Future of Information Exchanges and Interoperability

Proceedings of the 2019 Workshop on Linked Building Data and Semantic Web Technologies (WLS2019)

Editor: Aaron Costin, Ph.D.

Future of Information Exchanges and Interoperability

Proceedings of the 2019 Workshop on Linked Building Data and Semantic Web Technologies (WLS2019)

September 29 - October 1, 2019
Gainesville, Florida
Infotech, Inc.
2970 SW 50th Terrace
Gainesville, FL 32608

Sponsored By
University of Florida College of Design, Construction and Planning
and
Infotech, Inc.

Edited By
Aaron Costin, Ph.D.

Smart Construction Informatics (SCI) Laboratory
304 Rinker Hall
P.O. Box 115703
Gainesville, FL 32611

Published by Smart Construction Informatics (SCI) Laboratory

304 Rinker Hall
P.O. Box 115703
Gainesville, FL 32611

ISBN: 978-1-7351595-0-8
Manufactured in the United States of America.

Acknowledgements

The following members are recognized for their dedication, support, and contributions for the success of the 2019 Workshop on Linked Building Data and Semantic Web Technologies.

Organizing Committee:

Aaron Costin, University of Florida, USA
R. Raymond Issa, University of Florida, USA
Monelle McKay, Infotech, USA
Pieter Pauwels, Eindhoven University of Technology, Netherlands
Nora El-Gohary, University of Illinois at Urbana–Champaign, USA

Technical Committee:

Mike Conlon, University of Florida
Gonçal Costa, La Salle, Ramon Llull University, Spain
Aaron Costin, University of Florida, United States
Chuck Eastman, Georgia Institute of technology, United States
Tamer El-Diraby, University of Toronto, Canada
Nora El-Gohary, University of Illinois at Urbana–Champaign, United States
Masoud Gheisari, University of Florida, United States
Raymond Issa, University of Florida, United States
Saeed Karshenas, Marquette University, United States
Yongcheol Lee, Louisiana State University, United States
Maxime Lefrançois, MINES Saint-Étienne, France
Kris McGlinn, Trinity College Dublin, Ireland
Ivan Mutis, Illinois Institute of Technology, United States
Nawari Nawari, University of Florida, United States
Pieter Pauwels, Ghent University, Belgium
María Poveda, Technical University of Madrid, Spain
Ana Roxin, University of Burgundy, France
Georg Ferdinand Schneider, Fraunhofer Institute for Building Physics, Germany

Workshop Event Planning and Support:

Sara Ann Green
Heather Rene Clayton
Kjerstin Terry
Jessica Berg
Joshua Garland
Lacey Jones
Bob DeHoff
Hector Del Valle
Ron Perkins
Doug Couto
Darcy Herlihy
Carmen Jeffcoat
Travis Tooke

Student Volunteers:

Alireza Adibfar
Bing Qi
Grant Anderson
Jimmy Sebesta

Supporting Organizations

Sponsors

Supporting Organizations

Contents

SESSION #3 - DATA STRUCTURES, FORMATS, AND STANDARDS

PROCEEDINGS

CHAIR'S WELCOME

The Workshop on Linked Building Data and Semantic Web Technologies 2019 (WLS2019) was hosted by the University of Florida with sponsorship from the College of Design, Construction and Planning. The Workshop was co-hosted with Infotech, Inc, held in the city of Gainesville, Florida from September 29 through October 1, 2019.

Over the last few decades, the built environment and the Architecture, Engineering, Construction and Operation (AECO) Industry has seen an increase in the amount of computer software, technologies, and automation to help improve all facets of the industry. This new era of technologies is enabling transformative change in the way our communities are interacting among themselves and with the built environment. The Internet of Things (IoT), cyber infrastructure, Big Data, and Artificial Intelligence (AI) are among the new transformative changes that produce and share information from all the connected devices and technologies enabling Smart Cities and Intelligent Jobsites. With the increase of such innovations, seamless information exchange between the connected technologies within the different domain facets is a major need. The purpose of this workshop was to provide a focused overview on technical and applied research on the usage of semantic web, linked data, and web of data technologies for the AECO industry. The workshop aimed at gathering researchers, industry stakeholders, and standardization bodies of the broader Linked Building Data (LBD) community. This includes the buildingSMART Linked Data Working Group (LDWG) participants, the W3C Linked Building Data (LBD) Community Group participants, and others.

The 2019 Workshop, as a standalone event, received 20 abstracts, 14 full papers, and 10 extended abstracts for the poster and demonstration sessions. A total of 8 full papers and 15 presentation from countries around the world were accepted and included in the proceedings. The final set of papers was selected through a rigorous peer-review process, which involved the collection of at least two blinded reviews per paper. The review process was performed for both abstracts and full papers, ensuring that only the best contributions were selected. Finally, the authors had the chance to incorporate reviewers' comments into the final version. We are very pleased with the high quality of selected papers, and we wish to thank both the authors and reviewers for their efforts.

The success of organizing this workshop has only been made possible with the support of many. We are particularly grateful to the College of Design, Construction and Planning, the M.E. Rinker, Sr. School of Construction Management, and Infotech Inc. We hope that you enjoyed the workshop sessions, posters, demonstrations, and industry panel discussion during the workshop and that the results disseminated from this can foster new partnerships to promote new research directions.

Aaron Costin, Ph.D.
Conference Chair, Organizing Committee, University of Florida

SPONSOR LETTER

infotech

Innovation is a top priority at Infotech.

The 2019 WLS Workshop was the first of its kind in the U.S., bringing national and international experts to gather in Gainesville, Fla., where we are headquartered, to discuss big ideas about linked building data. It was our honor and privilege to be the primary sponsor and host for this event that brought forth important conversations regarding the future of information exchange and interoperability.

The highly interactive workshop and its diverse attendance brought academia, owners, and industry together to discuss the future of information exchanges and interoperability. It was quite a success, with discussions on data and technology from our three keynotes, 15 additional speaker presentations, and conversations with local students about cutting-edge topics.

Navigating the many disparate, fast-emerging technologies is no easy feat, but when everyone speaks the same language - the language of data integration - the obstacle of creating a seamless process becomes an exciting challenge. The WLS workshop partnership was born from the desire to create a space to connect key leaders and relationships in this niche field, to bring potential new opportunities to our city of Gainesville and to team up with academia and industry in gaining understanding about the future. We're excited to witness the results of this collaboration and to see what possibilities are on the horizon.

PROGRAM

Day 1 – Sunday 29 September

- 12:00 PM Registration
- 12:30 PM | Pre-Workshop Short Courses
- 6:00 PM | Opening Reception (Info Tech)
- 8:00 PM | End

Day 2 – Monday 30 September

- 7:00 AM | Registration
- 8:00 AM | Welcome and Opening Remarks
    - Aaron Costin, Workshop Chair
    - Chimay Anumba, Dean, College of Design, Construction and Planning
- 8:30 AM | **Keynote #1: Dennis Shelden, Ph.D. Georgia Institute of Technology**
- 9:05 AM | Plenary Session #1- Data structures, formats, and standards
- 10:30 AM | Coffee Break
- 10:45 AM |Breakout Session
- 11:45 PM | Session Recap and Discussions
- 12:15 PM | Session End
- 12:20 PM | Lunch (Info Tech)
- 1:45 PM | **Keynote #2: April Blackburn, PMP, FDOT**
- 2:20 PM | Plenary Session #2: Industry and owner perspectives
- 3:45 PM | Coffee Break
- 4:00 PM | Breakout Session
- 4:40 PM | Session Recap and Discussions
- 5:30 PM | Session End
- 6:00 PM | **Networking Reception**
    - Student Poster Session
    - Research Demonstrations
    - Software Demonstration
    - Industry Demonstrations
- 8:00 PM | End

Day 3 – Tuesday 1 October

- 7:00 AM | Registration
- 8:00 AM | Opening Remarks
    - R. Raymond Issa, Director, M.E. Rinker, Sr. School of Construction Management
- 8:15 AM | **Keynote #3- Ron Perkins, Jobsite Tech Group**
- 8:50 AM | Plenary Session #3: Technology, implementation, and outlook
- 10:15 AM | Coffee Break
- 10:30 AM |Breakout Session
- 11:05 PM | Session Recap and Discussions
- 12:00 PM | Workshop Conclusion and Closing
- 12:15 PM | Lunch (Info Tech)
- 1:30 | Mini-Hackathon (Info Tech)
- 5:00 | Dinner
- 7:30 | Mini-Hackathon Awarding and Closing Remarks
- 8:00 | End

STUDENT POSTER SESSION

Innovative Design for Sustainability: Integrating Embodied Impacts and Costs During Early Design Phase

Ruochen Zeng

Evaluating Transportation Services Based on Social Media Data: A Case Study in Miami-Dade County

Bing Qi

Fusing Bridge Information Modeling (BrIM) and Intelligent Transportation Systems (ITS) Data into IFC

Alireza Adibfar

Safety Training using 360-Degree Panorama and Virtual Reality Techniques

Ricardo Eiris

Energy Neutrality analysis for Occupancy Sensor integrated Smart Building: An LCA Study

Tarun Kumar

Factor analysis for emerging technology in industrialized construction: the USA v.s. China

Shuyu Qian

Improving Point Cloud Accuracy Using a Customized Unmanned Aerial Vehicle with Dual-Frequency GPS and Post-Processing Kinematic Technology

Gilles Albeaino

Intelligibility in Transitional Spaces of Healthcare Facilities

Mahshad Kazem-Zadeh

Ecological Performance Optimization of Green Building, Carbon and Water Footprint

Maryam Kouhirostami

Blockchain and the Built Environment: Automated Design Review Process

Shriraam Ravindran

Assessing the Challenges Faced with the Adoption to an Innovative Approach to Improve U.S. Residential Construction

Humberto Cantu

SESSION #1 - DATA STRUCTURES, FORMATS, AND STANDARDS

Keynote: The Future of Open Data for the Built Environment

Dennis Shelden, AIA Ph.D.

Associate Professor at Rensselaer Polytechnic Institute
Director of the Center for Architecture Science and Ecology

An expert in applications of digital technology to building design, construction and operations, he has worked in professional practice, technology entrepreneurship and academia across architectural, building engineering and computing disciplines. He has lectured and written widely on topics of computational applications to architecture and building industry transformation. He was Associate Professor of Practice in Design Computation at MIT's School of Architecture and Planning from 2005-2016, and has taught at UCLA's IDEAS Studio and the Southern California Institute of Architecture.

