Automation in Construction 81 (2017) 434–448

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Integrating building and urban semantics to empower smart water solutions

Shaun Howell*, Yacine Rezgui, Thomas Beach

BRE Trust Centre for Sustainable Engineering, Cardiff University, Cardiff, UK

ARTICLE INFO

Article history:
Received 28 June 2016
Received in revised form 20 December 2016
Accepted 26 February 2017
Available online 23 March 2017

Keywords:
Water management
BIM
Demand-optimized management
Interoperability
Intelligent sensing
Big data
Data analytics
Ontology
Semantic web
Internet of Things

ABSTRACT

Current urban water research involves intelligent sensing, systems integration, proactive users and data-driven management through advanced analytics. The convergence of building information modeling with the smart water field provides an opportunity to transcend existing operational barriers. Such research would pave the way for demand-side management, active consumers, and demand-optimized networks, through interoperability and a system of systems approach. This paper presents a semantic knowledge management service and domain ontology which support a novel cloud-edge solution, by unifying domestic socio-technical water systems with clean and waste networks at an urban scale, to deliver value-added services for consumers and network operators. The web service integrates state of the art sensing, data analytics and middleware components. We propose an ontology for the domain which describes smart homes, smart metering, telemetry, and geographic information systems, alongside social concepts. This integrates previously isolated systems as well as supply and demand-side interventions, to improve system performance. A use case of demand-optimized management is introduced, and smart home application interoperability is demonstrated, before the performance of the semantic web service is presented and compared to alternatives. Our findings suggest that semantic web technologies and IoT can merge to bring together large data models with dynamic data streams, to support powerful applications in the operational phase of built environment systems.

1. Introduction

Building information modeling (BIM) is increasingly being researched in operational buildings, alongside technologies such as energy simulation and building automation [5,32]. Also, smart approaches such as systemic optimization [45], and load forecasting [14] are demonstrating improvements in the efficacy, longevity and efficiency of water networks [25,37]. Smart water networks are touted to deliver leakage reduction, energy savings, water quality assurance, improved customer experience and operational optimization, amongst other key performance benefits [21,22,31,43]. Research is now looking to improve water demand profiles at the building level through adaptive pricing feasibility studies, consumer feedback interfaces, gamification, and smart appliances. Hence, a new research field is emerging from the union of BIM, smart appliances, intelligent sensing, and cybernetics.

However, this complex ‘system of cyber-physical systems’ faces similar interoperability challenges to those being faced by smart grids and smart cities, where the value derived from ICT penetration is tied to the ability to share knowledge. This has been stated by authoritative bodies to occur due to i) lack of machine communication protocols, ii) lack of common data formats, and iii) lack of common meaning of exchanged content [19]. The need for common protocols and resource discoverability is being addressed by the Internet of Things (IoT), such as through the recent Hypercat standard [17]. However, this still leaves semantic aspects unresolved.

In the smart grid and smart city domains, research is actively pursuing data models which facilitate data exchange, the integration of legacy systems, and promote system security and performance [7,19]. Given the growth of smart metering in the water industry [6,33], and recent interest in smart water [22,31], it is pertinent for smart water research to learn from smart grid research. Further, many similar key ICT features are required in the water domain, so interest in a similar approach is growing [18,36].

Significant advances have been made in the field of water semantic modeling, but primarily from an earth science perspective, and primarily at the catchment scale [28,46–48]. Very little modeling

---

* Corresponding author.

E-mail addresses: HowellSK5@cardiff.ac.uk (S. Howell), RezguiY@cardiff.ac.uk (Y. Rezgui), BeachTH@cf.ac.uk (T. Beach).

http://dx.doi.org/10.1016/j.autcon.2017.02.004

of water consumption at the utility or building level is evident, although BIM, smart appliance and intelligent sensing models are relevant to this domain. An integrated modeling approach would be highly beneficial to promote the effective interoperation of software i) with a feedback loop at the building level, ii) which optimizes and implements demand-side management (DSM), and iii) which uses dynamic consumption data to better inform clean and waste network management decisions. This should include a detailed and consistent vocabulary and semantic model across the building and network scales. It would also be beneficial to reuse the domain independent aspects of models from the power and smart city domains, and to adopt a similar modeling approach. Applied knowledge managment work is therefore required both directly and at a meta level, to support smart water systems as well as the sharing of knowledge between smart domains.

