An Integrated Web-based Decision Support System for Inter-Asset Streetworks Management

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Summary

Streetworks are the activities conducted in streets such as building or repairing roads, installing or replacing buried utilities, or street furniture. Sustainable streetworks requires an integrated approach taking account of the complex inter-asset relationships between human activities, different city infrastructure assets and the environment. To facilitate decision making by relevant stakeholders, an integrated web-based decision support system is presented in this paper which combines experts' domain knowledge, multiple geospatial datasets and an inference engine for automated inference of potential consequences. Users' feedback collected from two workshops showed that the system is widely considered as a potentially useful tool for practitioners.

KEYWORDS: web-mapping; reasoning; decision support system; sustainable streetworks; subsurface infrastructure

1 Introduction

Streetworks are the activities conducted in streets such as building or repairing roads, installing or replacing buried utilities, or street furniture. It is estimated that the direct costs of streetworks to local authorities are about £50M per year in the UK[1]. Critical urban infrastructure assets, such as roads, ground, and buried utilities (e.g. water, electricity, gas, sewage, communication) are highly interconnected. For example, breaking up or opening a road may damage the underlying ground and buried utilities, and a leaking water pipe can erode the surrounding ground, leading to loss of support to the overlying road and eventually causing collapse of the road (Clarke et al., 2017). In order to reduce the potential social, economic, and environmental impact, decision making in streetworks requires an integrated approach which takes into account the inter-asset dependencies, the localised contextual data (e.g. rainfall, traffic loading, soil type) and the state-of-the-art methods of asset investigation and management. However, in practice, there is no unified decision-making

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[1]Asphalt Industry Alliance (2017) Annual Local Authority Road Maintenance.

approach or fully integrated data management in current use across urban streetwork stakeholders. Urban infrastructure assets are maintained by different stakeholders who plan and conduct streetworks independently often without unified coordination; relevant data is held in disconnected platforms/depositories by different stakeholders, such as the Met Office, the Environment Agency, the British Geological Survey, the Highways England. It is difficult for a decision maker to have the knowledge of all relevant areas, nor is it easy or quick to gather all relevant data.

This paper presents a novel web-based decision support system (DSS), which addresses the highly challenging problem of inter-asset streetworks management. An integrated approach which combines the knowledge of experts from different domains, multiple geospatial datasets held by different owners, and an inference engine for automated reasoning about potential consequences is presented. A prototype of the proposed decision support system has been developed and demonstrated to a wide range of relevant stakeholders for evaluation.

The work is conducted within the Assessing The Underworld (ATU) project[2] - a large interdisciplinary UK programme grant that addresses challenges in sustainable management of city infrastructures taking into account the economic, social and environmental impact of street works.

2 System architecture

To determine the software environment of this decision support system, a survey was conducted by the ATU team in 2014 to collect the opinions of relevant practitioners. Results showed that 33% of the respondents preferred a *Web Mapping System*, 24% preferred a standalone *Geographic Information system*, 24% preferred a *bespoke software*, only 18% of them preferred *Excel*. Therefore, a web-based system architecture was selected for developing this prototype, by combining the functionalities of web mapping services and geographic information management.

The DSS system is composed of three layers (Figure 1): a) *a contextual data and knowledge layer* for storing various background data and experts knowledge; b) *a logic layer* for data query and automated reasoning; and c) *a web-based user interface layer* for events reporting, data visualisation and updating. The main components of this decision support system are described below.

Domain Knowledge Models. Based on the literature and discussions with domain experts (e.g. in civil engineering, geophysics and utility management), a suite of knowledge models/ontologies and logical rules were developed for this system to describe the main concepts and the complex intra-asset and inter-asset relationships in streetworks. For example, the **trigger ontology** (Clarke et al., 2017) describes the categories and properties of events which need some decisions to be made in streetworks, such as human activities (e.g. construction works), abnormal road observations (e.g. road cracks) and pipe observations (e.g. low water pressure). The **city infrastructure asset ontologies** (Figure 2) define the vocabulary for describing the conditions of roads, ground (Du et al., 2016), and buried utilities (pipes/cables), which are publicly available from the University of Leeds data repository[3]. And the **investigation ontology** summaries the available geophysical techniques

[2] `http://assessingtheunderworld.org/`
[3] `https://doi.org/10.5518/190`

(e.g. electromagnetic method, gravity method, seismic method) for shallow (0-5m depth) street-works surveys and their suitability for measuring different infrastructure asset properties.