Dr. Shelden has been an entrepreneur and innovation leader in several professional organizations and capacities. He led the development of architect Frank Gehry's digital practice as Director of R&D and Director of Computing. He then co-founded Gehry Technologies, serving as Chief Technology Officer on the development of several software products and Project Executive on numerous groundbreaking building projects. He has previously worked with diverse architecture, engineering and technology firms including Arup, Trimble, Cyra Systems and Consultant's Computation Bureau. He holds a BS in Architectural Design, an MS in Civil and Environmental Engineering, and a PhD in Design Computation from MIT, and is a licensed architect in the State of California.

Abstract: After a lengthy period of slow adoption, open data standards are entering a period of increasingly accelerated development and application. New use cases integrating cloud connected services are appearing in academia and industry. A steady influx of new startups is eclipsing the historical dominance of major software vendors as the exclusive purveyors and gatekeepers of information interoperability. These trends are occurring in parallel with a rapid expansion of interest and investment in the built environment by the tech and venture communities, as well as in house integrated system development initiatives by major architecture, engineering and construction firms. This keynote presentation provides an overview of industry trends in information exchange, recent developments in the building information open standards communities, and work being conducted at in academia with the goal of establishing a vision for the trajectory of open data platforms for the building industry and the their potential impact on the practices of building design, delivery and operations.

Web-Based Management of Building Data: An LBD Approach

Pieter Pauwels, Ph.D.

Associate Professor, Department of the Built Environment at the Eindhoven University of Technology

Abstract: Building Information Modelling (BIM) shifted construction industry to an era of digitization. With the Industry Foundation Classes (IFC), a strong standard has been put forward for interoperability, data exchange, and collaboration. Yet, as digital tools moved to the web, and changed into an environment with small data exchanges, fast web services, query engines, mobile devices, and distributed data management in the cloud, construction industry needs to evolve even further into a web-based industry (BIM Level 3 and Digital Twins). Our main industry standard, IFC, needs to evolve into a modular and web-native data standard that actively promotes and enables such distributed, community-based, and web-based data exchange. Linked (building) data makes that possible, yet a lot more other tooling is needed, including code libraries that bring building data directly in developer hands for creating a web-based world of building data.

1. Can interoperability be enabled by changing technology?

2. Can we build a BIM authoring tool in a web browser?

3. Centralized storage or data distribution?

Functional Modeling and Reasoning in Building Design

Andres Cavieres, Ph.D.

Assistant Professor, College of Architecture, University of Oklahoma

Abstract: Contrary to some assumptions, BIM does not provide formalisms to represent functional aspects of design in a machine-readable way. For instance, the description of functional requirements still follows a text-based, document-centric approach, despite progress in various database and semantic web implementations. This situation limits the scope of semantics required to support more effective interoperability and automation in building design. Part of the solution certainly involves the development of an ontology of functions, but this problem is far from trivial. An entire line of research in Artificial Intelligence and Applied Ontology has been devoted to this issue for more than two decades. So, what are the most promising efforts made in allied fields, and what can we learn from them to improve our own models and standards?

Semantic Interoperability and Semantic Technologies at a Crossroads.

Jack Hodges, Ph.D.

Siemens Corporate Technology, Artificial and Human Intelligence Group

Abstract: We report on a project to develop round-trip interoperability between the grid utility and building management systems (BMS), and between buildings running heterogeneous management systems, which have traditionally been information silos. The approach is based on the semantic integration of energy and building information models with a common, or system-

agnostic, semantic layer. Standards tend to have a very narrow focus of applicability, so growing a system-agnostic domain model involves the integration of several standards (in this case FSGIM, OpenADR, IFC, SAREF, QUDT, SOSA, NIST Tariff, and BRICK) into a cohesive model. The resulting information layer provides a foundation for round-trip translation, validation, logic, and reasoning, and is part of a cloud-based platform that provides a messaging hub. The approach is currently being tested in a pilot study with 23 buildings in the two primary California power utilities, PG&E and Southern California Edison.

1. The value of semantics has been demonstrated time and again but is nowhere near ready for widespread adoption, why?
2. Because the experts in the field are still developing ad hoc ontologies to solve niche problems => We need an approach, such as building standards as ontologies and integrating them into domain models, that will bring industry adoption.
3. Because the experts in the field have no common best practices for either design or implementation that would allow even other ontologists to read, understand, and appreciate an ontology => We need to develop best practices guidelines and make it easy to adopt and enforce them.
4. Because we don't have the requisite tooling to support semantic application development/deployment by subject matter experts or lay developers => develop them and make them available.
5. Because after so many years we still have no tried and true way of finding/discovering ontologies and knowing whether they are applicable to a particular application.
6. Because we still believe that we can, or should, implement ontologies as blobs rather than in a layered manner that will produce the most reuse => adopt the OOP approach to encapsulation.

Blockchain and the Built Environment: Automated Design Reviews

Shriraam Ravindran

PhD Student, School of Architecture, University of Florida

Abstract: Blockchain is a technology concept that originated from the first cryptocurrency known as Bitcoin and was soon noted to have a much wider range of applications beyond serving as the platform for digital cryptocurrency. A blockchain (BC) is essentially a decentralized and an immutable ledger that records every transaction made in the network. The implementation of decentralized technology in any industry would result in augmented security, enforce accountability, and could potentially accelerate a shift in workflow dynamics from the current hierarchical structure to a decentralized, cooperative chain of command by encouraging trust and collaboration. This paper present examines the potential integration with the BIM process in advancing the automation of the design review process. Moreover, the study explores how employing distributed ledger technology (DLT) could be advantageous in the automating the design review process by reinforcing network security, providing more reliable data storage and management of permissions, ensuring change tracing and data ownership. The paper evaluates the potential application of blockchain technologies such as Smart Contracts in cybersecurity, data ownership, and other aspects, as well as enhancing the framework for automating the design review process with a demonstration using Hyperledger Fabric.

1. Legal concerns: Could the efficacy and immutability of distributed ledgers warrant their implementation as binding legal documents? Are private keys satisfactory stand-ins for statutory signatures? Can the elimination of the requirement and complexity of contract litigations, in fact, give rise to newer disputes? How will Smart Contracts be judicially enforced externally, and what other legal implications/concerns would factor into implementation?
2. Implementation: For practical use in the industry, how does one address socio-technological factors such as the requirement of new cyberinfrastructure installation, personnel training, existent workflow dynamics, and organizational culture, or skepticism towards blockchains? What degree of automation is tangible/practical as of now?
3. Scope: Which other auditing/permitting operations at present could most benefit from Smart Contract automation? What other BIM-ICT applications can Smart Contracts lead to?

Machine Readable Taxonomy Delivery: CSI Construction Information Exchange (CIE), A Sole Source of Truth for Software

Greg Ceton

Director of Strategic Initiatives and Special Projects, Construction Specifications Institute

1. Construction taxonomies are present in many countries in Europe and North America and are an essential tool for project delivery and management. In the US and Canada. Delivery of information using taxonomies is nevertheless piecemeal, with variations from standard version differences, home brewed classifications, and other sources robbing the standard taxonomies of their advantages.

2. Delivery of information using web technologies has been available for decades, but the construction industry has tended to use these technologies in a product-specific atomized fashion, maintaining the fragmentation and siloes that have been present for even longer.

3. Despite knowledge that BIM and related technologies can break down these siloes, most firms do not engage in regular sharing of information. There are a variety of reasons for this: standards to do so are not adopted uniformly, professional culture discourages sharing of IP, perceived cost and risk of sharing, and failure of codes and contracts to recognize models and structured information as deliverables, relying instead on old contract document forms. Sharing information more freely and fully nevertheless seems like a necessary precursor to improving construction productivity.

4. Will a bottom up strategy, using tools already in place and used by firms, break down one set of barriers to this change without action by government or standard contract providers? What additional functionality will help with the adoption of taxonomies and improvement of standard use of structured information on any given project?

SESSION #2 - INDUSTRY AND OWNER PERSPECTIVES

Keynote: FDOT's Technology Governance Journey. Integrating and Aligning Information and Operational Technology

April Blackburn, PMP

Chief Technology Officer, Florida Department of Transportation

April Blackburn is the Chief Technology Officer (CTO) at the Florida Department of Transportation (FDOT). FDOT is responsible for one of the largest and most extensive transportation systems in the nation. With 30 years of experience, April specializes in developing and implementing technology.

As FDOT's CTO April is responsible for the strategy and operations of the department's technology environment in direct support of the agency's mission. She is also responsible for the alignment of information and operational technologies within the agency. April has led the development of FDOT's Technology Strategic Plan, Information Technology/Operational Technology (IT/OT) Alignment, Civil Integrated Management and is the leader of the newly developed Transportation Technology Office.

Abstract: For the Keynote I plan to cover the Florida Department of Transportation's technology governance journey. Not only what FDOT is doing to prepare for a more connected, technology rich future, but how to leverage that same technology and reap the benefits from the data. Our goal is to be a data driven organization and utilize fully the asset of data throughout our business. I plan to cover our organizational changes, culture changes and governance journey. Once I see the topics from the panel, I will adjust my remarks to provide a good starting point for the discussion and touch on each of the areas from our state agency's perspective. A couple of questions for consideration:

1. How do we harness the best of BIM for the transportation (horizontal) industry?
2. Is this really about modeling or is it more about information management?
3. Are the greater challenges with people or technology?

Capitalizing on Autonomy, Connectivity, and other Advanced Technologies to Enhance Mobility and Safety: The I-STREET testbed

Lily Elefteriadou, Ph.D.

Barbara Goldsby Professor of Civil Engineering, UFTI Director

Abstract: This presentation will discuss the I-STREET real-world testbed which is being developed in Gainesville, FL in collaboration with the Florida Department of Transportation and the City of Gainesville. Several infrastructure projects are underway or planned for deployment, including an autonomous shuttle which will operate in the downtown Gainesville as part of the Regional Transit Service (RTS). There are also several research projects underway which develop and evaluate sensors, apps, and other tools to enhance traffic signal control, improve safety for pedestrians, bicycles, and scooters using connectivity, and to develop a comprehensive data analytics platform, among others.

