INTEROPERABLE DECISION SUPPORT MODEL FOR ROUTING BURIED URBAN INFRASTRUCTURE

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ABSTRACT

Information interoperability initiatives in the infrastructure domain have consistently lagged behind their counterparts in the building sector. Urban infrastructure development involves a tremendous amount of stakeholders that necessitate a seamless exchange of information and a mechanism to capture and reuse knowledge. One of the processes that have been found to involve a large amount of information exchange and rely on a considerable amount of cross-sector knowledge is the process of infrastructure route selection. As such, this paper presents a schema for representing spatial constraints that pertain to buried urban utility systems. These constraints drive the process of utility route selection that is a vital step in design. Constraints that are included in the interoperable model include tacit knowledge that experienced designers use in route selection. Although these constraints can be considered as ‘best practices’ rather than hard constraints, they are motivated by criteria that are often overlooked in traditional engineering design guidelines (sustainability, impact on businesses, maintainability, constructability, etc…). As a design tool to assist infrastructure routing in urban environments, the aforementioned model is implemented in a prototype web-based GIS decision support portal that can be used by designers of new utility systems.

KEY WORDS

Decision Support System, Urban Infrastructure Design, GIS, XML.

INTRODUCTION

Route selection is one of the main processes in the design of infrastructure networks. Although this process can be very straight forward at times, routing buried infrastructure in congested urban environments can be a daunting task for designers. Complexities that arise in urban environments include: 1) The congested nature of underground space, 2) The large number of utilities that utilize the ROW and the associated need for coordination, 3) Relatively high traffic volumes that constrains construction methods and work zones, and 4) Impacts on surrounding businesses and residents that should be minimized. Generally speaking, the route selection process can be approached from two levels of detail: macro-level routing which is mainly concerned with corridor selection, and micro-level routing that focuses on location selection within a particular corridor.

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The focus in this paper is on the micro-level. This level is generally characterized by its reliance on a fragmented set of knowledge items that span various utility sectors and project stages. In order for this knowledge to be made explicit, shared and reused, a common knowledge representation schema is required. This paper presents an interoperable decision support model that is built on a schema for representing spatial constraints between infrastructure products. This schema is used to create a prototype GIS collaboration portal that can be used during the micro-level routing of buried infrastructure networks in urban settings.

BACKGROUND

INTEROPERABILITY

A recent study by the National Institute of Standards and Technology estimates the cost of inadequate interoperability among computer aided design, engineering and software systems in the U.S. capital facilities industry to be $15.8 billion per year (Gallaher et al, 2004). The term ‘interoperability’ is used to refer to the ability of systems or – in the boarder sense – organizations, to communicate in a collaborative environment. That being said, interoperability can be assumed to exist at three cascading levels of complexity. At the lowest level, data interoperability is concerned with achieving the ability to exchange data across different systems. This level is mainly concerned with low-level file format issues and data representation consistencies. At a higher level, information interoperability is mainly concerned with the ability to interpret, and understand the meaning of data that is being exchanged. In this regard, metadata standardization initiatives like the Industry Foundation Classes and Geography Markup Language (Lake et al, 2004) fall along the lines of information interoperability initiatives. Finally, the deepest level of interoperability is that of knowledge, whereby systems and organizations not only exchange and interpret information, but are able to deduce new information that is not explicitly defined. Ontologies can be considered to be one of the facilitators of knowledge interoperability. This paper focuses specifically on information/knowledge interoperability.

Information interoperability initiatives in the infrastructure domain have consistently lagged behind their counterparts in the building sector (Froese, 2003). In spite the tremendous challenges faced by infrastructure development, there is a shallow understanding of its stakeholder’s information exchange requirements. This paper attempts to shed light on these requirements during the process of micro-level infrastructure routing.

COORDINATING THE DESIGN OF URBAN INFRASTRUCTURE

Urban transportations corridors accommodate a plethora of buried utility systems that are managed by a multitude of agencies. One infrastructure renewal project that was examined by the authors in the City of Toronto required coordination among 11 different agencies that manage infrastructure along a single corridor. One of the main processes that are involved in design coordination is the process of route selection or routing. The routing process can be assumed to exist at two levels of detail; Macro-level and Micro-level. The following section compares between these two processes.

