteria adopted to evaluate the effectiveness of any route in terms of its potential impacts. A set of constraints are also defined to help represent/study the decision criteria. Second, a GIS-based system has been created to help visualize route data, interact with users, and support the needed discussions among stakeholders. The portal also achieves data interoperability through wrapping existing geospatial data with ontology structures. Finally, a set of reasoners have been created to help quantify/augment some of the constraints. The system is capable of (1) extracting the attributes of each routing option, (2) testing the interaction/conflicts between route attributes and the constraints of the surrounding area, (3) studying the impacts of a route as stipulated in the ontology, (4) referring users to existing best practices to help enhance routes or address conflicts and, when needed, (5) develop objective measures for comparing different routes. On the microlevel (street level), route options are evaluated through a "constraint-satisfaction" approach. On the macrolevel (city level), route options are evaluated through a fuzzy inference scoring system. The proposed system focuses on facility life cycle, sustainability, and community impacts. Construction costing, scheduling, labor, and equipment along with other management issues can either be added to the system or, better, analyzed through integrating the system with four-dimensional (4D) modeling tools. **DOI: 10.1061/(ASCE)CO.1943-7862.0000269.**

CE Database subject headings: Knowledge-based systems; Information management; Decision support systems; Geographic information systems; Routing; Urban areas; Infrastructure; Utilities.

Author keywords: Ontology; Knowledge management; GIS; Routing; Urban infrastructure; Semantic systems.

Introduction

Addressing sustainability and community impact aspects of infrastructure systems is crucial. One of the most important decisions to be made in this regard concerns the routing of underground utilities. At the macrolevel, the decision normally relates to which street(s) should be used. At the microlevel, the decision typically relates to which side(s) of these streets should be used.

It is almost impossible to develop a universal decision-making system with a standard set of decision parameters in this domain. First, decision criteria are context-sensitive (mainly to land-use type). What could be considered important criteria in an industrialized zone does not necessarily have the same relevance or importance in residential or commercial zones (Makropoulos 2003). Moreover, decision criteria and constraints in greenfield projects are different from those for brown fields. Of course, ecological boundary conditions such as weather, natural habitat, and degree of urbanization have a bearing on decision criteria and constraints. Second, some of the typical decision criteria include subjective issues, for example, the impact on a local community of elements such as noise levels and traffic impacts during construction, as well as constructability and maintainability concerns. Third, with the increasing role of communities in the decision-making process and the push for more context-sensitive design, more stakeholders with varying degrees of expectations and backgrounds are getting involved in the decision-making process, which brings about debates regarding the criteria themselves, their weights, and their assessment (Osman and El-Diraby 2006).

An increasing percentage of municipalities have adopted a computerized system to support their infrastructure maintenance programs (Vanier and Rahman 2004). Similar trends are being observed in the area of asset management. In spite of this prevalence, the current computer systems have two major shortcomings:

1. Weak knowledge representation: Most existing information systems focus on data handling and utilize database-driven applications. Such systems use a standard set of parameters and use data extracted from GIS databases to score these parameters. An operations research tool is then used to augment these scores (Halfawy et al. 2008). Little opportunity is provided to users to explore/document best practices and/or study the interaction between route attributes and related attributes of the surrounding environment.

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Note. This manuscript was submitted on April 13, 2009; approved on August 3, 2010; published online on August 5, 2010. Discussion period open until August 1, 2011; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 137, No. 3, March 1, 2011. ©ASCE, ISSN 0733-9364/2011/3-198–213/$25.00.

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2. Lack of interoperability: Information is typically spread over several utility organizations. Even though a good part of such information is represented in GIS-based systems, they usually lack interoperability.

To address these gaps, it is argued, we need to develop a flexible system to support (not make) decisions. The need is for fostering communication among the stakeholders (to facilitate agreement on parameter selection), capturing and/or reusing relevant knowledge about these parameters and their interrelationships with route attributes, and providing means to quantify some subjective issues when needed. The needed system should be interoperable and capable of wrapping existing legacy databases to allow for a seamless exchange of data among stakeholders—a necessary first condition for effective collaboration.

To this end, the system proposed hereinafter is meant to address these requirements. The proposed system is built as a Web-based knowledge-enabled decision-support system that rests on the following three pillars:

1. Knowledge formalization: State-of-the-art practice in a knowledge-enabled (or semantic) system starts by developing an ontology of domain knowledge (Osman and El-Diraby 2006). Knowledge in the proposed system is not reduced into a set of decision parameters but through an ontology that aims at providing a common representation of terms, relationships, constraints, objectives, and axioms. The use of this routing ontology ensures two things: (1) During preproject planning, stakeholders can use and reach consensus on the definition/meaning of various decision criteria and constraints. (2) During postproject evaluation, lessons learned will/can be documented in a semantic way that makes their future retrieval easier and more relevant, hence allowing for a formalized accumulation of knowledge from one project to the other. In other words, an ontology makes for a better understanding of the issues involved ahead of project execution while, at the same time, documenting project experience in the ontology's terms, enriching the ontology, and preserving the formal knowledge gained. Of course, the ontology augments and reuses many of the findings and best practices from existing systems.
2. Communication and knowledge sharing: the core mechanism for route selection in this proposed system is to foster collaboration among stakeholders ahead of the routing decision. The system allows users to select and discuss the relevant criteria and their weights. Further, the system does not use these criteria to find an optimal route. Rather, it uses a GIS-based portal (geographical information system) to provide users with a comparative analysis of the facts of the case at hand. It contrasts the attributes of the route (for example, location, depth, and diameter) with the attributes of the surrounding area and tests the satisfaction level of a set of user-selected constraints. Stakeholders can use/manipulate this information to build a common understanding of the decision criteria and project constraints.
3. Reasoners: A set of artificial intelligence (AI) tools (mainly based on fuzzy logic) is used to quantify some of the subjective criteria such as constructability and maintainability. While the main goal of the proposed system is to foster communication, this component was provided to help stakeholders in their assessment. In this regard, AI tools are used as an optional tool to support the decision not to make it.

In other words, the main challenges of this research lie in discovering how to create an ontology that encapsulates routing knowledge to support knowledge capture and reuse, how to integrate the proposed ontology into a GIS system to facilitate communication, and what AI tools can be introduced within this system to help users quantify some of its more subjective parameters.

Methodology and Scope

The research work spanned three stages: requirements analysis (RA), development, and evaluation. The RA stage utilized the following tools:

- Literature reviews: Analysis of product modeling studies and standards, utility routing issues, impacts, and decision-making criteria/constraints.
- The benchmarking of existing models: Several information models for utility infrastructure products were reviewed and analyzed. The purpose of this benchmarking process was to identify the strengths and weaknesses of each modeling initiative and reuse some of the concepts that were proposed by these product models to enrich the ontology.
- An analysis of design guidelines: An extensive review of design guidelines in all five major utility sectors (electricity, gas, telecommunication, water, and wastewater) was performed with special emphasis on those related to routing. Knowledge from these guidelines represents the explicit constraints encoded in the ontology.
- Case studies: Eight major infrastructure projects in Southern Ontario were investigated by the writers. Seven of these projects involved municipal infrastructure (water/wastewater), while one project involved a highway interchange reconstruction. The case studies were used to identify the main attributes of infrastructure products that could impact the design process, better understand the main issues facing designers during the process of design coordination, and identify and refine the main criteria that are usually considered during the routing at both the microlevel and the macrolevel.
- Engagement with industry: Over a span of two years, the first writer attended regular monthly meetings of the utility coordination committee in Toronto and two other related committees in the suburbs of Toronto, to observe, document, and discuss problem areas, challenges, best practices, and use cases.
- Expert knowledge: To ensure diversified input into the requirements analysis, a set of eight formal interviews were conducted. This is one way to capture/formalize some of the tacit knowledge in the domain. The interviews focused on two fundamental issues: the process of route coordination and the formalization of routing constraints. Experts' backgrounds were not limited to design knowledge but also included knowledge pertaining to construction, maintenance, and operation. During the interview, the experts were presented with a set of project plans for actual infrastructure projects. The experts were asked to select the best location for a new utility within the existing ROW. Through this procedure, it was possible to invoke the experts' thought processes, hence exposing many tacit constraints that are used by expert designers during the routing process. Next, the experts were asked to comment on the proposed list of constraints that were developed based on the tools referred above.

The development stage overlapped with the later part of the RA stage and was iterative. It included two parallel tracks: the development and enhancement of the ontology and the development of the decision-support environment (decision modeling and programming). The final stage of the work included a set of evaluation techniques for both the ontology and the decision-support system. More details about these two stages will be provided in subsequent sections.

The results of the RA stage clearly indicated that no single automated model is feasible. In other words, a model with a standard set of parameters and a single operations research means for scoring and augmenting these parameters is not suitable. This is due to the context-sensitivity of the problems, the subjectivity of data, and the varying objectives and expectations of stakeholders. In fact, the primary requirement is to coordinate the flow of information and expose the impacts of every decision to all stakeholders. The fundamental uses case for the proposed systems involves an infrastructure design team that is responsible for utility design within a large city. The team typically wants to understand the impacts of different route options for a new utility on surrounding businesses, traffic flow, local residents, and the environment. They need to exchange and streamline their expertise and constraints to assure that the route will be easily constructible, operable, and maintainable throughout its service life. Furthermore, they need the means to communicate and coordinate their decision with relevant stakeholders (operators of nearby utilities, business owners, and members of the community).