1. How do we maximize market penetration of connected vehicle technology, in order to maximize the benefits of connected vehicles?
2. How do we best inform transportation professionals and the general public about the (realistic) potential of advanced transportation technologies?
3. As a traveler/driver, what are your mobility/accessibility/safety needs which are not being met now?

SunTrax: Accelerating the Future of Transportation

Josh Pedersen, PE

Senior Project Manager, HNTB Corporation

Abstract: This presentation will provide an overview of the new SunTrax Connected/Automated Vehicle testing facility being developed by Florida's Turnpike Enterprise. Topics covered will include the purpose and mission of the facility, the importance of testing overall and closed-course testing in particular, the process of designing CAV-focused testing infrastructure, and where SunTrax and the State of Florida fit in the landscape of CAV deployments to come.

1. Most of the major OEMs are headquartered in Michigan. Is SunTrax / Florida an attractive location for major auto manufacturers?
2. Connected and autonomous vehicles are already on public roads both nationally and internationally, including here in Florida. Why then are proving grounds and test facilities like SunTrax still needed?
3. Considering how rapidly CAV technologies seem to be changing and evolving, how did you know what testing infrastructure to build?

Self Driving Vehicles and Advanced Mobility Transportation Options

Dean Bushey, Ph.D., Col(r) US Air Force

Advanced Mobility Consultant, Dean Bushey Enterprises; General Manager, Voyage Auto

Abstract: Self Driving vehicles offer the promise of safer roads, less congestion, environmentally friendly transportation, and mobility options for those who need it. What is the state of the industry?

What are the challenges? What is the timeline and how will this impact planning across multiple industries?

Migrating from 2D Plans to Digital Twins

Mark Lemieux, PE

Technologist, HNTB Corporation

Abstract: Will provide a quick look at how 3D models are created and used through the various phases of horizontal (e.g. road/rail) construction project. Will discuss some challenges and limitations of model development as we strive to leverage digital twins for managing assets.

1. How does the development of IFC schemas impact how 3D attributed model data is continually developed/updated through the design – construction – inspection > Operation lifecycle? Do we expect that subsequent teams will be able to update/embellish previous developed work?
2. How to influence the software vendors to fully embrace IFC? Concerned that some vendors will resist as the taxonomy is still being developed? Is it "all or nothing"?
3. As model content is shared between different software systems, how to know that data is being exchanged correctly between software? For instance, even with simple data we use now we’ve seen problems where surfaces are triangulated differently or where alignment stationing is calculated differently.

Life Cycle Information Models for Highway Infrastructure

Amlan Mukherjee, Ph.D., PE

Associate Professor, Dept. of Civil and Env. Engineering, Michigan Technological University

Abstract: In the field of pavement design and construction, significant progress has been made in the last decade through a participatory stakeholder driven technical working group led by the Federal Highways Sustainable Pavements Program. A pavement life cycle assessment (LCA) framework (Harvey et al. 2016) has been developed, and the pavement materials industries have also developed Environmental Product Declaration (EPD) programs. This study reports the next step in this process: the development of standardized data structures to reflect the unit and product system processes, and map them to consistent background databases for conducting pavement LCA. In addition, a pavement-specific pedigree matrix based on Edelen and Ingwersen (2016) was developed to characterize data quality, and it was used to review if the background data quality was 'sufficient and appropriate'. Therefore, the goal of this research is to ensure consistency, transparency and reliability of the collection, reporting and use of datasets for pavement LCA. This research is timely given legislative mandates such as the Buy Clean California Act (2017) that requires eligible construction materials to produce an ISO 14025:2006/EN 15804:2012 compliant EPD at the point of installation, for all publicly procured projects. It is significant as it lays the foundation for the long-term success of using EPDs to inform pavement design, procurement and construction decisions.

1. How do we integrate BIM information models with LCA information models?

2. As LCA is becoming part of public procurement how can we learn from lessons in BIM implementation?

3. What standards can be applied besides the ISO 14000 series to integrate LCA with BIM?

SESSION #3 - DATA STRUCTURES, FORMATS, AND STANDARDS

Keynote: AEC Tech Innovations: Technology | Implementation | Outlook for the Future

Ron Perkins, PMP

President, Jobsite Tech Group

Ron Perkins is the president of Jobsite Tech Group and has been an active member of the Associated General Contractors (AGC). His experience in the AEC industry goes back more than three decades, and has led sales and business development initiatives for firms such as Construction Market Data (CMD), Architects First Source and Autodesk; consulted for HP, SYNNEX, Infotech, Samsung, Dropbox, ARCOM, VIM™ and others and spent many years in SaaS, EDM, BIM and VDC solutions. He has been a speaker or panelist at numerous industry events including Autodesk University, ENR FutureTech, CMAA, FTBA, TRB, Meridian, Oracle, AIA, ABC, AGC IT Forum, AGC BIM Forum, CSI, and others. He is an active member of several Transportation Research Board (TRB) committees and Advisory Board Member on National Science Foundation (NSF) funded technology research grants. He has been published in Construction Executive, Design Intelligence, Florida Transportation Builder, and a number of other industry publications. Ron co-developed the Jobsite Tech University sales training program and authored The PULSE of Jobsite Tech for SYNNEX. Ron is also a former US Marine serving as an Assault Amphibian Crewchief of the LVTP-7 (YAT-YAS).

Abstract: The session will evaluate the current use of emerging technologies and explore research and statistics that point to the future trends of tech adoption across the AEC industry. Technology such as UAV, Laser Scanners, AR, VR and AI are at the forefront of the adoption curve. We will review real project scenarios and discuss product development paths of some of the leading technology providers to the industry. Leveraging these technologies is critical because of the accuracy and efficiency they bring to the project. Incorporating this data in the project workflow while maintaining integrity is only the first step in the process. Maintaining the data and adding functionality to manipulate or run analysis is the stage we will further explore during the session.

1. Identify data acquisition processes that will see the greatest benefit when embracing emerging technologies
2. Examine the most common use cases for technology adoption across various devices.
3. Suggest best path forward for organizations considering adopting new technology and best practices designed to streamline data acquisition.

Digital Workflow in a Federated Model Environment

Leif Granholm

Senior Vice President and BIM Ambassador
Structures Division, Trimble Solutions Corporation

Abstract: The current BIM practice is based on a federated model where every discipline - and often each phase within a discipline - create their own self contained models that are then combined in different ways together for coordination and other purposes. This concept can be successfully enhanced with linked data to provide a comprehensive workflow support with provenance and metadata management, natural data ownership and governance, and collaboration based on change propagation downstream and change requests upstream. This work is based on two research projects with Trimble, Aalto University and VTT as their main parties. In this paper we will present the main findings and concepts developed in those projects. Linked data is used to link object instances in different models and the many of the links can be created automatically as byproduct of design progression using new paradigm for BIM software that will be presented in the paper.

BIM Framework for Sustainability in Saudi Arabia

Fatma Hasanain

Ph.D. Student, School of Architecture, University of Florida

Abstract: This presentation will provide an overview of Saudi Arabia's Vision 2030 and what functions of BIM could be utilized to implement sustainable design principles in new and existing structures in Saudi Arabia by exploring the nature of the relationship between BIM platforms and sustainability. Due to the lack of a national rating system a BIM framework will be used to achieve the envisioned sustainability goals and implement sustainable design principles in Saudi Arabia.

Digital Twins of Urban Buildings with a Data and Computing Web Platform

Xuan Luo

Building Technology and Urban Systems Division,
Lawrence Berkeley National Laboratory

Abstract: This demo will showcase an open and free data and computing web platform – CityBES, which uses CityGML-based 3D city models, simulates building performance to identify retrofit measures that can cut building stock energy use by 50%, and evaluates city-wide PV potential. CityBES visualizes 3D-GIS integrated building performance in dozens of metrics (e.g., energy, water, demand, cost, GHG, savings, and regulatory compliance status) for each building at urban scale. The demo intends to introduce some of the applications and workflows of CityBES at the data level, regarding data integration, visualization, and utilization. Functionalities include integrating building data from different resources to compile and visualize building performance related database, and to construct city-scale building energy models. Utilizing the models to link and interact with district utility data and sensor network data, the platform is able to simulate and predict the spatiotemporal energy fluctuations of cities.

Ontology-Based Building Information Model Design Change Visualization

Ning Wang

Ph.D. Student, M.E. Rinker, Sr. School of Construction Management, University of Florida

Abstract: The use of Building Information Modeling (BIM) has become popular in the architectural, engineering, construction and Operations (AECO) industry, and BIM has been used in the lifecycle of projects. As more data is added to a BIM model, the complexity and data volume of the model increases. Further, many design changes are made to a building information model during design and construction phases, and it is difficult to extract and visualize the changed objects. Research on the use of ontology in BIM is also limited. The purpose of this study therefore is to use an ontology to visualize revised objects in BIM models. This research uses the Industry Foundation Classes (IFC) format, a widely-supported open standard for building information models. The changed objects in the BIM model are extracted by comparing the revised model to the original model, and a model report of the design change is provided. A prototype program using a sample IFC model is developed to validate the system. The results indicate that the proposed methodology is valid for the extraction and visualization of design changes in BIM models.

Semantic Web for Knowledge-Based Energy Management and User Engagement in Existing Buildings

Hervé Pruvost

Computational Analytics, Fraunhofer Institute for Integrated Circuits IIS

Abstract: The purpose of the presented work is to propose a novel ICT method for supporting energy-efficient operation of buildings by the means of semantic web technologies. So far, many developments and research have led to enhanced building automation systems embedding data analytics algorithms and performing energy-optimized building system control. The presented approach tries to bring a different and complementary added value to such systems through semantic modeling of building energy systems and knowledge reuse. It aims at providing an additional analysis layer compared to traditional algorithmic and model-predictive approaches in which a semantic analysis and interpretation of the operational state of a building is executed. This is based for a part on building data gathered during its operation through a monitoring system. For another part, it relies on information contained in initial BIM-compliant building design models. Moreover, in contrast to the classical goal of building automation which tends at achieving a fully automated and autonomous energy management, the method relies on the interactions between the building and its users. In particular, it aims at increasing the awareness and engagement of building users with regards to their habits about building energy use. For that purpose, it implements a knowledge base of energy conservation measures that prescribe building control actions and handlings that a building user or a facility manager may execute for saving energy.