Macro-level routing

This level focuses on the selection of a particular corridor in which the infrastructure will be located. The selection is performed between a set of feasible alternatives whereby the best route is chosen that will satisfy a set of pre-set project goals. These goals will include both cost and non-cost issues (Luettinger & Clark, 2005). In congested urban areas, community disruption has become a significant issue in urban infrastructure decision-making and hence this process will usually involve a high level of public involvement. The process is usually performed during project planning / early design stages where information pertaining to the surrounding environment is usually scarce and uncertain.

Due to the nature of infrastructure systems in urban areas, distribution systems will generally tend to be found on almost every street where the surrounding land-use requires servicing. Hence corridor selection does not tend to be an issue for distributions systems. On the other hand, for large transmission systems that convey a utility from one location to another, corridor selection is a long-term decision that must be carefully studied.

Micro-level routing

This level of routing is mainly concerned with the selection of the most suitable location for an infrastructure product along a particular right-of-way. The process is usually performed during detailed design stages where information pertaining to the surrounding environment is usually available and reliable. The scope of micro-level routing will usually include supporting structures (manholes, valve chambers, pedestals, etc…) in addition to conveyance products themselves (pipes, cables, etc…). Table 1 provides a comparison between the two levels of routing according to various classifying criteria.

Table 1 Comparison of Macro and Micro-level urban infrastructure routing

Criteria	Macro-level routing	Micro-level routing
Description	Which corrdior/street?	Where within a ROW?
Process	Selection among alternatives	Constraint satisfaction
Scope	Conveyance system	Conveyance system and supporting structures
Infrastructure type	Transmission	Transmission / Distribution
Project Phase	Planning / Early Design	Detailed Design
Information	Scarce, uncertain	Available, more certain
Public involvement	Usually high	Usually low

Traditionally, micro-level routing relies on the process of utility coordination whereby the owner/designer of the proposed system will communicate the preliminary design to all utility owners that have plant within the vicinity of the proposed system. Each utility owner verifies that the location of the proposed plant and all associated construction activity do not conflict with their own plant. If a conflict exists, the design must be revised or the conflicted utility relocated. Details of this decision are beyond the scope of this paper. Figure 1 depicts this process and the scope of the model presented in this paper.

In general, location-related conflicts among buried utilities can be attributed to:

- Errors in the utility records on which the design is based: These errors were found to be extremely common in cases where sufficient field verifications are not performed (Osman & El-Diraby, 2005).
- Failure to comply with clearance requirements set forth by individual utilities: Individual utilities have minimum clearance requirements around their plant to mitigate damage during construction activities in their vicinity.