The proposed system does not design the utility products involved. It focuses only on the routing of already designed products. It assumes that the decision maker has used existing technical codes and specifications to define the attributes of the proposed product as, for example, the size, type, and composition of a pipe and all relevant attributes of needed valves and access points. With this as input, the scope of the proposed decision-support system (DSS) is to help the decision maker find the best location of such products within the maze of buried urban utilities. This assumption does not mean mutual exclusivity between design and routing. In fact, the two processes are intertwined. For example, one route could locate the utility near the surface, allowing for a smaller diameter. Another route could locate it much deeper, thus demanding changes to the size or material type of the pipe concerned.

Finally, while infrastructure interdependency is of great importance to any routing decision, modeling interdependency is beyond the scope of this study. The routing criteria used in the DSS do not include interdependency issues and focus mainly on addressing the life cycle issues of the utility product being routed. They also focus on urban systems only. Further, they only consider the design stage of projects. Commitments made during this early stage have the most profound impact on project outcomes. The decision-support system is intended to support the case for a new utility in an existing development. This involves the case for introducing a new buried utility in an area that has an existing buried infrastructure. Given that the design and routing processes are concurrent, every change in the design of a route will require invoking the proposed DSS.

Related Work

The process of "route selection" or "alignment" of a utility system is a process where the best location is selected for a utility system. It is considered a highly knowledge-intensive domain of urban-infrastructure design because it is multidisciplinary (ASCE 1998). Macrolevel routing or corridor selection is usually approached as a multicriteria decision-making problem. Ryan (2001) and Luettinger and Clark (2005) proposed scoring systems to include the various noncost issues pertaining to urban-infrastructure routing at the macrolevel. Both studies focused on the routing of a large-diameter water transmission pipe from a known source to a predetermined destination. The routing criteria proposed for use in an urban context had some overlap with those listed in the Manual 46 (ASCE 1998), which is mainly dedicated to rural pipelines. Table 1 presents a comparison of six studies that relate to macrolevel routing of infrastructure systems. Typically, these studies focused on synthesizing a set of routing criteria (other than direct cost) and suggesting approaches to combine the scores for each criterion (e.g., weighted averages and analytical hierarchy process). All studies assumed that these scores should be assigned subjectively by an engineer. Most studies did not develop systematic/objective procedures for obtaining scores for routing criteria.

Criteria for urban-level routing reported in these studies can be grouped under the following nine categories (Luettinger and Clark 2005; ASCE 1998):

1. Constructability: Addresses the ability of the contractor to construct the pipeline in a timely manner without excessive interference from physical obstacles. These physical obstacles could include narrow ROW, limited site access, limited staging area, a steep slope, deep trench conditions, and crossings (over highways or waterways), which could have major negative impacts.
2. System compatibility/efficiency: Relates to the degree to which a route option meets its functional requirements such

Table 1. Summary of Some Relevant Utility Routing Studies

Study	Context	Incorporation of noncost issues	Knowledge incorporation	Domain	GIS use	Multicriteria decision approach	Comments
Buszynski (2004)	Urban, high-density land use	Main focus on public impact	N/A	Gas transmission	Unknown	Unknown	Focus on incorporating public concerns in pipeline routing
Dey and Gupta (2000)	Rural, cross-country pipeline	Minimal-only included environmental impacts	External	Petroleum transmission	No	Analytical hierarchy process	Focus on life-cycle costing
Hirst and Ruwanpura (2004)	Rural, cross-country pipeline	None	External	Gas transmission	No	Single criteria: Cost	Probabilistic approach based on simulation
Luettinger and Clark (2005)	Mainly urban, mixed land use	Yes, to a large extent	External	Water transmission	Yes	Weighted scoring method	Comprehensive coverage of noncost issues in urban environments
Raza and Darren (2004)	Rural, cross-country pipeline	Unknown	External	Generic	Yes	Analytical hierarchy process	Generic GIS-based pipeline routing
Ryan (2001)	Mainly urban, mixed land use	Yes, to a large extent	External	Water transmission	Yes	Weighted scoring method	Comprehensive coverage of noncost issues in urban environments

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as proximity to preferred delivery points, ease of operation and maintenance, and the flexibility needed to accommodate future expansions.
3. Community disruption: Addresses the impact that the pipeline route will have on the local community and businesses. This is very closely related to land use in the surrounding area.
4. Traffic: Includes negative impacts created by limiting access on key roads or disrupting public transportation.
5. Utility conflicts: Includes the disruption of utility services (which can prolong coordination with utility companies), or relocation of utilities as well as the possible negative impact of the pipeline on future access to adjacent utilities and utility crossings.
6. Seismic and geological considerations: Considers potential liquefaction zones and fault lines, corrosive soils, rocky conditions, or required special trenching techniques.
7. Environmental concerns: Addresses the environmental sensitivity of the areas along and around the proposed alignment and any possible contaminations.
8. Permit issues: Addresses the possible need for any special permits required by crossing, encroaching upon, or otherwise impacting the surrounding area.
9. ROW issues: Addresses the possible need for easement or ROW acquisition along the pipeline. The available space around the trench/construction operation can also put major constraints on constructability.

Microlevel routing is mainly concerned with the selection of the most suitable location for an infrastructure product along a particular (already defined) ROW. The process is most often performed during detailed design stages where information pertaining to the surrounding environment is usually available and reliable. The scope of microlevel routing will usually include supporting structures (e.g., manholes, valve chambers, pedestals) in addition to conveyance products themselves (e.g., pipes or cables). Formal knowledge in this domain is commonly found in manuals of practice and design guidelines. Design manuals/guidelines that address microlevel routing tend to focus on minimum or maximum clearance constraints that must be maintained between utilities. These manuals tend to be sector-specific, i.e., developed with the goal of maintaining the infrastructure of a single utility sector. This can sometimes lead to conflicting guidelines, hence the need for a common ontology.

Collier and Kranc (2006) adopted an optimization-based approach to the problem. Their model uses linear programming to minimize a function that includes the various costs associated with infrastructure-location selection within a highway ROW. Costs that were included in the model include installation costs, access (maintenance) costs, inconvenience costs, and costs associated with possible vehicular crashes with aboveground facilities. Costs are a direct function of the x-y coordinates of the utility. In addition to this "explicit" knowledge, a more "tacit" form of knowledge pertaining to microlevel routing is commonly used by design engineers. This knowledge does not specify distance-based clearance constraints, but rather entails a set of "do's" and "don'ts" with regard to routing. In general, this tacit knowledge tends to be more situation specific.

In summary, while the decision-making process is context-sensitive and requires the use of dynamic/varying criteria, most available routing models/systems tend to use the same set of standard parameters in all situations, which has negative impacts on the adaptability of these systems. Users need to have more control over the selection of decision-making parameters/criteria. This can be achieved through the use of an ontology that includes a variety of interrelated decision parameters and route attributes from which the user can make selections based on the specific needs of the situation at hand. Further, any new decision parameters and/or route attributes that are discovered or deemed necessary in the future can still be added, given the object-oriented nature of ontologies. The expandable ontology should have an overarching system that compares the selected decision parameters to selected route attributes. Based on this comparison, the users can negotiate a decision. When needed, the system should provide the means to quantify the parameters or the attributes through AI means (which are to be embedded in the ontology or as a stand-alone system component).

Ontology for Utility Routing

The proposed ontology (hereinafter called ROUTE-Onto) is meant to model the knowledge pertaining to the routing of utilities in urban settings. It supports the creation of systems to analyze the impacts/costs of different routes. It can also support the development of programs/systems to coordinate the selection of routes for collocated utilities. The ontology is built on top of a domain ontology for infrastructure products (Osman 2006).

The ontological model of ROUTE-Onto is an attempt to formalize the interaction between a route option and its surrounding area. Fig. 1 shows schematically the main ontological concepts in ROUTE-Onto, which are explained hereinafter. A route is a composition of a set of *products* (physical elements of a utility line such as pipes, manholes, and valves). The *attributes* of these products include physical and nonphysical features such as diameter and martial type of a pipe, the construction method, the location and the length of the proposed line. The *surrounding area* has many *entities* that can be impacted by the new line such as traffic, the surrounding community, and the environment. These entities also have a set of attributes, for example, soil conditions, traffic volumes, and level of business activity. The interaction between these two sets of attributes is what defines the efficiency of a route. The attributes of an infrastructure route (especially spatial attributes) create (or are related to) a set of *impacts* on *related entities* (other infrastructure products, street elements, local environment, businesses, and traffic). There is a desire to select a route that would minimize these impacts. To assess that, a set of *routing criteria* is used (such as enhancing constructability, reducing environmental impacts, supporting maintenance, and operation processes). The routing criteria are represented by a set of *constraints*.

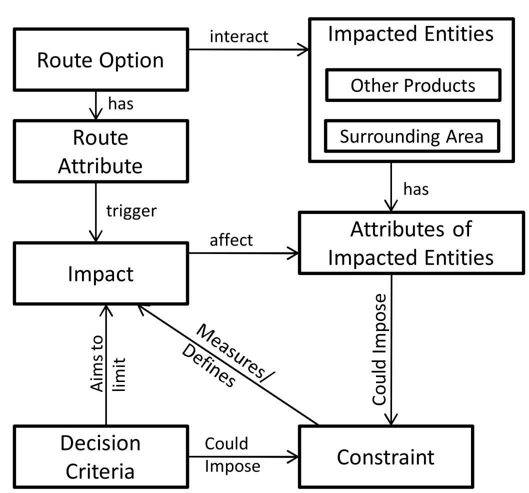

Fig. 1. Summary of the ontological model

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These constraints are imposed by regulators or the decision makers to limit possible negative impacts. Additional preexisting constraints such as area conditions are also present. Upon analyzing a route option, the decision maker must first know which constraints are being violated, understand how these constraints are linked to routing criteria, and develop the means to measure which route achieves the best results.