PROCEEDINGS

Functional Modeling and Reasoning in Building Design

Andres Cavieres, Ph.D.,[1] Charles Eastman,[2] and Russell Gentry, Ph.D.[3]

[1] College of Architecture, University of Oklahoma; e-mail: andres.cavieres@ou.edu
[2] College of Design, Georgia Institute of Technology; e-mail: eastman@design.gatech.edu
[3] College of Design, Georgia Institute of Technology; e-mail: russell.gentry@coa.gatech.edu

ABSTRACT

Building design requires different types of knowledge. However, only structural knowledge is explicitly represented in current Building Information models. Other types of knowledge, such as those related to functional and behavioral aspects of design, remain tacit or described in ad-hoc terms by relying on structural properties as representational surrogates (e.g. geometry). The lack of a formal, model-based representation of functional knowledge limits the scope of semantics required to provide better computational support in performance-based building design. To address this problem, the research proposes the development of a representational framework for the functional and behavioral characterization of building elements based on the Functional Representation (FR) schema, and its formalization under the DOLCE foundation ontology. Part of this formalization has been translated into the Web Ontology Language to explore capabilities of DL reasoners to support inference of functional interdependencies affecting performance. An overview of the main theoretical background adopted is provided. Preliminary results and future lines of research are also presented.

INTRODUCTION

Design, construction and operation of buildings are complex activities, often requiring the collaboration of experts from multiple disciplines, who must work together to ensure the satisfaction of different functional requirements, at specific levels of performance. Developments in Computer-aided Design, and more recently in Building Information Modeling have greatly facilitated these processes of collaboration, by allowing the creation and exchange of design information among different design and analysis applications with increasing levels of automation.

Although these developments have already provided major benefits to the AEC industry, some fundamental problems persist which limit the potential of BIM to better support interdisciplinary collaboration in the delivery of high-performance buildings. In particular, the semantics of building information models currently available do not provide formal, machine-readable characterization of functional and behavioral aspects that are the backbone of the collaborative process. Indeed, an explicit, shared understanding of these aspects – namely, what a given building element does (i.e. its function), and how it is supposed to work (i.e. its behavior) - is precisely what informs the process of collaboration, especially in the context of systems integration, when multiple and often competing sets of performance requirements have to be evaluated and satisfied concurrently. When such a shared understanding is lacking, evolving behavioral interactions between different building subsystems may go unnoticed, eventually leading to functional conflicts and poor levels of performance that are usually not caught until very late in the delivery process.

From a representational perspective, part of the problem stems from how functional and behavioral aspects are defined within the conceptualization of BIM applications, including IFC and associated standards and classification systems (e.g. COBie, BPie, OminClass, etc.). In general, functions and associated performance criteria are described in ad-hoc, tacit fashion, by relying either on structural entities as representational surrogates (e.g. geometric properties), simple value types or text without formal semantics. This is problematic for several reasons, including the fact that traceability of functional interdependencies needs to be performed without computational support (Kiviniemi 2005). Besides being time consuming and prone to error, the use of informal, document-centric representations leads to different types of inconsistencies, especially when both functional requirements and design alternatives change constantly, and the consequences need to be tracked down and propagated manually across various domain models (Kamara, Anumba et al. 2002) (Qamar, Paredis et al. 2012).

Furthermore, in order to capture the dynamic, cross-cutting structure of behavioral interactions and functional interdependencies, multiple functional viewpoints are required at different levels of abstraction (Eastman 1994). Current BIM applications however lack the formal semantics needed to meet these modeling requirements. Among the main reasons, the following theoretical issues are worth mentioning:

- **Partial ontological commitment:** The lack of formal semantics is result of limited ontological commitments implicit in the conceptualization of building information models. This limitation restricts the set of ontological categories and relations available to formally describe phenomena of interest, particularly time-dependent phenomena that need to be captured by different functional viewpoints (Smith 2012).
- **Reliance on extensional definitions:** This problem was first analyzed by Borgo et al. (Borgo, Sanfilippo et al. 2015). In this work, the ontological and computational implications of extensional definitions are discussed, especially in relation to the lack of consistent criteria for the classification of design entities based on prescription of normative property sets.

To address these problems, a formal, explicit representation is proposed to enable a machine-readable specification of functionality with associated performance criteria. This explicit representation should cover both the 'demand' side, concerned with the description of functional goals and requirements, as well as the 'supply' side, concerned with the behavioral characterization of building elements that may contribute in the satisfaction of such goals and requirements. In order to enable multiple functional viewpoints, and inference of cross-cutting elements with participation in a given functional requirement, the definition of functional entities should be made *intensionally*, based on conjunction of constraints that need to apply under certain context of use. This would allow dynamic classification of elements playing a functional role in a requirement, rather than relying on normative model view definitions that may be too brittle or incomplete to deal with the iterative and often uncertain structure of design processes.

SPECIFIC PROBLEM: INFERENCE OF ASPECT SYSTEMS

The research proposes the development of a representational framework for the functional and behavioral characterization of building systems and components. A main goal of this framework is to support the incremental inference of building elements (i.e. structural entities) that participate in the satisfaction of different functional requirements. In this research, the set of structural entities that participate in the satisfaction of a functional requirement is considered a special type of aggregation abstraction called the Aspect System of the functional requirement.

This abstraction has been originally proposed by Augenbroe in the context of performance-based design, with the goal of providing a more robust system-theoretical framework for the integration of design and analysis applications, particularly regarding the use of simulation models for performance evaluation under uncertainty (Augenbroe 2011).The key idea behind the notion of Aspect System is the fact that there is never a fixed, one-to-one mapping between a functional requirement and a building technical sub-system. Instead, the satisfaction of any give functional requirement, specially at certain levels of performance, can only be achieved by the participation of multiple elements, possibly from multiple technical sub-systems, and from different levels of the compositional hierarchy. This implies not only more complex mappings from requirements to technical sub-systems, but also that such mappings change overtime as the design requirements and design alternatives co-evolve.

From a modeling perspective, this means that the specification of input models for performance evaluation needs to be richer and more flexible than usually assumed in the definition of conventional model views. While the aggregation of building elements that are related by a common purpose or function is supported in in theory by IFC with entities such as *IfcGroup*, and its specialization *IfcSystem*, these modeling constructs are more like general containers, lacking formal criteria for class membership. In particular, the ad-hoc, extensional nature of these functional aggregations makes it difficult to implement automatic procedures for dynamic inference of Aspect Systems.

At a more fundamental level, the problem lies on the fact that reasoning capabilities required need to operate under conditions of model incompleteness, which are intrinsic to the very nature of the design process. For this reason, it is necessary for a functional modeling framework as proposed here to operate under an Open World Assumption (OWA) paradigm, as opposed to the Closed World Assumption (CWA) underlying relational models such as IFC.

This condition is key to support the types of query required to capture the *intensional* semantics underpinning the inference of Aspect Systems, along with the set of potential behavioral interactions and functional conflicts that can be derived from such inference. The first type of query can be exemplified by the following expression:

- Given a required function *f* and a design model *a*, return the set of building elements from *a* with functional participation in *f*.

This is the most general form of the query, for which the Aspect System of function *f* is inferred based on the participation relation of its members that is not qualified in positive or negative terms (i.e. the required function is affected in a positive or negative way). The second query involves the inference of an inverse relationship. That is, to return the set of functions a given building element participates in, either nominally or as result of a behavioral side-effect. This can also be described as the set of functional roles played by a building element by virtue of one of its intended effects, or unintended side-effects:

- Given a building element a_0, proper part of a design model *a*, return the set of functions $F = \{f_1, f_2, \ldots, f_n\}$ in which a_0 has some functional participation.

From these two queries, more specialized forms can be developed, by using additional constraints in the query expression. In any case, a building element inferred as member of several Aspect Systems, is deemed to co-participate in the satisfaction of the different functional requirements (one for each Aspect System). This inference provides not only the basis for the identification of possible behavioral interactions and functional conflicts, but eventually more complete input models for performance evaluation, as well as trade-off analysis for decision-making among competing design alternatives.

Currently, there is no means of formulating such type of queries in BIM applications, unless informal participation relations are hard-wired into the models. As discussed previously, providing a timely answer for this type of query during different phases of the design process is relevant because it would allow to convey the rationale for previous design decisions, in such a way that potentially problematic design changes could be avoided or properly handled. Furthermore, characterization of Aspect Systems by inference of implicit functional relationships would allow automatic generation and update of input models for analysis applications that otherwise would remain brittle or incomplete.

THEORETICAL BACKGROUND AND PROTOTYPE IMPLEMENTATION

The functional modeling framework proposed is grounded on the study of several theoretical models of functional representation and reasoning, developed in the areas of Artificial Intelligence and Engineering Design, as well as more recent efforts towards the formalization of functional meaning in the field of Applied Ontology. Based on the analysis of theoretical models addressing specifically the representation of different functional viewpoints at different levels of abstraction, two schemas have been identified as particularly relevant for this research. These include the Structure-Behavior-Function schema (Goel 1992), and the Functional Representation (FR) schema (Chandrasekaran and Josephson 2000). The latter has been formalized under the DOLCE foundation ontology using First-order Logic (Borgo, Carrara et al. 2009). This formalization, called in this research DOLCE-FR, provides the foundation for the implementation of a proof-of-concept for the proposed functional modeling framework. Specifically, the implementation involved the translation of a subset of DOLCE-FR axioms from First-order Logic into Description Logic using OWL-DL, in order to take advantage of available DL reasoners. Moreover, this choice was made to support future integration with IfcOWL specification under development (Pauwels, Törmä et al. 2015).

The following subsection outlines the ontological commitments with main categories from DOLCE, a subset of DOLCE-FR axioms and the formalization of the notion of Aspect System based on such axioms.

DOLCE CATEGORIES AND DOLCE-FR AXIOMS

The adoption of DOLCE as ontological framework allows an extended set of ontological commitments beyond those implicit the conceptualization of BIM models. These commitments are grounded on a robust formalization of categories and relationships, along with constraints on how these relationships can be established. Specifically, DOLCE provides the category of *perdurants*, which allows explicit description of time-dependent phenomena associated with functional and behavioral aspects of design. This in turn allows the specification of participation relations to be established between things such as physical or spatial elements, with functional phenomena described by perduranst. Moreover, specific relationships between perdurants are also supported, such as causality and composition relations. The former allows to describe notions of causal pre-conditions and post-conditions, normally used in the specification of functions. Composition relations between perdurants in turn are useful to formally capture notions of functional decomposition. Figure X summarizes the ontological commitments in DOLCE, in comparison with the implicit commitments underlying conceptualization of BIM models (first in the left).