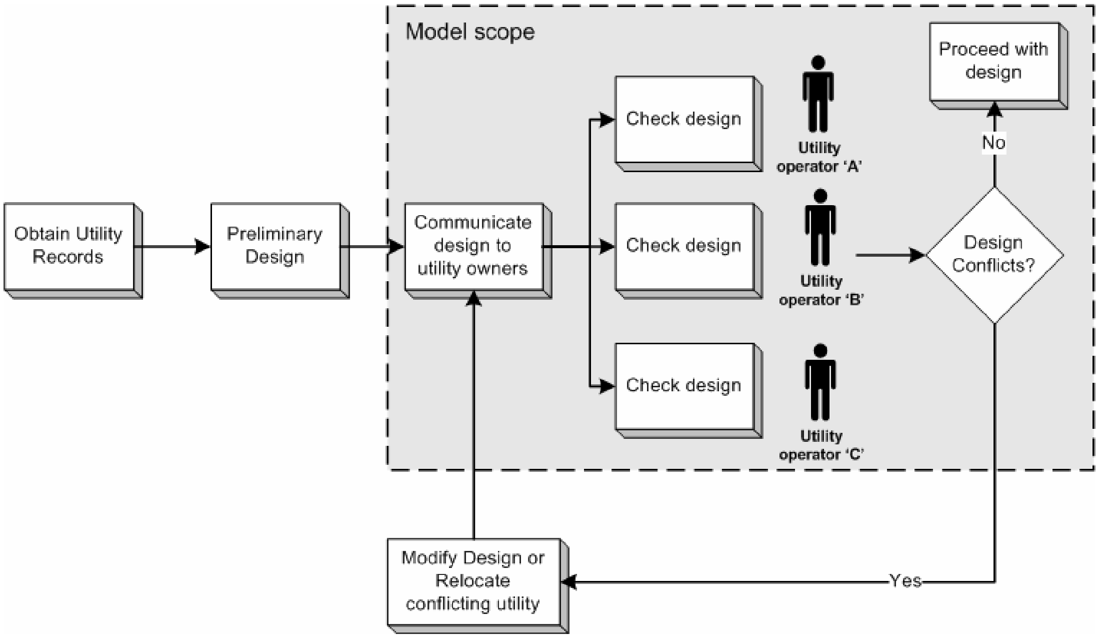

Figure 1 Utility design coordination process and scope of proposed model

This paper focuses mainly on the second source of error: the failure to include all clearance requirements stipulated by utility companies.

In addition to the failure to adhere to explicit minimum clearance requirements, the process of micro-level routing involves a deep level of cross-domain knowledge. Locating a buried utility line or any of its supporting structures (valves, manholes, pedestals, etc…) has a long-term impact throughout the life-cycle of all utilities that share the ROW. As such, there is a need not only to represent information (clearance requirements) but also to represent cross-domain knowledge in the form of best practices pertaining to the optimum route selection at the micro-level.

The proposed approach utilizes a sector-independent common information/knowledge representation schema that can be used to model spatial constraints impacting the micro-level routing of buried urban infrastructure.

CONSTRAINTS FOR MICRO-LEVEL ROUTING

Constraints that affect the process of micro-level utility routing can be classified as:

- Explicit Constraints: Include those constraints that are stipulated in design guidelines, codes, and manuals of practice. These criteria have evolved from industry best practices to become formally adopted requirements. They are usually hard constraints in the sense that they must be followed unless some extraordinary measure is adopted.
- Implicit Constraints: Include best practices that are systematically employed by designers in routing buried infrastructure. They have not yet evolved into explicit criteria that are documented in manuals of practice but are nonetheless utilized during the routing process. These criteria tend to be more situation-based compared to the more general explicit criteria.

The knowledge elicitation process for extraction of these criteria/constraints relied on the review of literature, manuals of practice, codes, etc… for explicit constraints and interviews with domain experts for implicit constraints. Experts from all domains of utility infrastructure (water/wastewater, electricity, gas, and telecom) were included in order to create a truly representative constraint model. Expertise did not only focus on design knowledge but also included knowledge pertaining to construction, maintenance and operation. The following section discusses details of the constraint model.

XML SCHEMA FOR SPATIAL CONSTRAINT REPRESENTATION

The XML schema for representing micro-level routing constraints is based on a situation-based representation for the conditions that trigger a constraint. Elements that describe any situation include:

InfrastructureProduct: The entity that is influenced by the constraint. To model constraints that are specific to a particular entity (e.g. sewer pipes greater than 500mm), this elements is extended by the *ObjectAttribute* element.

ObjectAttribute: Specifies the attributes for *InfrastructureProduct* for which this constraint applies. The attribute model for various infrastructure products is based on a cross-industry Infrastructure Product Ontology developed by the authors (Osman & El-Diraby, 2006).

Distance: Specifies the distance for which this constraint is triggered. The attribute *DistanceType* describes whether the constraint specifies a minimum or maximum distance constraint.

Object: Is used to describe the object(s) that the *InfrastructureProduct* interacts with within the constraint. This could be another infrastructure product (e.g. separation between watermains and sewermains) or between any entity in general (distance between manholes and business entrances). Again, the *ObjectAttribute* element details any specifics pertaining to the attribute values for the object(s).

SoilCondition: Describes soil conditions that trigger the constraint. The *SoilType* is based on the Unified Soil Classification system while the *GWL* element describes the level of ground water table. This is an optional element.

Temporal: Specifies the start and end dates that a constraint is valid through. This is an optional element.

LandUse: Describes the surrounding land use that may trigger a constraint and is based on the American Planning Association classification Land-Based Classification Standards (APA, 2005). This is an optional element.