Impacts

The model for impacts adopted in ROUTE-Onto is a modified version of that proposed by Surahyo and El-Diraby (2009) to represent the environmental and social impacts of highway projects. The model assumes that an impact is the result of an *impact source* (see Fig. 2). An impact source is an *infrastructure product*, represented through its attributes (normally physical attributes such as size, material type, and location). Also, the use of certain *methods of construction* (such as trenching) could trigger a set of impacts. An *Impact* affects one or more *impacted entities* that can be economic, social, or environmental in nature. The ontology assumes that a *best practice* can be used to mitigate the extent, severity, or duration of an Impact. For example, an *excavation* process using the *open-cut method* for any *pipe* (product) will cause an *economic impact* on *surrounding businesses* (impacted entities). This type of impact is usually a *short-term impact* that will occur on the *street or neighborhood* level during the *construction phase*. This impact can be mitigated by adopting the following best practices: *trenchless excavation methods, provision of customer access*, and *project phasing*.

Impacts are classified based on their life-cycle stage, type, extent, and continuity.

- Life-cycle stage: Four main stages in a product's life cycle can be used to classify impacts: manufacturing, construction, operation, and disposal. This is consistent with the mainstream literature on product life-cycle analysis (Molina et al. 1998; Giudice et al. 2006).
- Domain: impacts were classified according to the goals of sustainable development: *social impacts, environmental impacts and economic impacts*. these types are consistent with the three main categories for *impacted entities*.
- Extent: Four classes of impact can be generated using this modality. A *street-level impact* is defined as an impact that affects Impacted Entities within the limited vicinity of a street, whereas more extended (wider) impacts are categorized as *neighborhood-level impacts*, *city-level impacts*, and *regional-level impacts*.
- Continuity: Impacts can also be classified according to their continuity as either *continuous impacts* or *intermittent impacts*. Continuous impacts are those impacts that do not undergo any interruption. They last throughout the life cycle of the impact source and the impacted entity. Examples include the *limiting street tree growth impact* that occurs when a buried infrastructure product is placed too close to a street tree. On the other hand, intermittent impacts are those impacts that occur from time to time such as, for example, the *limiting pedestrian access impact* attributable to the sewer maintenance process that occurs every few years.

Three fundamental attributes are used to describe impacts:

- Duration: Impacts can be of short- or long-term duration.
- Spread (extent): This attribute specifies the radius around which a particular impact source has influence. It corresponds to the extent modality of impacts.
- Severity: Another very important attribute of impacts is *impact severity*, which describes the degree of impact of a particular Impact source on one or more *impacted entities*. Various scales

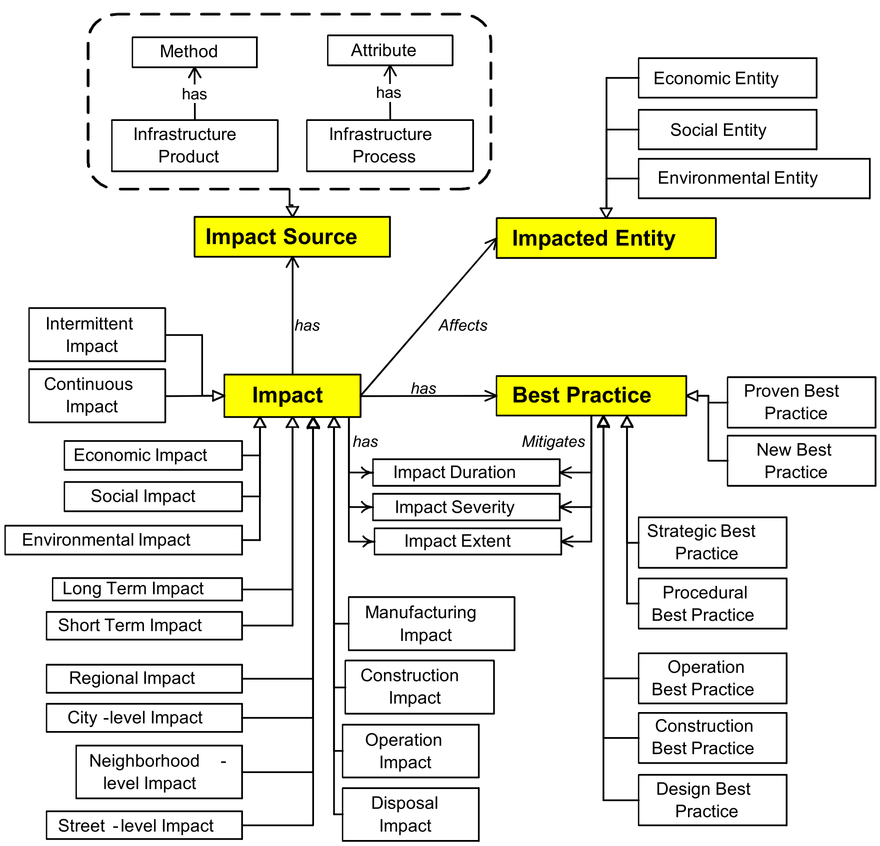

Fig. 2. Ontological model of impacts

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can be used to describe this attribute, which depend on the type of impact itself.

Best Practices

The Construction Industry Institute (CII) defines a best practice as a process or method that, when executed effectively, leads to enhanced project performance (CII 2002). A best practice will mitigate at least one of the three attributes of impacts (severity, duration, or extent). ROUTE-Onto classifies best practices according to three main criteria: (1) how they relate to processes or methods, (2) the degree to which they were proven to be successful, and (3) the phase in which they are implemented. The degree of success of a best practice is a relative measure. The classification is only intended to include the notion of effectiveness in the model. Finally, best practices in the infrastructure industry can belong to the design, construction, or operation phases.

Decision Criteria

The ontology includes eight decision criteria (listed below). These criteria are a reorganization/reclassification of the nine criteria suggested by ASCE (1998) and other researchers. Such reorganization was needed to assure semantic consistency and remove overlaps.

1. Constructability: Takes into consideration the effect of the existing infrastructure and surrounding environment (e.g., land use, soil conditions) on the ability to construct a buried utility.
2. Maintainability: Refers to accessibility, reliability, and ease of servicing and repair into all active and passive system components. This is intended to minimize costs and maximize the benefits of the expected life-cycle value of a facility (Dunston and Williamson 1999). The spatial location of an infrastructure product plays an important part in its accessibility and ease of servicing and repair.
3. Communities: A broad umbrella that includes any attributes of the infrastructure product that has an influence on the daily activities of residents living within the vicinity of the product.
4. Businesses: A broad umbrella that includes any attributes of the infrastructure product that has an influence on the commercial vitality of businesses within the vicinity of the product.
5. Traffic: Any attributes of the infrastructure product that has an influence on the performance of the transportation network within the vicinity of the product.
6. Environment: Refers to the negative consequences that can occur to environmentally sensitive entities, for example, water bodies, air quality, fauna, and flora.
7. Infrastructure safety and security: Refers to the design characteristic that enables the infrastructure to perform its function without disruption in service due to external events and without compromising the quality of the medium being conveyed.
8. Utility conflicts: this set of criteria concerns the interaction between a proposed route and existing utility lines. Does it require realigning existing utilities? Would it make future operation and maintenance of other utilities more difficult?

Constraints

The proposed routing DSS is fundamentally a constraint checker. Most of the constraints encoded under this category in the ontology are spatial constraints, attributable to the overwhelming role of location and clearances in achieving most decision criteria and the dominance of such distance-based criteria in regulations and existing software systems. In addition, using spatial constraints can help eliminate some of the subjectivity in decision making. However, nonspatial constraints were also encoded. These nonspatial constraints may include, for example, impacts on business, corrosion susceptibility, impact on residents, and maintainability issues. Other relevant conditions/limits were embedded indirectly in the form of limitation on some attributes or in the form of axioms.

A constraint can be triggered by one of three main situations (scenarios):

1. Product-product scenario: Requirements set forth by code could limit the location of one product on the basis of the existence of other products. For example, a minimum clearance is normally required between sewer lines and waterlines.
2. Product-street elements scenario: The attributes of a product can have an impact on (or just a relationship to) a street element. For example, a manhole could be located so close to a tree that it could impact the growth of the tree. Similarly, a pipe could be located so close to the curb that the future maintenance of such a pipe would be very costly.
3. Product-area features scenario: Product attributes have to take area conditions into account. For example, certain soil types could mandate the use of certain pipe material. Weather conditions could limit the use of certain construction methods. Intensity of business activity could also limit the use of certain construction methods such as encouraging directional boring over open trenching.

All constraints can be categorized according to their degree of formality/enforcement as follows (see Fig. 3):

1. Hard constraints: These constraints that are both mandatory and completely objective. The sources of these constraints are usually codes of practice and design standards. The knowledge they represent is usually explicit knowledge. An example of such a code would be that the minimum cover for electricity utilities must be 30 cm.
2. Soft constraints: These constraints could be mandatory or not and it is up to the discretion of the utility designer to enforce them or not. Not enforcing these constraints will usually lead to an unwanted impact, however. The source of these constraints is a combination of design manuals and best practice. The knowledge they represent is both tacit and explicit in nature. An example of such a constraint would be that it is not preferred to route new utilities beneath existing manholes unless absolutely necessary.
3. Advisory constraints: These constraints are not mandatory and reflect rules-of-thumb or best practices. The source of these constraints is the accumulated experience of domain experts and hence tends to be tacit in nature. For example, locating drain valves in close proximity to and slightly above catch basins is beneficial during cleaning operations.