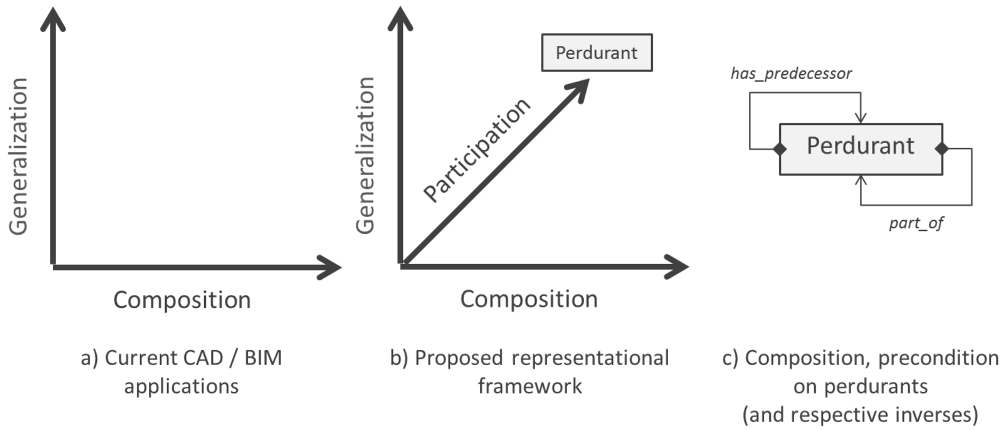


Figure 1. Partial ontological commitments of BIM models (first on the left). Extended ontological commitments of proposed framework based on DOLCE (center and right).

These additional ontological commitments, along with the formal criteria for the definition of categories and relations in DOLCE provide the basic vocabulary for the formalization of the Functional Representation (FR) schema adopted in this research. In particular, the FR notions of 1) *function as effect*; 2) *function as a role*; and 3) *function as behavioral constraint* introduced in FR are formalized in DOLCE-FR using different participation and composition relations. This in turn allows the formalization of functional viewpoints and levels of functional abstraction following the notions of *mode of deployment*, *device-centric* and *environment-centric functions* proposed in the FR schema. All these definitions are used in the formalization of Aspect Systems, providing the semantics required to enable the queries described above, which constitute the core of the functional modeling framework presented here.

FORMALIZATION OF ASPECT SYSTEM UNDER DOLCE-FR

The meaning of an Aspect System is formalized primarily based on the axiomatic definition of environment-centric function ($EnvFunc(b_0, b_1, a, a', e)$, and a small set of auxiliary definitions dealing with participation, causality and parthood (Borgo, Carrara et al. 2009). The following listing provides a preliminary, general formalization using an equivalent class axiom in OWL-DL. IN the formalization, the environment-centric is referred to as *_E_function.*

Listing 1: OWL-DL Equivalent class axiom for an Aspect System. General form.

```
Class: Aspect system
        EquivalentTo:
                (part some (participant-in some (_c_causes some
                        (inverse (_DF_outPD) some _E_function))))
                and (proper-part-of some Environment)
```

Different types of structural and behavioral constraints, as well as constraints on participation, causality and composition, can be added to this general definition of an Aspect System, either by changing the object properties types involved (i.e. object relations), or by adding extra logical connectives. This is illustrated in the two queries below, which provide variations of the most general form. The example is based on a case study developed for this research, dealing with the design of photovoltaic racking systems for commercial building rooftops. Specifically, each variation specifies different constraints for the inference of the Aspect System associated with the functional requirement "*fe7 .1_maintain_position*", which along with "*fe7 .2_maintain_form*", are sub-functions of the environment function of maintaining overall structural integrity of the PV racking system.

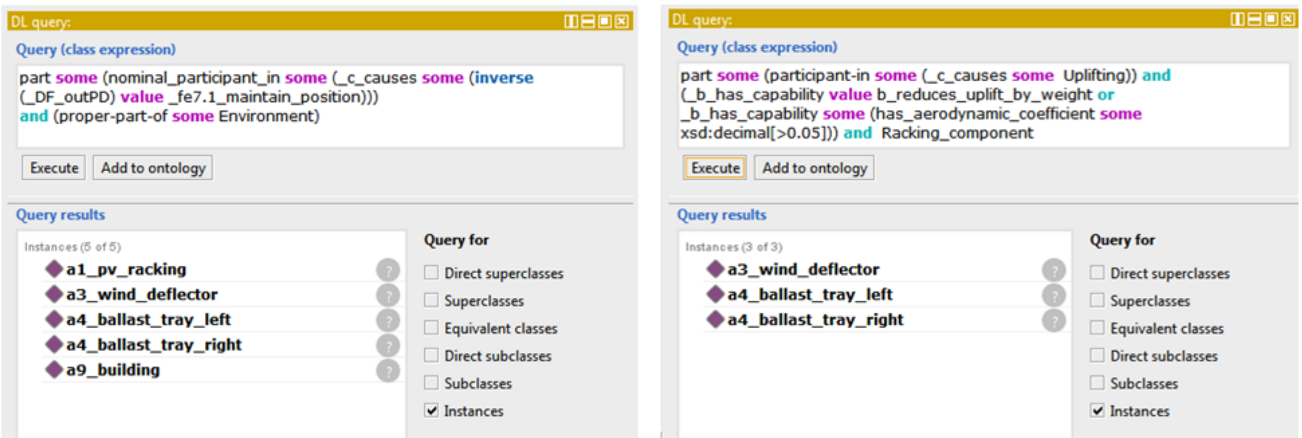
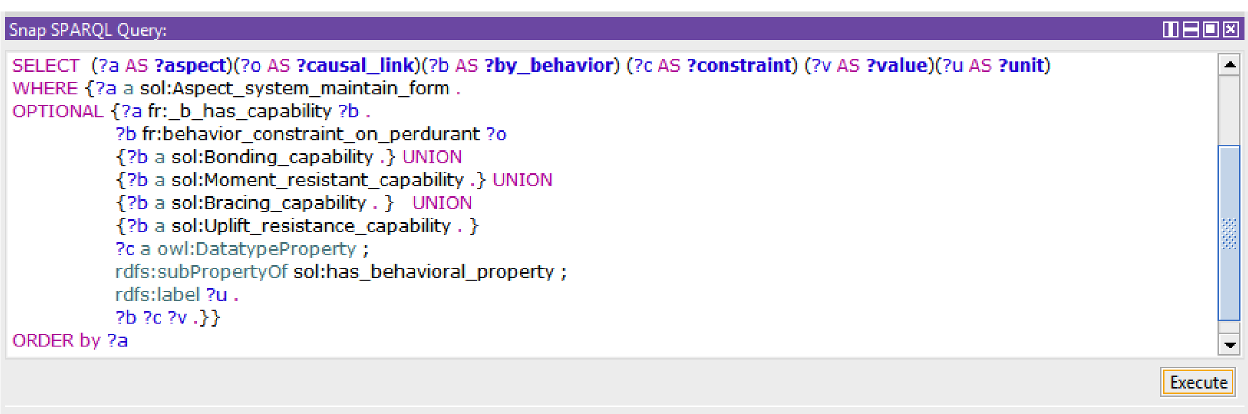


Figure 2. Variations of the general axiom of Aspect System (in Protégé). Additional constraints reduce the set of inferred elements with functional participation.

This type of PV racking system usually relies on a combination of ballast and wind deflectors to maintain its structural form and position, without any penetrating connection into the roof. For this reason, weight per area and aerodynamic drag coefficient are important behavioral constraints, along with friction coefficients of rubber pads used in footings for interfacing with roof membranes. In the Figure, some of these constraints are added in the specification of queries for the Aspect System of structural position function. Co-participation of inferred members in other functional requirements can be deduced by querying other Aspect Systems. In this model, equivalent classes are used for the query, in an approach known as DL Query. However, the modeling framework also supports use of SPARQL queries.



?aspect	?causal_link	?by_behavior	?constraint	?value	?unit
sol:a1_pv_racking	sol:e_bracing	sol:b_bracing_capability	sol:has_tensile_capability	65	psf
sol:a1_pv_racking	sol:e_moment_transfer	sol:b_moment_resistence_capability	sol:has_bending_moment	725	lbf·ft
sol:a1_pv_racking	sol:e_bracing	sol:b_bracing_capability	sol:has_compression_capability	50	psf
sol:a1_pv_racking	sol:e4.1_uplift	sol:b_reduces_uplift_by_deflection	sol:has_aerodynamic_coefficient	0.09	Cd
sol:a1_pv_racking	sol:e_electrical_continuity	sol:b_bonding_by_torque	sol:has_electrical_resistitivity	20	milliohms

Figure 3. SPARQL query of Aspect System for maintenance of form function. Behavioral constraints are specified in terms of functional capabilities. Specific performance properties can also be included.

DISCUSSION / CONCLUSIONS

A functional modeling framework has been implemented, based on a subset of the Functional Representation schema formalized under the DOLCE foundation ontology. The prototype implementation involved the translation of axioms from First-order Logic into Description Logic using the Web Ontology Language OWL-DL. This allows leveraging the capabilities of available OWL-DL reasoners to support the dynamic inference of building elements from different building sub-systems with participation in the satisfaction of functional requirements. Inferred building elements represent cross-cutting aggregations that explicitly capture functional interdependencies that emerge across different building components and subsystems, and that are relevant for multiple criteria performance evaluation. Such an aggregation, called the Aspect System of a functional requirement, is considered a necessary abstraction to provide better computational support, particularly in collaborative tasks involving design-analysis integration, conflict resolution, trade-off analysis and decision-making.

Envisioned inference capabilities of the proposed functional modeling framework are based in part on information asserted during the design process in different BIM applications. However, the current implementation does not deal with such type of integration, relying instead on a simplified OWL representation of hypothetical design models. The focus so far has been on the formulation of functional and behavioral models as an independent layer of semantics, that could be added on top of different building models. In this regard, the development of the IfcOWL standard offers the most direct path towards the integration of the proposed functional modeling framework with different BIM applications. This would allow to study issues of modularity and scalability of functional models, along with soundness and completeness of inferences dealing with real-world design models and use case scenarios.