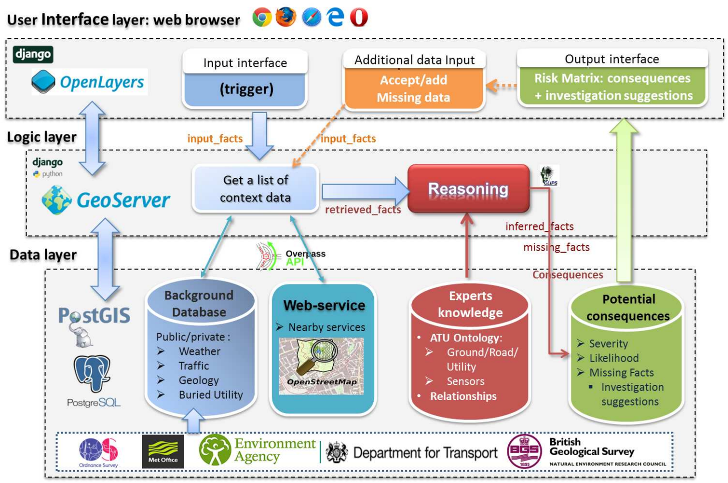


Figure 1: A three-layer system architecture of the decision support system.

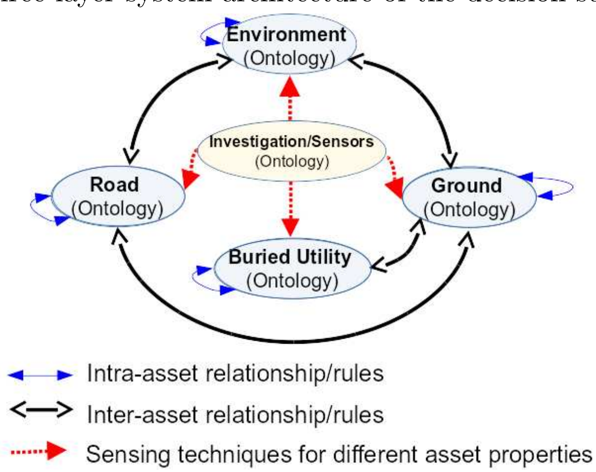
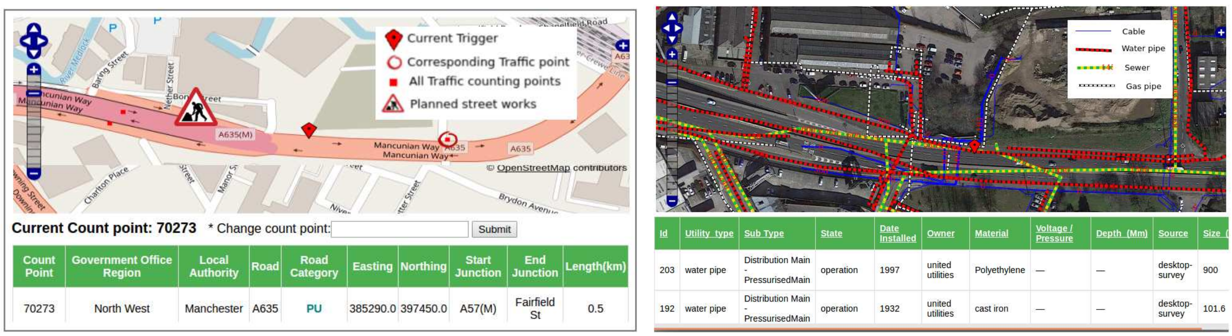


Figure 2: Inter-linkages between road, ground, utility, environment and investigation ontologies.