A constraint can be defined as a function in five main entities/attributes, two of which are optional:

1. Infrastructure product: This is the product being routed. Some constraints only pertain to products that have specific attributes such as pipes larger than a certain diameter. The three main attributes that were common in defining clearance constraints included dimension, material, and location attributes.
2. Physical product: This is a product that already exists along the ROW such as a manhole or pipe or a street product (e.g., a driveway, bus shelter, or curb), both of which are qualified through attributes.
3. Area condition: Attributes such as soil condition and land use impose several constraints on the route of a utility. For example, heavy traffic in an industrial area could suggest greater depth for some utilities. Harsh weather conditions could also push some lines deeper, as could the high probability of erosion for some utilities such as gas lines.

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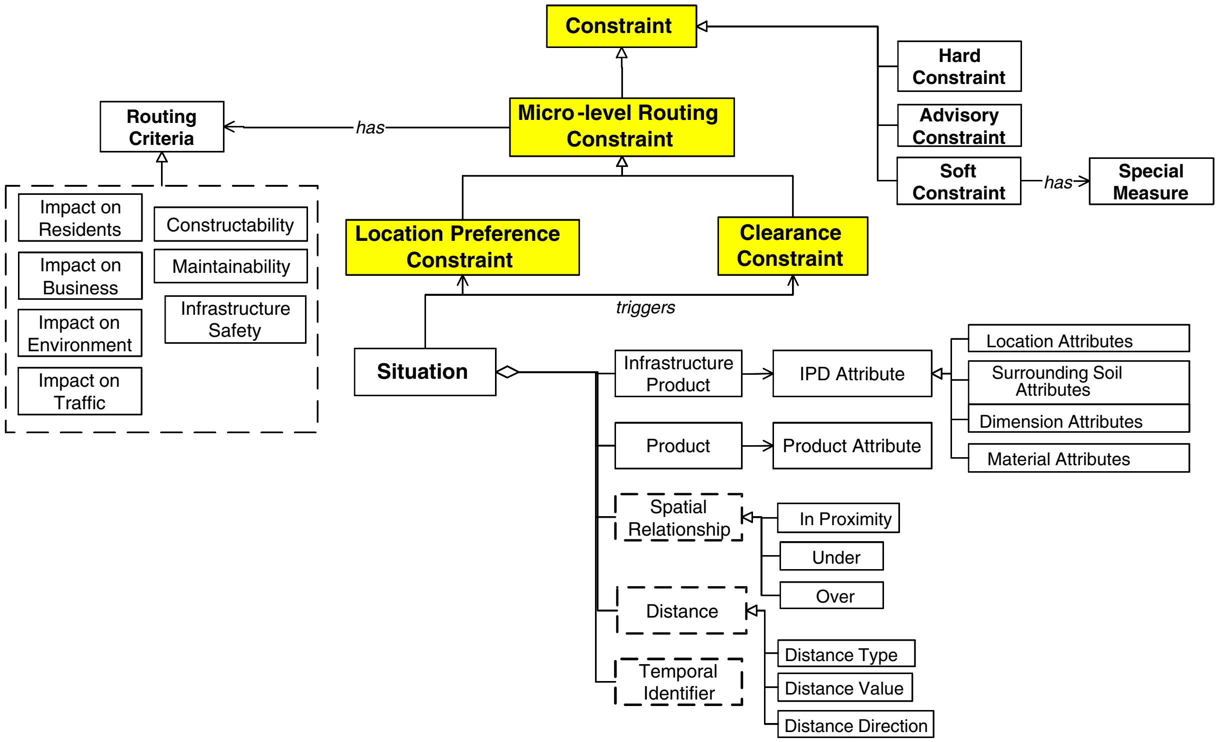

Fig. 3. Model for microlevel routing spatial constraints

4. Clearance parameters: Clearance constraints are identified by the minimum or maximum distance threshold upon which they are triggered. Three clearance parameters are used:
   a. Distance type: Minimum or maximum distance.
   b. Distance direction: Horizontal, vertical, or generic.
   c. Distance value.
5. Temporal identifier: Specifies a reference to the time span (start and end dates) of a the applicability (or existence) of a constraint.

Spatial Constraints

A spatial constraint is defined as a constraint that is triggered as a result of a location-related attribute of an infrastructure product or one that affects a location-related attribute of an infrastructure product.

In the domain of urban infrastructure systems, spatial constraints can be broadly classified according to two distinct criteria—*knowledge type* and *spatial perspective*. Spatial constraints can be classified according to the knowledge type as follows:

1. Explicit constraints: These include those constraints that are stipulated in design guidelines, codes, and manuals of practice. They must be followed unless some extraordinary measure is adopted.
2. Tacit constraints: These include constraints that are systematically employed by designers in routing buried infrastructure. They have not yet evolved into explicit criteria documented in manuals of practice but are nonetheless utilized during the routing process. These criteria tend to be more situation-based when compared to the more general explicit criteria.

Although most of the constraints tend to be tacit in nature, many have evolved into widely accepted rules-of-thumb within the industry. An example is that of placing drain valves close to existing catch basins, which is beneficial during the cleaning of watermains.

The spatial perspective is used to denote the type of spatial relationship that a constraint is built upon:

1. Clearance constraints are mainly used to represent the minimum or maximum distance that two infrastructure products (or an infrastructure product and another object) must maintain. These constraints tend to be mostly explicit constraints (although some are tacit). An example is the rule that the minimum separation between watermains and sewermains must be 2.5 m. Another example of a clearance constraint is the rule that the minimum cover for direct buried telecommunication cable must be 900 mm. The purpose of this constraint is to help maintain the structural integrity of the cable throughout its service life. It is a soft constraint and one that can be relaxed if the cable is encased in a duct structure. The distance being described is a vertical distance between the cable and the pavement surface. Clearance constraints are assumed to exist between two infrastructure products such as the separations between electricity ducts and watermains, minimum cover for telecommunication cables, or between an infrastructure product and a street element (e.g., the separation between trees and gas lines or manholes and driveways).
2. Location-preference constraints: In contrast with clearance constraints that clearly spell out actual distances to be maintained among products, these constraints specify preferred and nonpreferred locations for an infrastructure product within a ROW. An example of this constraint is the stated preference that water valves not be placed in driveways. The purpose of this constraint is to allow for easier access during times of service/maintenance and to minimize disruption to residents. The model for a location preference constraint is similar to that for clearance constraints except that it does not include clearance parameters because they are not needed. Instead, a concept of spatial relationship was introduced. Three types of generic spatial relationships are proposed: below, above, and in-proximity.

Nonspatial Constraints

Similar to spatial constraints, the ontology has a taxonomy (formal categorization) of nonspatial constraints. They are modeled using most of the attributes and modalities of spatial constraints. However, it was clear that the nonspatial constraints found in the literature and through expert input are rather heterogeneous (and domain-specific), at least in their semantics and measurement techniques. The sections on microlevel and macrolevel routing discuss the proposed nonspatial constraints in greater detail (and in their respective place).

GIS Portal

Fundamentally, the proposed system is a constraint checker that extracts data from GIS maps, matches them to ontology concepts, and builds a three-dimensional (3D) database of the route attributes, area attributes, and user-selected decision criteria (or constraints). The portal is a means for interaction, discovery, and communication of route information between/among its users. It provides the following functionalities:

1. Extracting route attributes either through a GIS database (for physical attributes) or user input (e.g., the construction method);
2. Extracting area attributes such as soil conditions, land use, and traffic volumes through a GIS database for physical attributes or user input;
3. Selecting a set of constraints that reflect/measure the evaluation criteria. Some of these are built-in while others are to be selected and/or customized by the user;
4. Establishing a database of both sets of attributes and the constraints; and
5. Checking constraints by examining the interaction between the two sets of attributes against the selected constraints. The interaction is reported back to the user in two ways: a constraint-satisfaction checker (in the case of microlevel routing), or through a scoring system based on fuzzy logic to measure the extent of any violation in the case of macrolevel routing.

Most spatial constraints are extracted from GIS data. However, given the subjectivity of data and the context-sensitivity of every decision, it is not feasible to automate all data entry. Users are required to enter some data (especially of nonspatial constraints). These include, for example, traffic volumes, expected width of construction zones, and number of hours construction overlaps with typical business hours. Users are also encouraged (required) to negotiate constraint selection as an indirect means to foster collaborative decision making. Such a semiautomated approach is in line with the original intent of the proposed system: fostering communication to support decision making rather than total decision automation.

The system architecture includes three layers: client, kernel. and data (see Fig. 4).

Client Layer

The user interfaces with the ontology portal (entry point to modify/extend the ontology) and the GIS portal (entry point to access DSS supported by the product ontology). The GIS portal gives the user a Web-based GIS interface for accessing utility product information. In addition to accessing and updating utility product information, the portal allows the user to access the routing DSS, where the user can enter routing criteria and select routing constraints for the analysis. The user can also save the results of the analysis and visualize them in the GIS.

Kernel Layer

The kernel layer is where data is processed and reasoning is conducted. It includes the following major components:

1. Ontology manager: Responsible for maintaining the knowledge within the ontology. This includes adding, removing, and editing concepts, relationships, and axioms.