REFERENCES

Augenbroe, G. (2011). The role of simulation in performance based building. Building Performance Simulation for Design and Operation. J. L. M. Hensen and R. Lamberts, Spon Press: 15-36.

Borgo, S., M. Carrara, P. Garbacz and P. E. Vermaas (2009). "A formal ontological perspective on the behaviors and functions of technical artifacts." Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM 23: 3-21.

Borgo, S., E. M. Sanfilippo, A. Šojić and W. Terkaj (2015). Ontological Analysis and Engineering Standards: An Initial Study of IFC. Ontology Modeling in Physical Asset Integrity Management. V. Ebrahimipour and S. Yacout. Cham, Springer International Publishing: 17-43.

Chandrasekaran, B. and J. R. Josephson (2000). "Function in Device Representation." Engineering with Computers 16(3-4): 162-177.

Eastman, C. (1994). "A Data Model for Design Knowledge." Automation in Construction (3): 135-147.

Goel, A. K. (1992). "Integrating case-based and model-based reasoning: a computational model of design problem solving." AI Mag. 13(2): 50-54.

Kamara, J. M., C. J. Anumba and N. F. Evbuomwan (2002). Capturing Client Requirements in Construction Projects, Thomas Telford Publishing 200.

Kiviniemi, A. (2005). Requirements Management Interface to Building Product Models. Doctor of Philosophy Dissertation, Stanford University.

Pauwels, P., S. Törmä, J. Beetz, M. Weise and T. Liebich (2015). "Linked Data in Architecture and Construction." Automation in Construction 57: 175-177.

Qamar, A., C. J. J. Paredis, J. Wikander and C. During (2012). "Dependency Modeling and Model Management in Mechatronic Design." Journal of Computing and Information Science in Engineering 12(4): 041009-041009.

Smith, B. (2012). "Classifying Processes: An Essay in Applied Ontology." Ratio 25(4): 463-488.

A Graph Database and Query Approach to IFC Data Management

Zhengyang Chen[1], Yiying Pu[2], and Dennis R. Shelden[1]

[1] School of Architecture, Georgia Institute of Technology, 245 4th St NW, Atlanta, GA 30332, USA
[2] School of Computational Science and Engineering, Georgia Institute of Technology, 266 Ferst Dr., Atlanta, GA 30332, USA

Keywords: Industrial foundation class, Graph database, Database management systems

OVERVIEW

The Industry Foundation Class (IFC) Model implemented by schema and data format definition in EXPRESS language is the industry standard for open data modeling and exchange. This data model, based on E-R model with deep object class instance hierarchy for both elements and relationships – has presented challenges in implementing scalable database approaches for managing and serving BIM objects while maintaining requisite relationships necessary for inferring relationships across the complex E-R network. Alternative models based on alternative data encodings with associated data topologies, database strategies and supporting tool sets such IFCXML, IFCJSON and RDF/IFCOWL have been proposed, with associated affordances and limitations in terms of semantic richness, validation and querying capability and scalability.

Graph databases are a recent development in modern databasing technology that is gaining prominence in the broader computing community. Graph databases promise general support of complex entity-relationship networks in a manner that supports rich semantic inference at scale. Consider those limitations stated above, this paper propose a method of database mapping between IFC Model to Graph database, and presents opportunities for drawing on graph querying capabilities to develop inferences about the semantic relationships among objects in IFC BIM models. The implementation and examination of this mapping is achieved by translating the IFC data and then store them into Neo4j, a commonly used graph database application. As part of this translation, broadly available IFC to XML conversion utilities were used to convert the BIM software output to XM. A python based parser was developed and used to parse the IFC component information and generate a Cypher script - the structural language for graph database construction.. This Cypher script - encapsulating the IFC E-R model – is imported into the Neo4j graph database in batches with Neo4j-Shell.

By implementing this mapping method, we can benefit from the flexibility of relationship management in graph database, as it provides the interface for dynamic relationship inserting, updating, deleting and modifying. Significantly, user-defined queries can be constructed for graph database, similar to the ambitions of the IFCOWL approach. Those cascaded queries or relationship path finding which need to self construct the data graph algorithm in normal SQL database are no longer an issue here since they are embedded in graph database and have optimized querying performance. Moreover, by executing this mapping rule application we keep the relationships which is essential during data exchange, and provides capability to migrate the model to other technical software which provide interface for graph database. Further work suggests that advanced algorithms and techniques network analysis algorithms in machine learning could be developed via the node-edge model provided by the graph database.

METHODOLOGY & APPLICATION FUNCTIONALITY

The goal of the proposed work flow is to utilize the flexibility of transformation between SQL and NoSQL database and typically trying the possible schema and data exchange in between. To implement this the paper focuses on the scope of making mapping rules to extract schema definition in IFC(national standard database model for BIM) EXPRESS-G schema and data from IFC file into Neo4j Graph database. It is an urgent need for BIM to solve the data exchange and interoperability problem. Chuck Eastman, stated in recent years that BIM are facing five main limitations during data exchange, among which the information loss on relationship between IFC entities is expected to be solved as an important issue. Hence, by proposing this workflow, a possible approach on solving this problem can be explained by utilizing graph database as a media for IFC data exchange.

Automatic converting from IFC file exported from BIM project instances in commercial BIM to Neo4j database will be the main functionality of the application. By using this application, we can store IFC data as an option for further exchange into other software. Typical user of application based on this work flow will mostly be the engineers and BIM project managers of technical side in AEC industry. Contemporary practice in BIM database today are mostly functions and plugins embedded in commercial BIM software like project schedules in Revit, however, these functions are mostly based on relational database. The normal query approaches at the back end by writing SQL can also be achieved by NoSQL languages, specifically, graph database queries with more flexibility, e.g. the most familiar SQL query to us, namely, SELECT-FROM-WHERE query series, can be written in typical graph database query called Cypher in MATCH-WHERE-RETURN query series. Moreover, by mapping IFC data into graph database we keep the relationships which is essential, and provides capability to migrate to other technical softwares. Another groups of typical user will be BIM developers, as recent years more and more researchers and developers focuses on web-based BIM application. The robust information stored in graph database provides an option for them to choose for implementing their back end.

SYSTEM INTERFACE AND DATABASE DESIGN

As stated before, the application of this work flow can achieve converting IFC data and manage them in graph database. With a provided IFC file as data source, the application is built to parse all the IFC component information inside IFC file and generate the Cypher script as output, which can be used for batch import in graph database application browser, namely, Neo4j browser. The output script file contains all the Cypher commands to create nodes and links, which representing entities and relationships in graph database, respectively. Here, the work flow of IFC data format conversion from IFC to XML, which could be easily implemented by external libraries, will be briefly introduced here, rather than go into detailed discussion in section 5 of the paper.

Such format transformation process is actually realized by converting the original file to XML file. The IFC file is converted into well-structured XML file by IfcConverter, the application included in the open source software library called IfcOpenShell. The IFC objects in the original file include some very fundamental objects like the measurements, directions and basic geometry types (points, curves). This part of information is integrated in the XML file as the value of objects' attributes. The concise and well-organized XML file helps to build a graph database without redundant and abstract information.

As this work flow engaged the exchange between SQL based IFC database model to NoSQL based graph database by creating the mapping rule. Some modifications will also happen during the exchange and the main change of design will be so-call the ‘pruning’ of original IFC file.(figure 1)

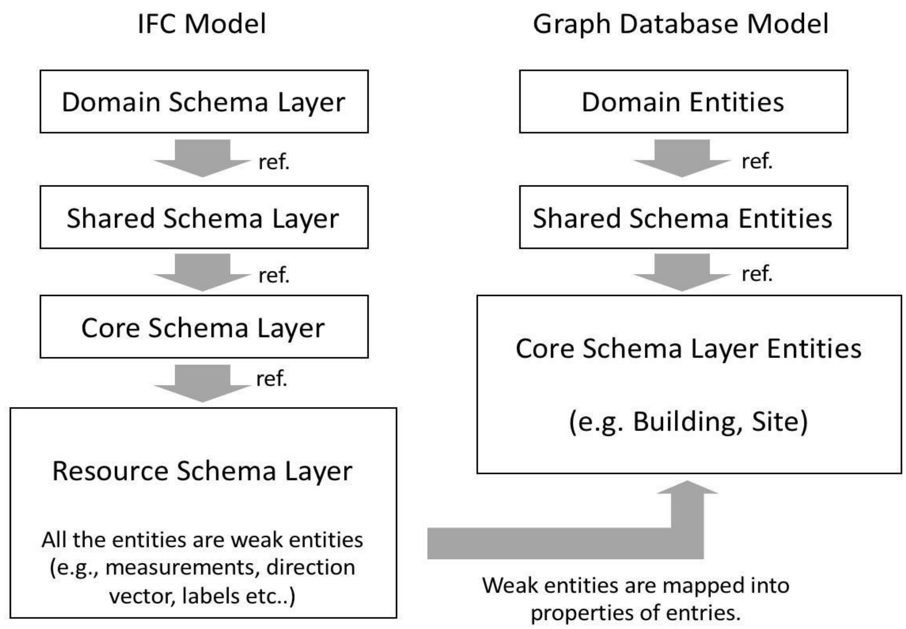


Figure 1. Pruning process of the database schema.

IFC Model has a strict layered schema definition, and follows the ‘ladder principal’ - the entities defined in higher layer schema can reference the entities in the same layer or lower layer schema, and those entities remain in the lowest layer schema(called ‘resource layer schema’) cannot be independently exist. Recall the content in class we can easily figure out that all entities definition in that lowest layer, are so-called ‘weak entities’. Revise the entities in IFC schema definition we discovered that they usually contain one or several properties indicating the same kind of information type. And those supertype entities in the lowest schema layer are also well categorized. Hence, our plan is to aggregate these weak entities into properties and apply them to those higher-layer schema entities who referred them. By doing this major change the amount of schema layer had reduced from 4 to 3, and hence reduce the depth of query and simplified the structure.

Notice that the no entity will exist independently in this lowest layer(‘resource schema layer’), and on the contrary, since they are of the most fundamental entities, if higher layer entities will exist, they must refer some entities in resource schema layer, and add them as ‘entity-attribute’, thus once an instance of independent element is initialized, resource layer entities related to them actually plays the role of attributes, thus we do not suffer information loss when pruning the lowest layer.