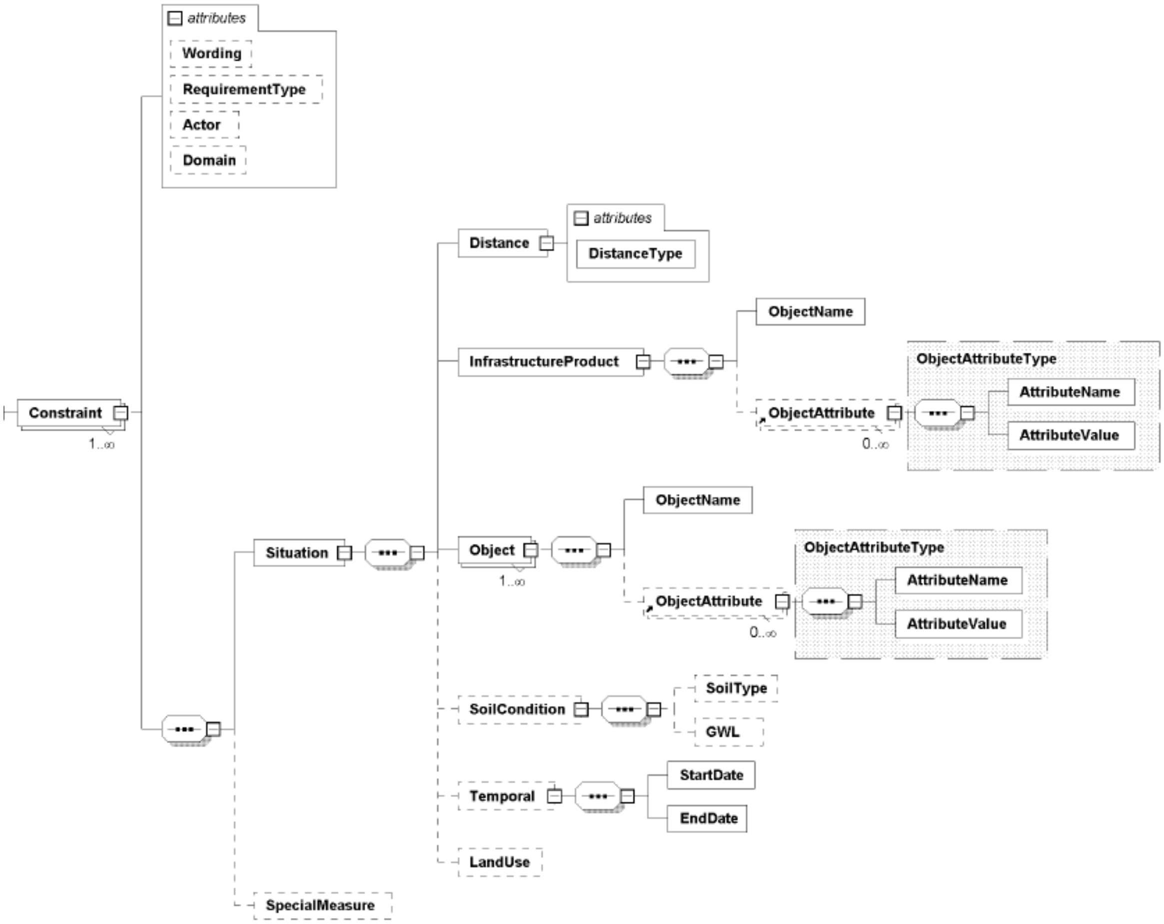

Figure 2 XML schema for representing routing constraints

SpecialMeasure: Describes a process that should be performed in order for the constraint to be relaxed. Examples include the special containment of watermains to allow them to be placed in close vicinity of sewers or installation of root deflectors for tress within close vicinity of gas pipes.

Besides the situation-based description of a constraint, several optional classifying meta-data is used to further describe the constraint:

Wording: The wording of the constraint in natural language.

RequirementType: Specifies the grade of the constraint as either being a ‘hard constraint’ that must always be followed, a ‘soft constraint’ that must be followed but can be relaxed in case a *SpecialMeasure* is performed or an 'advisory constraint' that should be followed if possible but can be relaxed if required. Implicit criteria / best practices usually fall under advisory constraints.

Domain: Specifies the reason for implementing the constraint. This could be for safety, environmental, maintenance, or economic reasons.

Actor: Specifies which organization or entity issues the constraint.