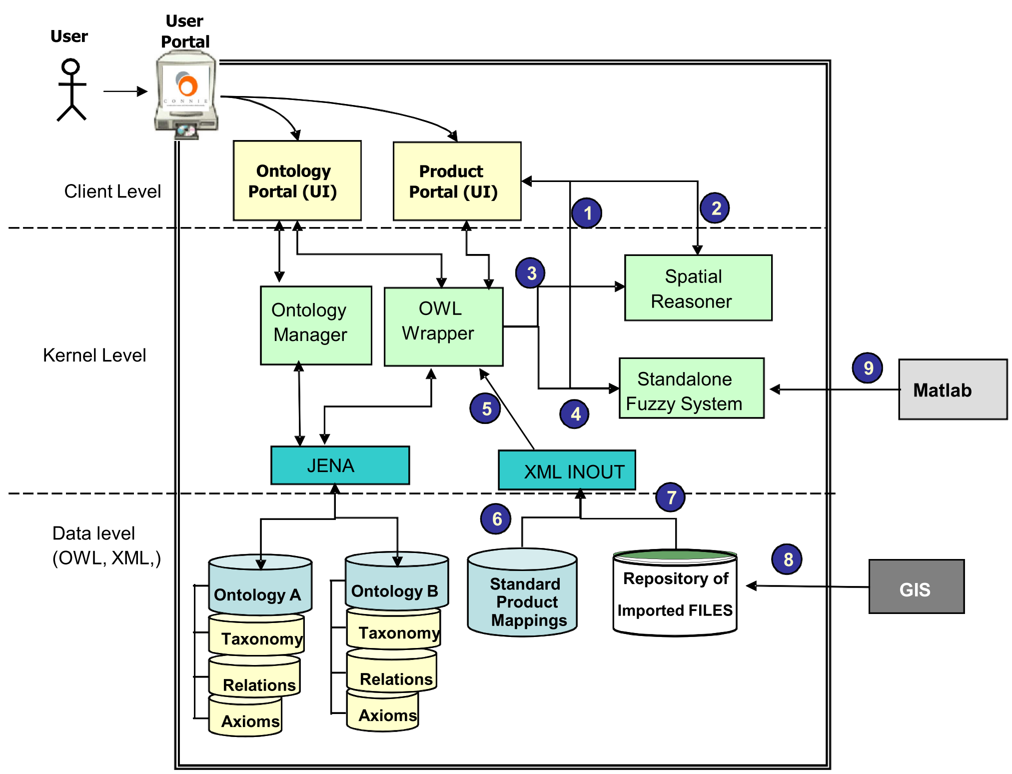

Fig. 4. General architecture of the route management system

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2. OWL geospatial data wrapper: Intended to map existing utility infrastructure geospatial data into an ontology-compliant format. The wrapping system is composed of three main matching procedures: product matching, attribute matching, and attribute-value matching. Product matching is performed to identify the infrastructure product (e.g., water pipe, gas valve). Since infrastructure-product geospatial data is always stored as layers of distinct products, the system assumes that each data file contains only one type of product. Attribute matching relates a set of geospatial field names (commonly referred to as attributes in GIS terminology) to their equivalent attributes in the ontology. Finally, attribute-value matching matches a set of geospatial field values (commonly referred to as attribute values in GIS terminology) to their equivalent attribute lists in the ontology. For example, an attribute could be "gas pipe material" while its attribute-value could be "high-density polyethylene." The semantic representation of utility products and their attributes in the ontology allows this matching to proceed in a semiautomated fashion. Details of the semantic matching procedure can be found in El-Diraby and Osman (2009).
3. Constraint quantification modules: The previous two steps are common in the case of macrolevel and microlevel analysis. However, when it comes to the quantification of constraints/criteria, two different approaches are used. The macrorouting DSS relies on a fuzzy inference system (FIS) to provide a score for each route. This is done through support from Matlab. The microrouting DSS uses a constraint-satisfaction approach. It utilizes a spatial constraint reasoner (SCR) to test and report on constraint satisfaction or violation. The rationale for using two different approaches will be clarified in the next two sections.

Other modules in the kernel layer include the Jena engine and the XML IN/OUT module. The Jena engine (HP 2009) is an OWL-based API that allows direct access to and manipulation of the ontology files written in OWL. The XML IN/OUT module is a software application that acts as middleware between the ontology and XML-based geospatial data. OWL stands for Web ontology language, the de facto standard for ontology representation. API stands for application protocol interface, XML stands for extensible markup language, and XML IN/OUT is a protocol to handle XML data.

Data Layer

The final layer in the architecture is the data layer. This layer is composed of the actual files that describe the ontology in OWL, the geospatial data in XML, and mappings between standard utility data models and the ontology in XML. This layer is tied to a GIS tool that is the primary means for data input and output (visualization). The product and routing ontologies also reside in this layer.

The main flow of events in the system is shown in Fig. 4:

1. Data acquisition: The user acquires data that is required for the analysis. This will usually be in the form of GIS-based spatial information and tabular records.
2. Route proposals: During this step, the user selects a number of various routes for the analysis. These routes are entered as a GIS layer.
3. Data wrapping: This process involves using the OWL geospatial data wrapper. This process combines several GIS layers into a single consistent OWL-instance file that is compliant with the Ontology.
4. Criteria selection: This is the first step in the analysis of routes. The user selects the routing criteria that are required in the analysis. The user can select any (or all) of the seven criteria.
5. Analysis results: In the microlevel DSS, a list of satisfied and unsatisfied constraints is provided. In the macrolevel DSS, using the FIS, a score is assigned for each of the routing criteria selected in the previous step. Scores are assigned at a segment level and then augmented at the route level.

Microlevel Routing DSS

This software implementation is intended to assist infrastructure designers in selecting the best location for a utility along a street (see Fig. 5). First, users upload route options as GIS layers. They then can select the constraints to be checked. Table 2 shows a sample of these constraints and their relationship to decision criteria. The OWL spatial constraint satisfaction reasoner (OSCSR) builds a 3D database that relates the attributes of the route concerned and those of surrounding area/products to the constraints. The database is subsequently examined by the constraint violation algorithm. The algorithm iterates through instances of all products and checks to see if any routing constraints have been violated. Products that violate a constraint are added to a database that links up instances

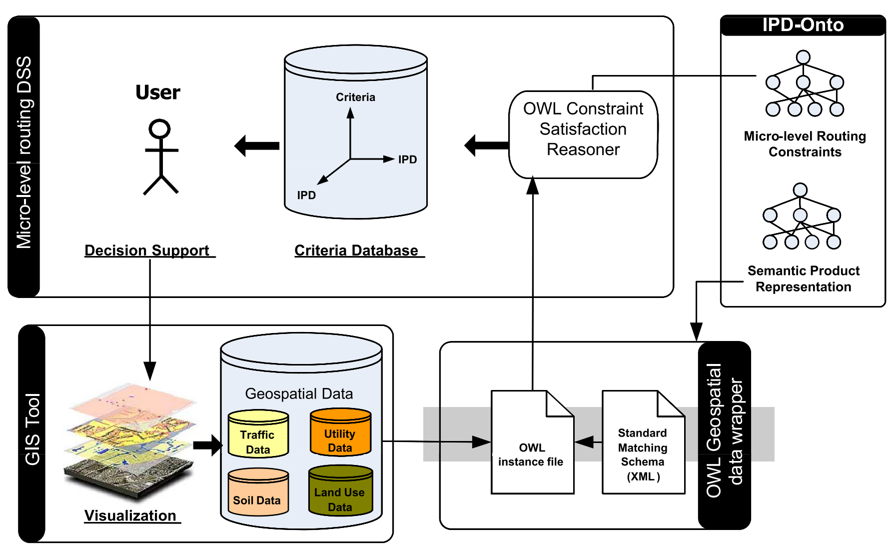

Fig. 5. Microlevel routing DSS

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Table 2. Sample Spatial Constraints Used during Microlevel Routing

Constraints	Constraint type	Routing criteria/constraint purpose
Minimum separation between water mains and sewer mains is 2.5 m	Hard/clearance	Infrastructure safety
Minimum vertical clearance between sewer lines and any utility is 300 mm	Hard/clearance	Infrastructure safety and security maintainability
Minimum distance between street poles and water lines is 1 m	Hard/clearance	Infrastructure safety and security maintainability
It is not preferred to route any utility below existing manholes	Soft/location preference	Constructability/community impact
If possible always route a new utility in the sidewalk	Advisory/location preference	Traffic impact/maintainability
Running utility lines in close proximity to tress may threaten the livelihood of trees	Advisory/location preference	Environmental impact/community impact

of infrastructure and generic products with other violated routing constraints.

The system then reports on the violated constraints. Because of the scope of DSS use, the user may wish to investigate only constraints that are related to a code or a certain type of product. For example, during early design stages, designers may be interested only in investigating hard constraints (code stipulations), while during later detailed design stages, they may be more interested in refining their design via advisory constraints (lessons learned/best practices). Summary charts can be created to view the multidimensional relationships between violated constraints and the infrastructure products that cause violation. For example, the user can visualize what products are in violation of which constraints, or simply visualize a breakdown of violated products by sector. Fig. 6(a) shows a screen shot of a microlevel routing case. Fig. 6(b) shows one of the typical charts produced by the system. In this case, 18 infrastructure products were either in direct violation of a hard/soft constraint or were a source of concern for an advisory constraint. The figure shows that the water and sewer pipes were of concern for sustainability issues while the gas pipes posed specific maintainability concerns. The figure also shows that for the violated constraints, all safety-related constraints are hard while those pertaining to constructability, maintainability and sustainability were either soft or advisory in nature.