DATA EXTRACTION AND PREPROCESSING

BIM data in common practical use are stored in forms of IFC files, which are already in constraints of IFC Schema definition. The IFC files are exported from Revit, where all the building information is defined by users within the graphic user interface. The IFC data files are exported from the existing BIM projects. In current stage, the files used for testing can vary from simplest building structure to other ones of a realistic construction project.

The IFC schema file written in EXPRESS-G is used for understanding how the IFC objects are defined. IfcConvert is applied to convert the IFC file into XML file. This is an application converts IFC file into several file formats. This application is conveniently used with Windows command line. To parse information from XML file, the ElementTree module is used with python to work with XML. The re module for regular expression is also applied for string modification and information filtering.

COMPUTATION IMPLEMENTATION FOR MAPPING AND RELATED QUERIES

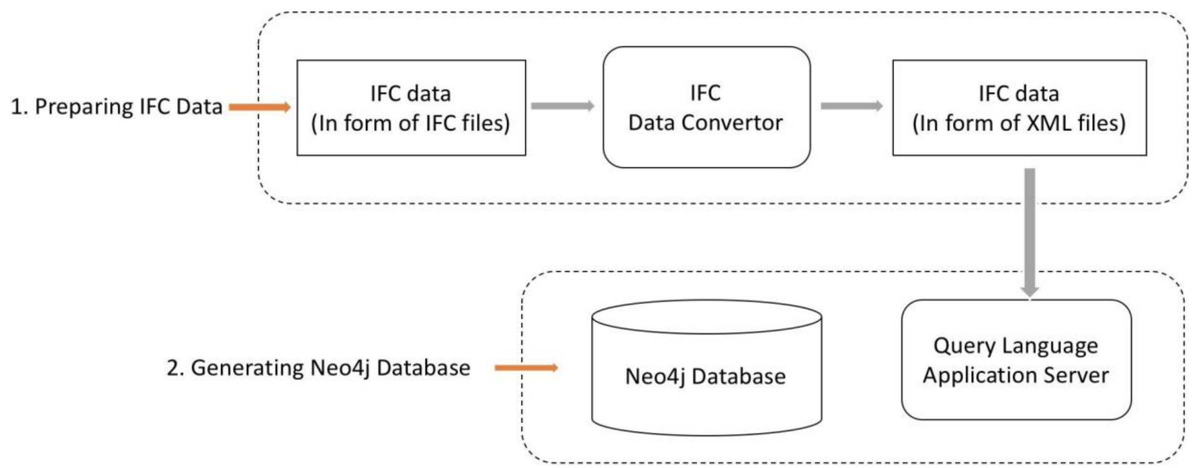


Figure 2. Work flow diagram

The mapping conversion workflow is realized mainly in two parts with three steps (see figure)- The first step is to realize the converting process from IFC to XML, then the next step is generating valid Cypher commands with XML based on the mapping rule conducted, which then lead to the final step of creating the Neo4j database with Cypher scripts.

The original IFC file written in EXPRESS G has the following format: every entity has its unique object ID with its type and attributes defined. The Cypher script will be generated by executing the python file in command line. Then the Cypher script is used with Neo4j-Shell to import information and build the graph database. The main challenge for the automatic database generation work is making use of the XML file structure to parse information and generate the valid Cypher command.

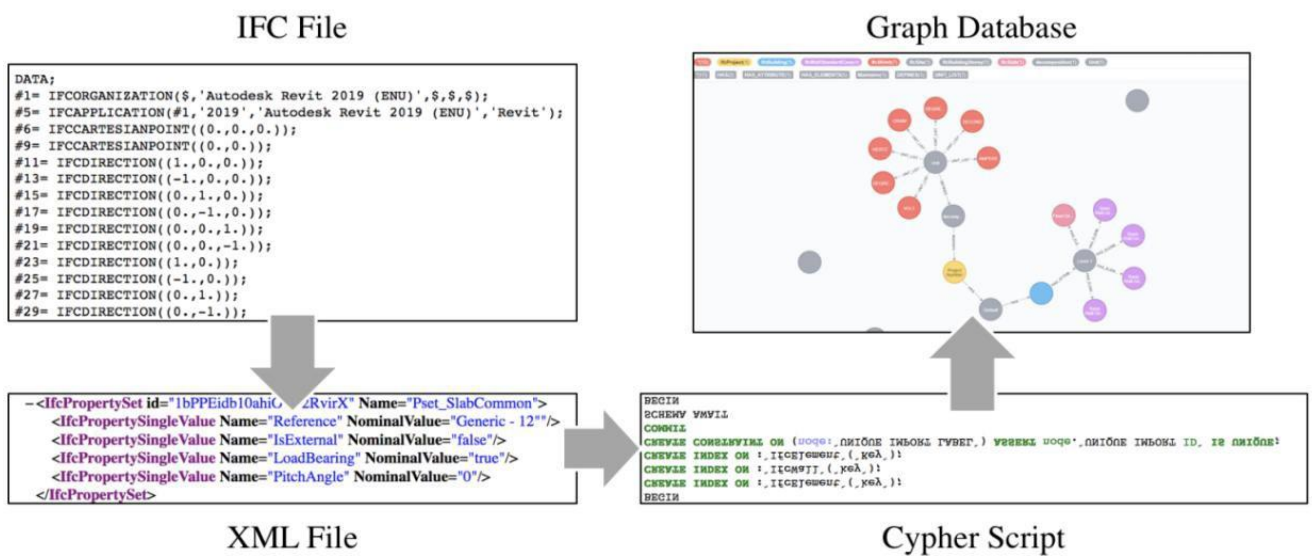


Figure 3. Programming process of work flow.

To implement this arithmetic steps needs the implementation of regular expressions, Advantages of XML files could benefit us by its initial layered-structure, where we can extract it into tree data structure and apply traversing algorithms. the key to success is to precisely recognize the node label, and by applying reg expressions we transform them into attributes and integrate them into Cypher.

Original IFC database are defined in IFC EXPRESS schema under the principal of Entity-Relationship model. The implementation of the IFC model in EXPRESS is achieved by writing 'entity-attributes', which describes all the data structure schema into entities. Attribute values in ER-Model are described as entities with property values. Relationships in ER-Model are described in relational entities with 'IfcRel-' suffix in name, and such entities are referencing other non-relational entities and aggregate them together to represent a relationship.

Hence it is easy to transform and implement them into relational database with proper normal form applied. However, graph database does not emphasis on how to construct proper data table that enables SQL queries. On the contrary, it is looking for the description of 'graph', which consists of vertex and edges, namely, the entities and relationships.

Thus the algorithmic implementation will mainly be two steps - the construction of entity nodes, and the construction of relationships in between. Cypher query language for constructing nodes are described as CREATE query:

Query 1: CREATE(return_variable :Entity_name{ property_name_1: property_value] , property_name_2 : property_value, ...property_name_n:property_value})

Where variable name are used for return query result. Hence if given XML file describes an 8-inch wall case with name, id and object type, we want to construct it in graph database and return the constructed node, we can transform it according to Query 1a as:

Query 1a (single entity construction):

```
CREATE (n:IfcWallStandardCase{ Name:"Wall", id:"0001", ObjectType:"Basic Wall:Generic - 8"})
RETURN n;
```

We can also do multiple create in an integrated query to construct several entities:

Query 1b (multiple entities construction):

```
CREATE (m:IfcWallStandardCase{ Name:"Wall", id:"0001", ObjectType:"Basic Wall:Generic - 8"}),
(n:IfcWallStandardCase{ Name:"Wall", id:"0001", ObjectType:"Basic Wall:Generic - 8"})
RETURN m,n;
```

The relationship construction could be constructed in full path CREATE query:

Query 2: CREATE(return_variable_1:Entity_name{ property_name: property_value , ... }) - [return variable: relationship_name{property_name_: property_value , ... }] -> (return variable :Entity_name{ property_name: property_value ,...... })

This query returns a triple - entity1,entity2 and relationship in between. Thus if we wanted to add 'aggregation' relationship between two IFC elements we can write the query as:

Query 2a(full-path create query):

```
CREATE r = ( a: IfcElementType1{ name: "sample element 1" , id:"0001" }) - [b: IfcRelType
{name:"aggregation"}]-> ( c: IfcElementType2{ name: "sample element 2" , id:"0002" })
RETURN r;
```

However, if we want to add relationship to existing IFC elements in the graph database, we will need to do MATCH-CREATE-RETURN query:

Query 2b (match-create-return):

```
MATCH ( a: IfcElementType1) , (b:IfcElementType2)
WHERE  a.id="0001" AND b.id="0002"
CREATE  (a) - [r: IfcRelType{name:"aggregation"}]-> ( b)
RETURN  r;
```

Advanced query comparable to aggregated query in SQL could also be written in Cypher for further graph database maintenance and operation after the graph database is fully constructed, which is beyond this paper's scope and will not be discussed.

So the key to succeed the final stage of mapping method is quite explicit - the first step is to traverse the XML by applying tree algorithms, parse the information of entity names and attributes by writing regular expression in python and overwrite them into CREATE Cypher query to construct nodes. The next step is to figure out the relationship, which need to find the entity label and index them in Ifc EXPRESS schema definition to extract the involved relationship entity, then use the regular expression to parse the relationship attributes and generate the relationship query sentence. At this step we have the option of full-path create query (Query 2a) and match-create-return query (Query 2b).

However, in real BIM projects, the model built by BIM application users are tremendous in size, and the correlated IFC data always result to be tens of thousands in entity cases, thus it is not possible to input the generated Cypher sentence by sentence. So practically we ll need batch import, where the generated Cypher query should be integrated into paragraph. To succeed in batch import, simply connect each sentence together is not sufficient and will potentially lead to fatal errors of creating too much wrong and duplicated relations. The reason of this kind of error is caused by MATCH queries - when we proceed multiple look ups by doing MATCH queries, the return value from each sentence will be stacked and when we then do CREATE to construct relationships, it will bring in all the return value of previous MATCH as the CREATE input and build relationship between them, thus redundant and wrong relationships will be added. The key solution to this is to UNION all the MATCH-CREATE-RETURN queries, which will group the result at the end of total batch import paragraph, rather than stack the return values sentence by sentence.The UNION can be achieved either by doing UNION ALL query or UNION query:

Query 3a (union all):
```
MATCH ( a: IfcElementType1)    RETURN   a.id AS id UNION ALL
MATCH (b: IfcElementType2)     RETURN   b.id AS id;
```
Query 3b (union):
```
MATCH ( a: IfcElementType1)    RETURN   a.id AS id UNION
MATCH (b: IfcElementType2)     RETURN   b.id AS id;
```

The difference between these two is that union all will keep duplicates while union will not, thus, to achieve batch import we will need aggregated CREATE - MATCH - UNION - CREATE - RETURN query series to succeed.