Integrated Contextual Database. Data in this decision support system is sourced from different data owners, preprocessed and integrated into one spatial database. The meteorological data (e.g. amount of daily/hourly rainfall, maximum and minimum air/concrete/soil temperatures) is sourced from the UK Met Office[4]. When a trigger is reported, the weather observation stations within $10km$ to the trigger are retrieved to obtain the historic weather data up to the reporting day, then the obtained data at each time point is averaged as the local weather data of the trigger. The traffic loading data is sourced from the UK Department for Transport (DfT), which collects street-level traffic data at thousands of traffic counting points every year[5]. For a reported trigger, the nearest

[4]Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-current).
[5]Department for Transport (DfT) traffic statistics.

road segment is first retrieved from the road network database to identify the traffic counting point for obtaining the historical traffic data (Figure 3a). Then, the weighted annual traffic on this road is calculated based on the traffic volumes and the wear factors[6] of different types of heavy commercial vehicles like buses, heavy-goods vehicles. The data of buried utilities is sourced from different



(a) Road Information (b) Buried utilities

Figure 3: Examples of retrieved contextual data of a reported trigger (background maps of (a) OpenStreetMap, (b) Google satellite image).

asset owners (e.g. United Utilities, National Grid, North West Electricity)[7]. Multiple attributes of the utility assets are recorded in the database, including the utility type, location, depth, material, diameter, year of installation, asset owners, operation status, etc. Based on the location of a trigger, all the buried utilities within a 200m radius are retrieved. An example of the extracted utilities around a reported trigger and their attributes is shown in (Figure 3b). The data of sensitive services (e.g. hospitals, schools) around a trigger ($\leq 2km$) is fetched from the OpenStreetMap[8]. To assess the potential impact on each service, the shortest driving distance from the trigger to each retrieved nearby service is calculated using the widely used path planning A* algorithm (Hart et al., 1968). The relevant ground condition data of a trigger (e.g. ground water level; artificial, superficial and solid geology) is retrieved from multiple datasets of the British Geological Survey (BGS)[9].

In this prototype, different datasets were sourced for demonstration purposes only. For maintenance of the contextual database in a fielded system, the freely available government datasets (e.g. Department of Transport, Environment Agency) can be updated manually regularly (depending on the temporal resolution of the data) or automatically; the private datasets with licensing can either be updated when changes are reported by the data owners or be directly linked to external data repositories via WFS, etc.

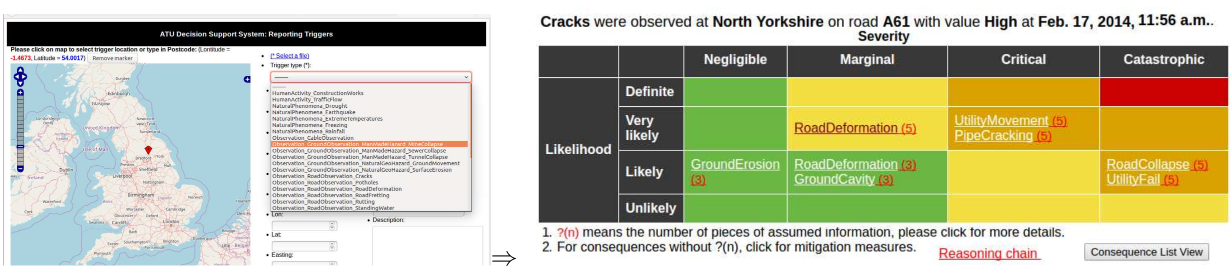
Automated Reasoning Module. Our system has an automated reasoning module which mimics human experts to make inferences of the potential consequences of triggers. When a new trigger

[6]UK Design Manual for Roads and Bridges (2006).
[7]For proof-of-concept purpose only.
[8]`https://www.openstreetmap.org`
[9]`http://www.bgs.ac.uk/`

is added, the localised contextual data is retrieved from the data platform (as described above), mapped to the established ontology concepts and fed into an *inference engine*, which applies inference rules stored in the knowledge base to the known facts to infer new facts using a forward reasoning method. Then, potential consequences (e.g. road collapse, road deformation, utility movement) are identified from the inferred facts and displayed in a matrix table on the user interface with the estimated severity and likelihood (Figure 4b).