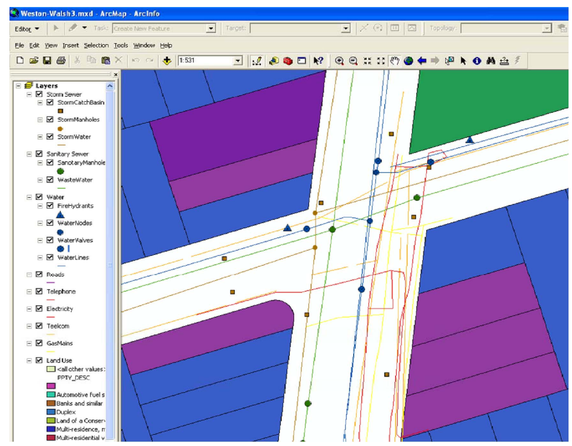
Macrolevel Routing DSS

The relationship between attributes and routing criteria is not a straightforward one. Because of the subjective nature of the domain, no formal mathematical models exist. Typically, engineers rely on heuristics, rules of thumb, and common sense to provide a sensible score for routing criteria (Luettinger and Clark 2005). In addition to the ability to use the constraint-satisfaction algorithm, the macrolevel routing offers a fuzzy inference system to help quantify a single measure of the performance of the route. Fuzzy logic lends itself nicely to macrolevel routing problems because it (1) involves imprecise data, (2) requires subjective judgments, and (3) involves the uncertainty associated with human perception (Ross 2004).

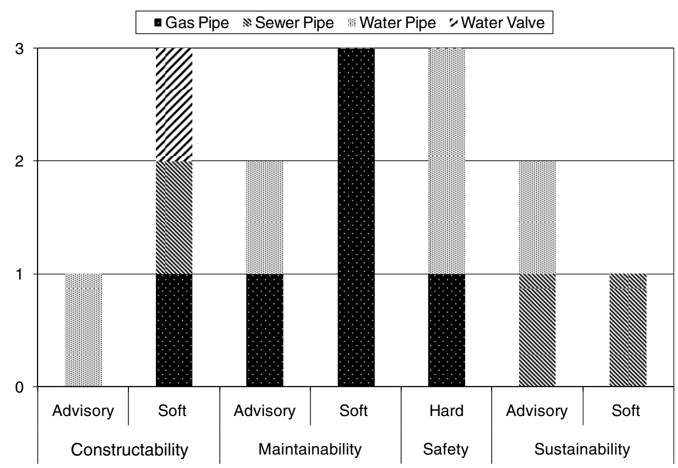
The use of a macrolevel routing system follows the following basic steps:

Fuzzy Inference System

A route is typically decomposed into a series of homogeneous segments that exhibit the same (or similar) attributes. The FIS provides a score for each segment with respect to the selected routing criteria. The user can also opt to perform the analysis on any subset of the criteria. Scores are represented on a 1 to 10 scale (with 1 standing for the least impact and 10 the greatest impact possible). For each criterion, a corresponding set of evaluation factors was compiled. For each criterion, a minimum of three and a maximum



a. Composite Utility and Land Use map



b. Constraint Violation Summary Report

Fig. 6. Example of constraints summary produced by the system

of five influencing factors were used. These factors were then presented in fuzzy numbers, which are functions of data that can be extracted from the GIS file or user input.

It is not feasible to show all the fuzzy formulas that were used in this regard. Some appropriate illustrative examples will be provided.

Traffic Impacts

Assessing the exact impact of road closures on traffic flow is possible through the use of formal analytical methodologies. Examples range in complexity from a simple delay analysis that estimates the effect on traffic along the street to more complex microscopic traffic simulations that analyze the impact on the entire road network.

Through our interviews with domain experts, the use of the analytical methods were deemed unsuitable during macrolevel routing because: (1) The information needed to perform these analyses are usually unavailable at the early project-planning stages, and (2) The cost of performing some of these analyses is usually beyond the budget of most routing studies. As such, only three variables were selected. The output value for impact on traffic is a 10-point rating scale (1 being best and 10 being worst). This variable was further fuzzified into five distinct membership classes: very low, low, average, high, and very high.

Traffic Flow

The intensity of traffic in the proposed route can be measured by the average annual daily traffic per lane of roadway for any particular street. The fuzzification of this variable included dividing it into three linguistic terms: low flow, medium flow, and high flow as follows:

$$\mu_{\text{low}} = \begin{cases} 1; & x \leq 800 \\ (-x + 1,600)/800; & 800 \leq x \leq 1,600 \\ 0; & x \geq 1,600 \end{cases} \tag{1}$$

$$\mu_{\text{medium}} = \begin{cases} 0; & x \leq 800 \\ (x - 800)/800; & 800 \leq x \leq 1,600 \\ 1; & 1,600 \leq x \leq 2,400 \\ (-x + 3,200)/800; & 2,400 \leq x \leq 3,200 \\ 0; & x \geq 3200 \end{cases} \tag{2}$$

$$\mu_{\text{high}} = \begin{cases} 0; & x \leq 2,400 \\ (x - 2,400)/800 & 2,400 \leq x \leq 3,200 \\ 1; & x \geq 3,200 \end{cases} \tag{3}$$

where x = average per-lane traffic volume; μ_{low} = membership function for low traffic flow; μ_{medium} = medium traffic flow; andμ_{high} = high traffic flow.

Percentage of Right-of-Way Occupation

The percentage of width of road ROW that will be occupied during the construction process is calculated as follows:

$$\%\text{ROW occupation} = \frac{\text{Expected width of construction zone}}{\text{ROW width}} \tag{4}$$

This variable was subdivided into three linguistic terms: low percentage, medium percentage, and high percentage. The following membership functions were assigned:

$$\mu_{\text{low}} = \begin{cases} 1; & x \leq 20 \\ -0.05x + 2; & 20 \leq x \leq 40 \\ 0; & x \geq 40 \end{cases} \tag{5}$$

$$\mu_{\text{medium}} = \begin{cases} 0; & x \leq 20 \\ 0.05x - 0.1; & 20 \leq x \leq 40 \\ 1; & 40 \leq x \leq 60 \\ -0.05x + 4; & 60 \leq x \leq 80 \\ 0; & x \geq 80 \end{cases} \tag{6}$$

$$\mu_{\text{high}} = \begin{cases} 0; & x \leq 60 \\ 0.05x - 3; & 60 \leq x \leq 80 \\ 1; & x \geq 80 \end{cases} \tag{7}$$

where x = %ROW occupation; μ_{low} = membership function for low occupation; μ_{medium} = membership function for medium occupation; and μ_{high} = membership function for high occupation.

Construction Method

The expected method of installation, i.e., trenchless or open-cut. Trenchless construction methods are less evasive and have lower impact on traffic. This is a crisp variable (0/1).

Constructability

Addresses the ability of the contractor to construct the pipeline in a timely manner without excessive interference from physical obstacles. These physical obstacles could include narrow ROW, limited site access, a limited staging area, steep terrain/slope, deep trench conditions, or other undesirable surface conditions. This decision criterion depends on two fuzzy variables and one crisp variable.

Excavation Depth

The expected depth of excavation (in meters) required to install the infrastructure product. Larger excavation depths tend to negatively impact the ease of construction. This variable was subdivided into three linguistic terms: small work zone, medium work zone, and large work zone. A statistical analysis by Chong and O'Conner (2005) that investigated the construction productivity of reinforced concrete pipes and precast concrete box culverts along highways identified three types of excavation depths that impacted productivity. "Shallow" excavations tended to be less than 3 ft in depth, whereas "deep" excavation depths were greater than 10 ft.

Width of Workzone

The expected width of the construction zone may differ across corridors depending on the available ROW. This variable was subdivided into three linguistic terms: small work zone, medium work zone, and large work zone. Chong and O'Conner's same statistical analysis (2005) also identified three types of work zone widths that impacted productivity. "Small" work zones tended to be less than 5 ft width, whereas "large" work zones were greater than 15 ft.

Need for Dewatering

This is a crisp variable that indicates the need for dewatering. It takes on the value of "Yes" or "No." If excavation depth > depth of ground water table then "Yes." Otherwise, "No."

Soil stiffness is classified into three main groups: loose, stiff, and rocky. This is a crisp variable.

Impact on Residents

Two of the three factors that affect impact on residents were fuzzified based on recommended ranges from the literature and input from industry experts.

1. Population density: The average population density per square meter along a particular corridor. This variable was subdivided into three linguistic terms: low density, medium density, and high density. The values for the membership functions were based on percentile population densities for the city of Toronto. Proxies to this variable such as dwelling density (dwelling per hectare) can be also used.
2. Percentage residential land use: The percentage of residential land use along a particular corridor. This variable was subdivided into three linguistic terms: low percentage, medium percentage, and high percentage.
3. Construction method: The expected method of installation; trenchless or open-cut. This is a crisp variable.

Impact on Businesses

Two of the three factors that have an impact on businesses were fuzzified based on recommended ranges from the literature and input from industry experts.

Percentage of Construction Schedule Overlap

This variable is a function of the expected daily construction schedule and the predominant business operating hours along a particular corridor. It is calculated as

$$\%\ \text{Schedule overlap} = \frac{\#\ \text{of hours construction occurs while businesses are open}}{\#\ \text{of daily business hours}} \tag{8}$$

This variable was subdivided into three linguistic terms: low percentage, medium percentage, and high percentage.

Percentage of Commercial Land Use

The percentage of commercial land use along a particular corridor. This variable was subdivided into three linguistic terms: low percentage, medium percentage, and high percentage.

Construction Method

The expected method of installation, i.e., trenchless or open-cut. This is a crisp variable.

Utility Conflicts

All three factors that affect potential for utility conflicts were fuzzified based on recommended ranges from the literature and input from industry experts.

Average Number of Service Connections/100 m

This variable is used as a proxy for utility congestion in light of the usual unavailability of a detailed composite utility map for all routes under consideration during early planning stages. It is calculated as

$$\begin{aligned}&\text{Average number of service connections per 100 m}\\&\quad= \text{Average number of land parcels per 100 m}\\&\qquad * \text{Number of buried utility systems}\end{aligned}$$

This variable was subdivided into three linguistic terms: low, medium, and high. The ranges for these variables were obtained by analyzing various sets of utility plans in Toronto.