Semantic interoperability in smart water networks is therefore a literature gap, which this paper takes a step towards addressing. The work was conducted within a European research project, which aims to integrate data and software across domestic and water utility resources. The project, 'Water analytics and Intelligent Sensing for Demand Optimised Management' (WISDOM), is utilizing semantics and web-enabled sensors to integrate business operations across the water value chain. A water value chain is defined as the artifacts, agents, and processes involved in delivering potable water to consumers from natural water sources and safely disposing of foul and runoff waste water. This paper proposes a smart domain water ontology, and a software platform which uses this to integrate services. This extends the state of the art of both the BIM and IoT fields towards meaningful interoperability of things and software in smart water networks.

The next section presents related work observed in the literature, Section 3 presents the use case driven methodology adopted, Section 4 then presents the main contribution; the semantic water modeling, and Section 5 presents a platform which uses the models to deliver interoperability. Ontology validation and platform experiments are presented in Section 6, and the findings are discussed along with concluding remarks in Section 7.

2. Related work

This section provides a state of the art overview of research on semantics and applications in the water domain. As such, it is structured into three sub-sections focusing on (a) the foundations of semantic modeling, (b) water modeling at the catchment and network levels, and (c) the modeling of cyber-physical systems at the building level.

2.1. Introduction to semantic modeling and ontologies

Semantic models, such as ontologies, promote interoperability as shared data formats and domain knowledge models, and play a prominent role in the World Wide Web Consortium (W3C) 'semantic web stack' [39]. They also play a role in the IoT and linked data fields, where they assist data contextualization, resource discovery, consistency and scalability [1]. Ontologies have been defined as explicit specifications of a conceptualization [49]. Therefore, an ontology describes the concepts, relationships, data properties and restrictions within a domain, in a machine-readable manner, and is often instantiated for a target system.

In use, ontologies typically support application back ends through a triple store, by capturing meaning, contextualizing data, standardizing terminology, facilitating rule application and producing new knowledge beyond that which is inputted. This assists the development of knowledge-driven applications which integrate heterogeneous resources. Critically, ontologies are vendor-neutral, which promotes extensibility, accessibility, and knowledge reuse. The following subsections describe existing semantic models in the target domains, which are summarized in Table 1.

2.2. Smart water and associated knowledge management issues

Smart water networks aim to improve the management of water and waste water systems through more intelligent approaches, such as artificial intelligence (AI) [24] and optimization [45]. Given the steeply rising number of sensors and volume of big data in the domain, comprehensive solutions must be available for these resources to be understood by machines, to support their best use in AI and advanced applications. Mounce et al. express this by stating that ontologies are a key technology for the acquisition, structuring and filtering of knowledge [23]. Further, the Smart Water Networks Forum has emphasized that as well as network interoperability, semantic understanding of data is critical to overcome the interoperability hurdle currently observed [15]. The geospatial community has produced several notable semantic models such as CityGML and its Utility network extension [28], and the INSPIRE utility network schemas [20]. This supports the fundamental

Table 1
Summary of relevant semantic models.

Acronym/name	Description	Owner	# entities	Date
SWIM	Device level IoT semantic model for the water industry.	Aquamatix	41	2016
WISDOM	Cyber-physical and social ontology of the water value chain.	Cardiff University	492	2016
SAREF	'Common denominator' of 23 smart appliance domain models.	ETSI	154	2015
WaterML2	Common format for hydrological time series data exchange.	OGC	131	2014
IFC4	Open format for building information model exchange.	buildingSMART	768	2013
Utility network schemas	Water and sewer network model; part of a large European directive for geospatial data exchange.	EC-INSPIRE	65 types	2013
WatERP	Lightweight ontology of generic concepts for water sensing and management.	EURECAT	29 classes	2013
WDTF	Format for transferring flood warning and forecasting data to the governing body. Precursor to WaterML2.	Australian Bureau of Meteorology	337	2013
CityGML UtilityADE	Domain extension for modeling utility networks in 3D city models, based on topology and component descriptions.	OGC	317	2012
SSN ontology	Describes sensors and sensor networks, for use in web applications, independent of any application domain.	W3C	80	2012
SWEET	Middle-level ontology for environmental terminology.	NASA	6000	2011
Hydrologic Ontology for Discovery	Supports the discovery of time series hydrologic data collected at a fixed point. Precursor to WaterML2.	CUAHSI	4098	2010
HydrOntology	Aims to integrate hydrographical data sources: town planning perspective, top down methodology.	Vilches-Blázquez et al.	250	2009