Since the experts we consulted were unable to formulate definitive rules relating different concepts, the system makes use of the qualitative confidences attached to the rules they supplied. These qualitative confidences can also be attached to human supplied data. The automated reasoning system is able to propagate these qualitative confidences in a reasoning chain (Mahesar et al., 2017). Moreover, even if some of the premises (facts) of an inference rule are currently missing[10], the system can still activate the rule by assigning default values to the missing facts and infer the potential consequences. In this case, the system informs users about the missing facts for deriving each consequence (marked with red numbers in Figure 4b) and suggests appropriate investigation methods to obtain this information based on the *Investigation ontology*.

Interactive User Interface. *The interactive user interface* allows users to a) report new triggers (Figure 4a), such as extreme weather event, pothole, pipe leakage, or planned streetworks; b) visually examine the retrieved localised contextual data (Figure 3); c) inspect the potential consequences, their given/missing facts and reasoning chains (Figure 4b); and d) add or modify the values of missing/given facts for recursive inference. A video demonstrating the user interface is available at `http://bit.ly/2mdyIY4`.



(a) Interface for reporting new triggers

(b) Interface of potential consequences

Figure 4: (Left) The interface for reporting new triggers (map: ©OpenStreetMap contributors, CC BY-SA); (right) Potential consequences of a reported trigger.

3 User Feedback

The prototype of this decision support system was demonstrated to a wide range of potential users in two workshops in 2017 to collect users' feedback. Open-ended questions were asked regarding

[10]Note that at least one fact in the antecedent of a rule must be present and not assumed.

the usefulness of the demonstrated system, the specific functionalities that interested the users and what improvement is needed for future development of the system.

Results showed that 56% of the respondents considered this system as a potentially useful tool for practitioners (e.g. incident managers, survey company developers, constructors, asset owners, local authority) to mitigate risks, prioritise and justify their expenses and activities; 17% also considered the system to be useful for the general public. The potential benefits for training novice or junior staff in streetworks were also mentioned by one of the participants. Regarding the specific functionalities of the system that interested the users, 56% of them were interested in the ability of the automated reasoning module to help determine the impact of an incident in a short period of time, identify potential consequences from seemingly insignificant triggers and potentially reduce the streetworks disruptions. 50% of them were excited about the integrated data platform that brought various critical contextual data together. As for future improvements of the system, adding additional contextual data sources, such as bus routes, agriculture data, archaeological data, was suggested by most of the participants. It was also recommended to develop a smart phone application for easier access to the system.

4 Conclusion

This paper has presented an integrated web-based decision support system for inter-asset streetworks management. This system comprises: 1) multiple domain knowledge models and logical rules which encode the experts' knowledge of road, ground, utilities, human activities, environment and their inter- and intra- relationships; 2) an integrated geospatial database which contains various critical contextual datasets; and 3) an automated reasoning module which allows inference of potential consequences of reported triggers based on encoded experts' knowledge and localised contextual data. Users' feedback collected from two workshops showed that the system is widely considered as a potentially useful tool for practitioners to quickly obtain contextual data and infer potential consequences of triggers based on multi-domain knowledge and inter-asset relationships. Larger scale user evaluation with ATU partner organisations which are involved in underground asset management is being conducted to gain deeper insights into the utility of the DSS.

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6 Biographies

Lijun Wei is a postdoctoral research fellow in the School of Computing at the University of Leeds. Her research interests include underground utility and archaeology sites mapping, high-definition map generation for intelligent vehicles localisation/navigation, multi-sensor fusion and decision support systems.

Barry Clarke is a Professor in the School of Civil Engineering at the University of Leeds. He has been actively involved at a strategic level in the construction industry and is a past President of the institution. His research interests include construction processes and the performance of the ground.

Derek R. Magee is a Lecturer in Computing at the University of Leeds. His research interests are in the area of qualitative and quantitative data analysis, in particular remote sensing, buried asset management and medical imaging.

Vania Dimitrova is an Associate Professor in the School of Computing at the University of Leeds. Her research focuses on developing intelligent systems that augment human intelligence, including knowldge capture and modelling, behaviour modelling, adaptation and personalisation.

Anthony G. Cohn is a Professor in the School of Computing at the University of Leeds and is a Fellow of the Royal Academy of Engineering, AAAI, and EurAI. He has received Distinguished Service awards from IJCAI and AAAI. His research interests cover AI, Robotics, Sensor Fusion, and Decision Support Systems.

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