WEB-BASED GIS COLLABORATION PORTAL

The aforementioned constraint model is implemented in a web-based GIS collaboration portal. Primary users of the portal include local municipalities and utility companies who own/mange infrastructure within a ROW. The system relies on three main components: (1) An object oriented geo-datamodel that is built on an Infrastructure Product Ontology developed by the authors (Osman & El-Diraby, 2006), (2) The XML-spatial constraint model discussed in the previous section, and (3) A dynamic spatial constraint knowledge base which is built according to the XML-schema.

The primary use-case of the system assumes the following process flow (Figure 3):

1- The designer of a new utility system uploads a new design to the system in either CAD or GIS format. In case the uploaded file is a CAD file the user will be later asked to attach related attribute data.

2- The system will start resolving semantic differences between the uploaded data and that utilized by the OO geo-datamodel. Examples of semantic inconsistencies include layer, attribute and value naming (e.g. the uploaded data might refer to a 'Gas_Pipe' whereas the OO geo-datamodel uses 'GasLine'). The semantic matching is made possible by the Infrastructure Product Ontology running at the back-end, but nonetheless the user is prompted to confirm semantic matching.

3- After all semantic differences are resolved the existing geospatial utility data is appended with the new design.

4- The user selects which subset of constraints to check for based on the spatial constraint model. For example the user may want to check the design only against 'hard' constraints first to ensure that all minimum clearance requirements are satisfied and then to check 'advisory' constraints to know how the design may be improved. Alternatively the user may want to select on those constraints that have to do with Telecom infrastructure or those that are related to maintenance issues, etc…

5- Based on the selected constraint subset, the GIS system invokes a series of spatial queries that are stored in the spatial constraint knowledgebase in XML format. The output of this process is a violated constraint list that registers all constraints that were violated by the proposed design.

6- The user can append the design accordingly until it is ready for final submittal after which other affected parties (agencies that have utilities within the ROW) are notified. These agencies can then view the proposed new design using the system and invoke any subset of constraints to check the quality of the design against the knowledge base. The system allows for approvals and comments to be communicated among the collaborators to expedite the design coordination process.