Number of Utility Agencies

The total number of utility agencies that require coordination along a particular corridor. This variable was subdivided into three linguistic terms: few, average, and many. The ranges for these variables were obtained by analyzing several utility projects in Toronto and input from industry experts.

Number of Buried Utility Systems

The total number of buried utility systems along a particular corridor. This variable was subdivided into three linguistic terms: few, average, and several. The ranges for these variables were obtained by analyzing several utility projects in Toronto and input from industry experts.

Maintainability

This decision criterion is divided into two subcriteria: corrosion susceptibility and accessibility. The subcriteria for maintainability were assigned a 10-point rating scale.

Corrosion Susceptibility

Describes how likely a buried infrastructure product will deteriorate over its life cycle because of corrosion. This subcriterion is a function of three fuzzy variables and one crisp variable. Three of the four factors that affect corrosion susceptibility were fuzzified based on recommended ranges from the literature and input from industry experts.

Soil resistivity: A measure of how well a saturated soil allows the flow of electrical current, measured in ohm/cm. Soils with a lower resistivity are considered more corrosive. Fuzzy membership functions to represent soil pH were modeled after the 10-point scale proposed by the AWWA (1999) to predict soil corrosion susceptibility based on soil resistivity. Soil resistivity (measured in ohm per cm) is divided into five logical triangular fuzzy sets of very low, low, average, high, and very high.

Soil pH: A measure of concentration of hydrogen ions as it relates to acidity and alkalinity. Fuzzy membership functions to represent soil pH were proposed by Markopoulos et al. (2003). The pH levels are divided into three logical distinct fuzzy sets of acidic, neutral, and alkaline. The fuzzy function proposed by Makropoulos et al. (2003) to represent soil pH is a generalized bell curve function. This function takes the general form

$$\mu(x) = 1/[1 + |(x - c)/a|^{2b}] \tag{9}$$

The parameters for the function take on the values

$$\mu_{\text{acidic}}(x)\colon \{a = 4.5, \quad b = 3.9, \quad c = 0\}$$

$$\mu_{\text{neutral}}(x)\colon \{a = 1.35, \quad b = 1.2, \quad c = 7\}$$

$$\mu_{\text{alkaline}}(x)\colon \{a = 4.5, \quad b = 3.9, \quad c = 14\}$$

where x = pH; and μ_{acidic}, μ_{neutral}, and μ_{alkaline} = fuzzy sets of acidic, neutral, and alkaline soils, respectively.

Percentage of fines: This is used as a surrogate measure for a soil's drainage characteristics. Soils with a greater percentage of fines are more likely to retain moisture leading to higher soil corrosivity (Sadiq et al. 2004). This variable was subdivided into three linguistic terms: low percentage, medium percentage, and high percentage.

Cathodic protection: As it relates to susceptibility to corrosion, metallic pipes with cathodic protection will be less susceptible to corrosion. The type of cathodic protection system implemented is beyond the scope of this analysis. This is a crisp variable.

Accessibility

Describes the relative ease with which a buried infrastructure product can be accessed for maintenance or repairs. This subcriterion is a function of two fuzzy variables and one crisp variable.

Traffic flow: The ease of accessibility for a buried infrastructure will tend to decrease along streets that have higher traffic volumes. This variable suggests that performing maintenance activities on buried utility systems becomes more difficult on streets that have higher traffic volumes especially if the access points are located in the roadway.

ROW location: This variable represents the expected location within a ROW. Access points that are located in sidewalks provide for easier maintenance than those located within the roadway. This is a crisp variable.

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Number of access points per 100 m: This variable represents the number of available access points (manholes, chambers, junction boxes, etc.) for a particular utility line. Although maximum spacing for access points are usually specified in design codes, designers may opt for smaller spacing to enhance maintainability.

Scoring

Scores for individual segments are combined to create an overall score for the route they belong to. The system provides the user with four options for decision support: (1) single-criterion selection, (2) simple average score, (3) weighted average score, and (4) AHP pair-wise comparison. The first procedure is a single-criterion decision-making approach while the other three are multi-criteria approaches. In all cases, an overall route score that takes into account all routing criteria is calculated. The route with the least overall score is considered the one with the least impact and hence the most favorable. The following is a description of each decision-support procedure.

It is assumed that the planner or routing engineer has a finite decision space of feasible routes (denoted as A through N)

$$\text{Route Decision Space} \supseteq \{A, B, C, \ldots N\}$$

Any given route R is assumed to be composed of a series of route segments. Si:

$$\text{Route } R \supseteq \{S_1, S_2, S_3, \ldots S_n\}$$

where n = number of segments that constitute route R.

The overall score of route R with respect to a routing criterion k is calculated as the weighted average of its constituent segments. The overall score is calculated as

$$\text{Score}(R^k) = \sum_{i=1}^{n} [\text{Score}(S_i^k) \times L_i] \Big/ \sum_{i=1}^{n} L_i \tag{10}$$

where $\text{Score}(S_i^k)$ = score of segment Si with respect to a routing criterion; k and Li = length of segment Si.

Rule-Based Compilation

In a fuzzy inference system, the knowledge pertaining to a given problem is characterized by a set of linguistic rules based on expert knowledge: If a set of conditions are satisfied, then a set of consequences can be inferred.

Ross (2004) lists three principal methods used to determine the relevant inference rules. One is to elicit them from experienced engineers. Another is to obtain them through common sense. The third method is to elicit them from some sort of database. The rule base was compiled using the first two methods and subsequently validated using a case study. The base is composed of 180 rules. The number of rules for each routing criterion was a direct function of the number of impacting attributes. The fuzzy inference rules relate relevant product attributes and surrounding conditions to routing criteria though combinations of if-then statements. An example of a rule used for the constructability criteria is

$$\begin{aligned} &\text{If Workzone Width} = \text{“Small” and Excavation Depth} \\ &\quad = \text{“Deep” and Dewatering} \\ &\quad = \text{“None” and Soil Type} \\ &\quad = \text{“Loose”} \\ &\textbf{Then } \text{Constructability} = \text{“Low”} \end{aligned} \tag{11}$$

Table 3. Sample Rules for the Routing Criteria of Utility Conflicts

No.	Average # of service connections/ 500 m	Number of utility agencies	Number of buried utility systems	Utility conflicts
1	Low	Few	Few	Very low
2	Low	Few	Average	Very low
3	Low	Few	Many	Low
13	Medium	Average	Few	Medium
14	Medium	Average	Average	Medium
15	Medium	Average	Many	High
25	High	Several	Few	High
26	High	Several	Average	Very high
27	High	Several	Many	Very high

Table 3 shows a sample of the rules that were used. A total of 180 rules were used. Of course, as more rules are discovered they can be embedded into the ontology and will, then, be usable by future users.

Evaluation

The evaluation of the proposed system started with the typical procedure in software development to test all aspects and track any bugs. User testing was carried out in two different ways: a forum of potential users was consulted to evaluate the functionalities of the system and two case studies were conducted that included actual usage of the proposed system. First, six potential end users were interviewed (in the form of a user forum) to comment on the usability of the system. The forum participants were city engineers and consultants who are typically engaged in routing coordination projects. The forum started with a detailed demonstration of the system and its functionalities. Then, users were asked to experiment with the system through a set of demo cases. At the end, user comments and discussions were recorded. The assessment showed that the most important benefits of using the system are:

1. Time savings: This is realized first during spatial data integration. An extensive amount of time is spent by city technicians in assembling and integrating data from geospatial and nongeospatial sources. The data integration capabilities provided by the ontology and made possible through the use of the OWL-wrapper can save considerable amounts of time. Second, time savings are realized because of the system's automated constraint checking. City staff were specifically interested in the clearance constraints used by the system (based on code requirements). The fact that the GIS system contained information on the horizontal and vertical locations of buried infrastructure allowed for a quick (and accurate) check to be performed against code requirements. Traditionally these checks were time consuming and sometimes inaccurate due to the fragmented nature of the data (CAD files, specifications, and survey information). Finally, time savings could also be realized during the approval phase. Approval of a proposed route from utility companies can often take a considerable amount of time. This is because of (1) the traditional hard copy drawing circulation procedure required by some utility companies and (2) the manual constraint-checking process used in the review.
2. The rationalizing of the prescreening process to enhance public communication: This was more relevant in macrolevel situations. Because of the normal sensitivity of these projects to local residents, the public consultation process could be

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quite contentious. Consultants believed that the system could be helpful in rationalizing the prescreening process by eliminating those routes that are infeasible right from the start of the project. The fact that the tool is readily accessible to the general public would add considerable credibility to the prescreening of routes.

3. Reliability and improved coordination: City staff usually conduct several utility coordination meetings with utility companies that operate infrastructure within the vicinity of any proposed project. The use of the Web-based GIS system would have greatly improved the efficiency of these meetings by allowing most technical issues to be exposed. More importantly, it would have provided assurance that all constraints had been addressed, thereby contributing to increased reliability in decision making.

As with any computerized systems, there are costs that could be incurred from the implementation of the proposed DSS. The costs associated with a knowledge-management system can be categorized into:

- Development costs: The costs associated with the analysis, design, implementation, and deployment of the system.
- Training costs: The costs associated with training staff to use the system and the lower productivity that might be expected due to learning-curve effects.
- Maintenance costs: The cost associated with maintaining the system infrastructure and contributing knowledge to the system.

In addition to the forum, two test cases were conducted in collaboration with city officials and consultants from Toronto.

Microlevel Routing: Weston-Walsh Watermain Replacement Project

This project involved the replacement of a 1050 m distribution waterline along Weston Rd. and Walsh Ave. in Toronto. The project was completed in 2005 and cost the City of Toronto CAD$600,000. The then existing 200 mm cast-iron watermain was replaced in part by a 400 mm PVC pipe and a 300 mm PVC pipe in another part. The project was selected because of its relatively accurate and detailed level of buried utility information (a full subsurface engineering study was conducted for the project). Project data was extracted from city documents and prepared for use by the system. A set of relevant engineers were asked to use the system to decide on a route (see also Fig. 6).

Using an already implemented project provides several advantages. First, we can validate the results of system use against an actual decision made independently of the system. It also allows for comparing the effectiveness of a decision-making process with and without the system. The final conclusion made by the test group matched the decision made by city officials during the actual project-planning stage. They also provided positive feedback on the impact of the proposed system on communication efficiency and duration.

The raw data that was obtained from the City of Toronto was processed using the proposed system:

1. CAD/GIS data integration. The data provided by the city was in both CAD and GIS formats. The consultant that performed the subsurface utility engineering (SUE) study delivered the nonmunicipal utility mapping in CAD, the design of the new watermain was in CAD, while the city's existing utility assets and land use were in GIS. All CAD data was transferred to GIS. This task took 1.5 h. Fig. 6 shows some screen shots of the proposed system, which also portrays part of the CAD/GIS integrated data view.
2. Wrapping. This data was subsequently transformed into an ontology-compliant format using the OWL geospatial data wrapper. Because the city's data did not follow any standardized schema, the matching process between the city's data model and the ontology took 2.5 h. Had a standard matching schema been available, the wrapping process could have been completed in approximately 15–20 min. Based on feedback from the City of Toronto engineers involved in the project, the following potential benefits would have been attained from using the system.

Time savings: in terms of the spatial data integration, using the OWL wrapper would have eliminated an estimated 40–60 h of data preparation by city staff. In terms of automated constraint checking, city staff reported that all the constraints that they needed to use were available in the system—again they were very interested in clearance constraints (which are articulated in detail). The quantification of some subjective constraints/criteria such as constructability and maintainability was welcomed by the staff too. Finally, on this project, utility review and approval consumed nine business days by the time all approvals were received. The use of the Web-based GIS system would have significantly reduced this time. If users are relatively prompt, it should not take more than one business day.

Improved utility coordination meeting efficiency: On this specific project, two coordination meetings were held during the actual project time. The use of the Web-based GIS system could have greatly improved the efficiency of these meetings by allowing most technical issues to be exposed

Macrolevel Routing: Avenue Road and Duplex Avenue Feedermain Replacement Project

This project involved the replacement of 6.3 km of a water feedermain constructed on Avenue Road and Duplex Avenue from the High Level Pumping Station. The existing cast-iron watermains on Avenue Road and Duplex Ave were built in 1915 and 1923 respectively. The city has identified that the existing cast-iron watermain should be replaced with approximately 4 km of 900 mm diameter and 2.3 km of 750 mm diameter concrete encased steel lined watermain to increase the security of supply and improve system hydraulic performance.

The City of Toronto conducted a Schedule "B" Municipal Class Environmental Assessment. This case study focused on the assessment and evaluation of alternative routes. The consultant who conducted the routing study developed four routing options and the following set of constraints:

- Mandate that watermain connections be made to the existing feedermain chambers at two locations;
- Minimize the impacts to items such as trees, driveways, parking, school zones;
- Width of roadway and existing streetscaping features;
- Number of existing utilities within the road corridor;
- Difficulties of traffic management and possible road closures;
- Required connections to all intercepting smaller watermains that are now receiving service from the existing main;
- Existing watermain must remain operational until the new watermain is ready to be operational;
- Yonge Street (a busy commercial street) was eliminated from consideration due to extremely high volume of traffic; and,
- Minimize the number of watercourse crossings.

This case was conducted while the project was being investigated by the consultant. The same project data and decision criteria were used in both situations. The consultant that conducted

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the routing study on behalf of the city was asked to utilize the system to investigate the vitality of the four routes following a 1-h demonstration of the system. The consultant was asked to comment on its usefulness had it been used during the routing study.

Based on feedback from the consultant that prepared the routing study, the following potential benefits would have been attained from using the system:

1. Spatial data integration time savings: The OWL wrapper would have eliminated an estimated 80–90 h of data preparation by the consultant's staff.
2. Rationalizing of the prescreening process: Owing to the sensitivity of the project to local residents, the public consultation process was quite contentious. The public was somewhat unconvinced about the four routes that were proposed during the prescreening process. The consultant believes that the system can be helpful in rationalizing the prescreening process by eliminating those routes that are infeasible from the start of the project. The fact that the tool is readily accessible to the general public would add considerable credibility to the prescreening of routes.

City staff and the consultant commented on ways in which the system could be improved. Their recommendations included:

1. Adding functionality to the system to allow for comments by approving utility companies to be sent though the Web-based system. This again confirms the importance of communication in this context over reasoning. This can also help indirectly in the preservation of corporate memory. A project blog has been added to support this need.
2. Extending the fuzzy model to include other routing criteria and/or product attributes. The items suggested include scheduling, labor and equipment issues and other project management concerns. While these are very valid criteria, extending the proposed model to include such items could result in an overwhelmingly complex system. It is therefore suggested that future work focus on integrating the proposed model with existing 4D systems. Such systems are very mature and can provide business-type value and presentation levels. In other words, the proposed system can be used to screen out routes that have substantial impacts on the sustainability of a local community. 4D and other software can then be used to select the most economical route.
3. The relatively complex nature of the fuzzy inference system and its rules. Unfamiliarity with fuzzy systems could render the macrolevel routing as vague or give the feeling that the decision maker is dealing with a black box. In contrast, users felt more comfortable with the criterion-by-criterion format of the microlevel DSS. Accordingly, the macrolevel DSS was changed to provide both options: to use FIS or to check on each individual criterion as in the microsystem. Of course, the use of Matlab means that each organization can customize the rules and the FIS based on their needs.

Conclusions

The aim of this project was to establish a knowledge-enabled system to support the collaborative routing of buried urban-infrastructure utilities. The proposed system attempted to address the complexities of such decisions though a communication-oriented portal that supports exchange of information and helps in decision reasoning. This was achieved through the creation of three developmental components:

1. An ontology for design coordination of a collocated urban infrastructure. This ontology is a representation of concepts, attributes, decision criteria, constraints, and axioms for the routing decision making. The proposed ontology encapsulates route attributes such as the physical attributes of the utility being routed (e.g., diameter and material type) and surrounding area attributes (e.g., traffic volumes and business activity). The ontology also encapsulates decision criteria such as constructability and maintainability, constraints both spatial and nonspatial, and potential impacts. The formalization of these concepts into an ontology facilitate their use in the GIS portal and the decision-support system. Further, it helps in the preservation of existing and future knowledge.
2. A CAD/GIS portal for checking constraints. The fundamental belief of this work is that a universal or automated routing decision-making system is not feasible. What is feasible (and more relevant) is a communication portal that helps diversified stakeholders to share information and reach agreements. In addition to wrapping CAD and GIS data to achieve interoperability, the portal employs a set of algorithms driven by the ontology to test the satisfaction of user-selected constraints. The system does not select the optimum route. Rather, it submits information to users to facilitate just that.
3. The creation of quantification tools. For users who want help in quantifying some of the rather subjective criteria/constraints, the system used a set of AI tools to provide the means for such quantification.

The fundamental features of the proposed system include:

1. Flexibility: Users can use the current ontology, an updated version of it or a completely new ontology. Further, they can update/change the constraints (this may require some training, however), and can opt to use the quantifying tools or not.
2. Addressing problems associated with urban environments: Most studies have focused on rural/cross country pipeline infrastructures. Routing criteria that are specifically sensitive to urban areas (e.g., traffic impacts, business impacts, resident impacts) were not well-addressed in the literature.
3. An implementation that allows for stakeholder involvement in decision making: All systems described in the literature were stand-alone systems that were designed to allow only one actor (usually a consultant) to analyze the impacts of routes. As such, systems were quite inflexible in allowing multiple stakeholder participation in the routing analysis.

As a decision-support system, the fundamental benefits of the proposed system can be summarized (based on expert input and lessons from other domains):

1. Cost reduction: The proposed system is not meant to replace humans, but rather support their decision making. Traditionally designers and decision makers from various infrastructure jurisdictions meet frequently to coordinate their plans. Like any other computer program, it is anticipated that the use of the proposed DSS will increase the efficiency of these meetings and help handle the issues under discussion in a more effective way. This could eventually increase the efficiency of the design and coordination processes.
2. Communication enhancement: Communicating project plans to local communities is becoming a major issue for all urban projects. The availability of a Web-based semantic system will make such communication much easier and help expedite public consultation. At the professional level, all designers and decision makers can access project information online and reduce interorganization communication needs.
3. Corporate memory: The documentation of best practices and domain knowledge in the ontology and the routing criteria will help preserve corporate memory in light of the increasing turnover rates for personnel. In addition, the preservation of project data in electronic formats and according to ontology concepts

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will allow for future trend analysis and data mining that could lead to further discovery of knowledge.

4. Design integration: The ontology allows for the incorporation of expertise from various domains. Concerns from related domains can be integrated in the decision-making process in a formal manner. It could also assure a minimum level of inconsistency in this process.

Notation

The following symbols are used in this paper:

i = route segment counter;

k = criteria counter;

L = length of segment;

n = number of route segment;

R = route;

S = a route segment; and

$\mathrm{Score}(S_i^k)$ = score of segment i relative to criteria k.

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