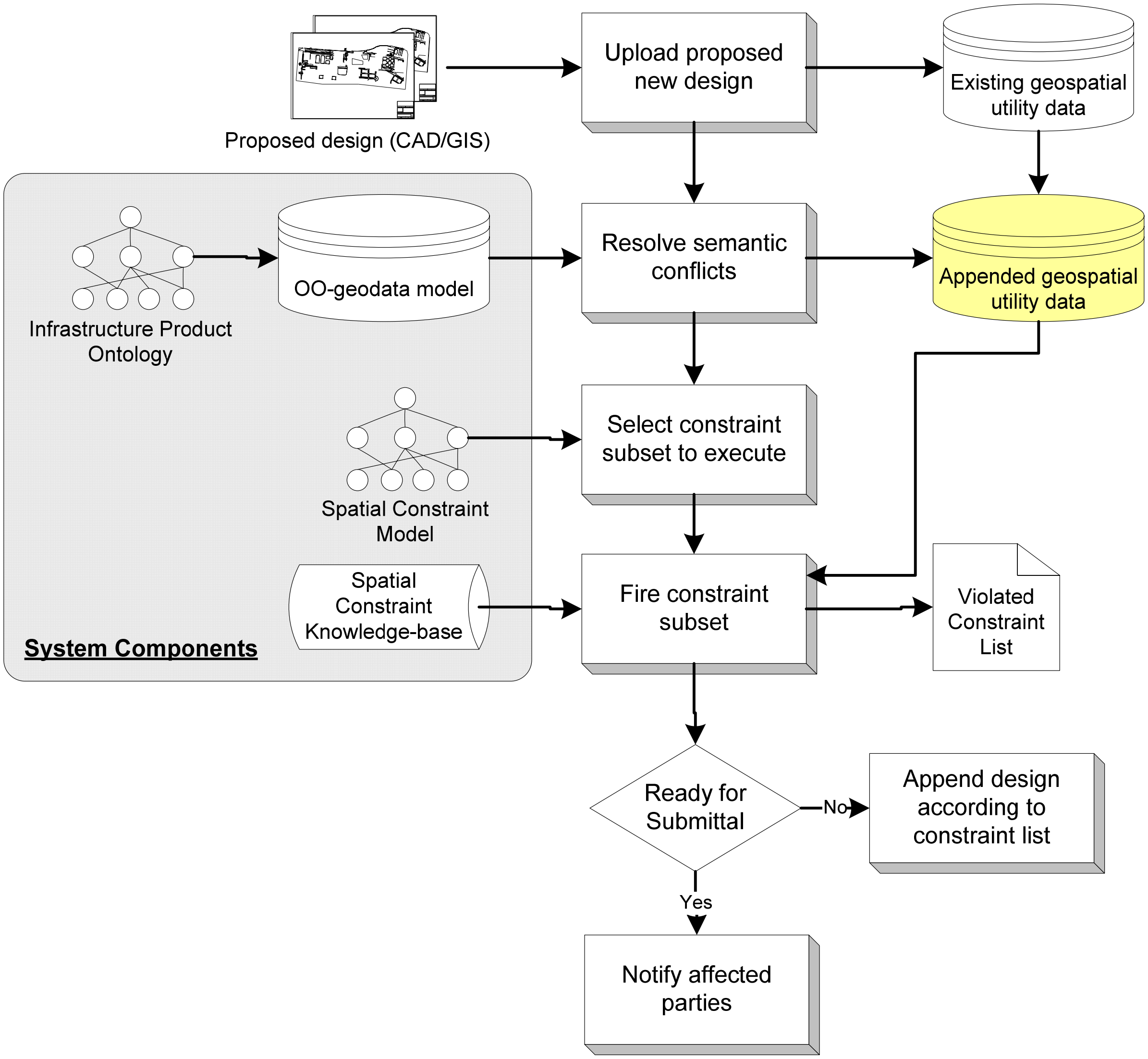

Figure 3 Process flow for primary use-case of web-based GIS collaboration portal

It should be noted that the proposed portal assumes that: (1) Various agencies are willing and able to share their geospatial data, (2) Agencies are willing to specify their spatial constraints according to the proposed common schema, and (3) Mechanisms are in place within these organizations to capture knowledge throughout a project life-cycle.

As such, the prototype can provide its users with the following benefits:

1- Creates a core knowledge base for representing best practices related to infrastructure routing. This knowledge base allows for continuous updates as new knowledge is created. The flexible schema allows for life-cycle knowledge (best practices relating to construction, operation, and maintenance) to be included. The fact that most designs cannot be expected to be aware of cross-industry as well as life-cycle knowledge makes the system of value to designers in various utility sectors.

2- Creates a single dynamic repository for codes and regulations pertaining to clearance requirements between buried utilities. The large amount of agencies that manage utilities within urban cores creates a need for such a repository.

3- Proposes a unified cross-sector schema for representing spatial constraints among utilities. This schema enables all constraints to be represented in a consistent fashion that is understood by all agencies.

4- The collaborative web portal eliminates current practices of drawing exchange and review cycles (Figure 1) that create bottlenecks in the design process.

5- The fact that the designer of a new infrastructure can check the design against all mandated clearance requirements and receive constructive feedback about ways to enhance route selection will eventually produce a route that has minimal conflict/impact on surrounding utilities and land use.

SUMMARY & CONCLUSIONS

The large number of stakeholders involved in urban infrastructure development along with the lack of understanding of their information exchange requirements were the main impetus for this research. This research aimed to achieve knowledge interoperability among stakeholders involved in the micro-level routing of buried urban infrastructure.

The micro-level routing process is approached as a spatial constraint satisfaction problem. Spatial constraints between utilities are made explicit via an XML-schema. The schema ensures that design guidelines that govern utility routing are made explicit and shared in a format that is understood by all agencies involved during the design phase. Constraints that are included in the interoperable model include tacit knowledge that experienced designers use in route selection. Although these constraints can be considered as ‘Best Practices’ rather than hard constraints, they are motivated by criteria that are often overlooked in traditional engineering design guidelines (sustainability, impact on businesses, maintainability, constructability, etc…). The model was implemented in a web-based GIS collaboration portal that serves to streamline the utility design coordination process and acts as a dynamic knowledge repository for urban utility routing.

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