To summarize, the computation process for this application is described in following steps:

Step 1. import ifcConverter and transform the ifc data file format into xml;

Step 2. traverse the xml file using tree traversing algorithm start from root, and store all children information into tuple list **ENTITIES[]**;

Create batch query string list **B_QUERIES[];**

Step 3. for each entity **E** in **ENTITIES[]**:

use regular expression to extract entity information;

append CREATE query string **c_query** to string list **C_QUERIES[];**

return **C_QUERIES[]**;

Step 4a. for each entity **E** in **ENTITIES[]** : find

its referencing entity **E_ref**;

find its parent entity
E_par; find its child
entity **E_chi**;
concat and store **E_ref**,**E_par**, **E_chi** into entities tuple
E_Rel[]; If all related entities found, go to **Step 4b.**

Step 4b. for each relationship pair <**E,E_R**> (i.e.**for each E_R** in **E_Rel**):
call regular expression to traverse ifc EXPRESS schema to find IfcRel-entities, get the return value in CREATE string **c_query_r**;
append MATCH query string **m_query** to list
M_QUERIES[]; append **c_query_r** to **M_QUERIES[]**;
if (**E_R** has **E_Ref**, **E_parent, E_child**): go to **Step 4a** and
recurse; return **M_QUERIES[];**

Step 5. for each query string **CQ** in
C_QUERIES[]: append to
B_QUERIES[];
for each two query strings **MQs** in
M_QUERIES[]: append **MQs** to
B_QUERIES[];
if (**MQs** is the last item): **break** ;
else append UNION query string **u_query** to
B_QUERIES[]; **Step 6.** append RETURN query string **r_query** to
B_QUERIES[];
return **B_QUERIES[]**;

A generated graph database from ifc file exported from Sample Project in Revit can be displayed in figure 4.

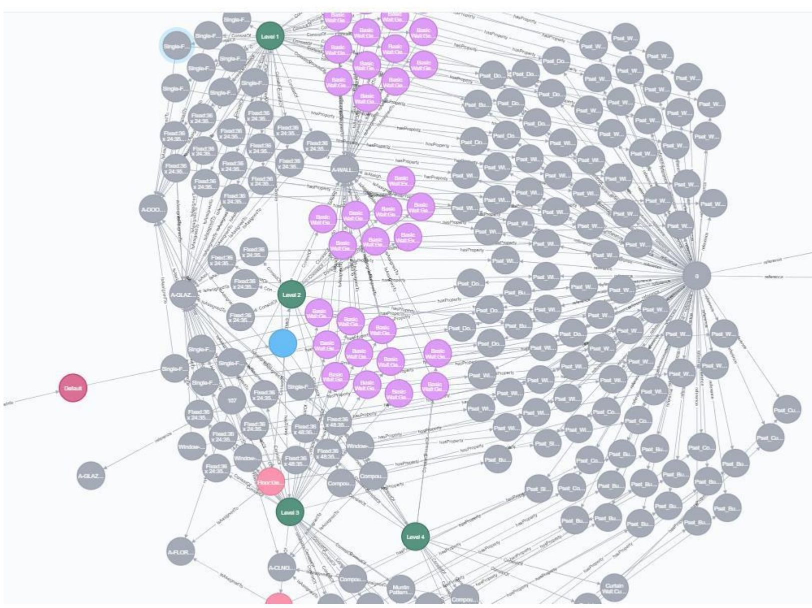


Figure 4. Generated graph database from Revit project.

CONCLUSION

By implementing this mapping method, application users and developers can benefit from the flexibility of relationship management in graph database, as it provides the interface for dynamic relationship inserting, updating, deleting and modifying. Also, user-defined queries could be constructed for graph database. Those cascaded queries or relationship path finding which need to self construct graph algorithm in normal SQL database are no longer an issue here since they are embedded in graph database and have optimized querying performance. Moreover, by executing this mapping rule application the workflow keep the relationships which is essential during data exchange, and provides capability to migrate the model to other technical software which provide interface for graph database. Advanced algorithms and techniques could also be developed based on the graph database, e.g. network analysis algorithms in machine learning could be run via the node-edge model provided by it.

REFERENCES

Eastman C.(1981) Database facilities for engineering design, Proceedings of the IEEE, 1981(69):1249-1263

You, S.-J., D. Yang, and C.M. Eastman. (2004) Relational DB Implementation of STEP based product model, in CIB World Building Congress, Toronto, Ontario, Canada

Eastman C.,Y.-S. Jeong; R. Sacks, I. Kaner (2010) Exchange Model and Exchange Object Concepts for Implementation of National BIM Standards, Journal of Computing in Civil Engineering /Volume 24 issue 1.

Nour M.(2009) Performance of different (BIM/IFC) exchange formats within a private collaborative workspace for collaborative work [J]. Electronic Journal of Information Technology in Construction, 2009(14):736-752.

Smart Grid/Building Semantic Integration for Interoperability

Jack Hodges, Ph.D.[1] and Wei Xi Xia, MS[1]

[1]Siemens Corporate Technology, Artificial and Human Intelligence Group, 1936 University, Suite 320, Berkeley, CA 94704; e-mail: jack.hodges@siemens.com, brianxia@siemens.com

ABSTRACT

We report on a project to develop round-trip interoperability between the grid utility and building management systems (BMS), and between buildings running heterogeneous management systems, which have traditionally been information silos. The approach is based on the semantic integration of energy and building information models with a common, or system-agnostic, semantic layer. Standards tend to have a very narrow focus of applicability, so growing a system-agnostic domain model involves the integration of several standards (in this case FSGIM, OpenADR, IFC, SAREF, QUDT, SOSA, NIST Tariff, and BRICK) into a cohesive model. The resulting information layer provides a foundation for round-trip translation, validation, logic, and reasoning, and is part of a cloud-based platform that provides a messaging hub. The approach is currently being tested in a pilot study with 23 buildings in the two primary California power utilities, PG&E and Southern California Edison.

INTRODUCTION

Demand response between a utility and a consumer has, to date, been a one-way relationship. The utility provides incentives to consumers in the form of reduced power rates and in return, during demand events the utility can reduce power to the consumer. This is of course a high-level look at something substantially more complex, since contracts and tariffs vary all over the map, and vary with time of day, day of the week, and season. So far, demand events are determined by the utility and the metrics they use to declare a demand event (generally lasting 4 hours during peak demand) are not transparent to consumers, though they are generally dictated by forecast temperatures.

In recent times, Time of Use pricing has been employed, whereby the utility provides a price event, in the form of an OpenADR price payload, and commercial customers (those with systems that can manage building consumption) can decide how much power to use based on price. This has also been a one-way interaction since the utility is not expecting to see the forecast values returned, so it cannot really adapt to forecast demand across the community.

In this paper we present a semantic platform designed and implemented to support round-trip interactions between the utility and BMS (using OpenADR), as well as to mediate interactions between buildings using like/dislike management systems to help stabilizing supply and demand. We recognize that the utility information models are based on a different set of standards than buildings, and that this produces information silos which are challenging to negotiate in terms of interoperability. As such, we have developed a standards-based, system-agnostic (or common) information model that serves as both a translator as well as a negotiation mediator between the players. This information model makes it possible for the utility to publish a pricing event and to receive forecasts and then to turn around and publish new prices, etc., until the demand meets the supply. It also enables buildings that act as a single VEN (in the OpenADR context) to collaborate on their respective forecasts until they meet tariff requirements. Being an integrated information model allows this approach to adapt to changing metrics for defining demand events, as well as to negotiate using different building information, without changing any code, since the models reside outside the Utility and the BMS, and are fully declarative (can thus be modified at run time).

The remainder of this paper will present the architecture of this system as well as the information model and the mechanisms we used to integrate the ontologies used in the platform.

BACKGROUND / RELATED WORK

Smart Grid and Smart Building each have compliance standards that apply to various aspects of their operation. Implementing and integrating these standards can improve generality and interoperability without sacrificing legacy models. In the case of the Smart Grid, there are many standards, but in terms of interactions with buildings, energy use and management ASHRAE Standard 201, implemented in the Facility Smart Grid Information Model (FSGIM, ANSI/ASHRAE/NEMA 2016) provides ample content for representing electrical loads, generation, measurement, and management. The OpenADR (IEC/PAS 2014) and BACnet (ASHRAE 2016) protocols provide messaging and payload models for representing demand response interactions between a utility and buildings, or between building devices, respectively. On the building side, we also see standards such as the Industry Foundation Classes (IFC, ISO. 2014), and SAREF (Poveda-Villalon 2018), which represent building architecture and systems. These standards (and others) provide the foundation material for growing an interoperability model used in this project.

There have been growing pains in this regard, most notably the acquisition of standards into high-quality OWL ontologies, and the integration of acquired models. With respect to model acquisition, many standards have no structured (or, at least, not in OWL) implementation so they must be translated. Modern declarative modeling languages such as OWL provide the ability to define semantic relationships precisely enough to support machine-to-machine (M2M) interoperability (i.e., interaction and understanding) but the translation process of acquiring standards into OWL models is anything but standardized.

Two similar efforts, to convert the IEC 61970 standard, and later the ASHRAE 201 standard, from UML to OWL were reported in (Crapo 2010 and Dangi 2012), respectively. In each of these cases assumptions and choices are made that would differ across ontologists.

A second problem is the basic ontology implementation approach, and this covers several metrics covered under the rubric of best practices, from naming conventions to design principles. In order to integrate ontologies they must be mapped to each other, but the intentions of the designers and the manner in which the ontologies were developed often makes integration challenging. On the intent side, many ontologies are developed without M2M understanding in mind, so they are ambiguous from an M2M perspective (Obrst 2007). Also, most ontologies are currently developed in-house, with no broad-based international consensus or input involved, to resolve interoperability needs in an enterprise environment. One way to resolve the preciseness problem is to implement models with a layering approach (Hodges 1993, Kitamura 2002) so that lightweight models and heavyweight models can be integrated and continue to provide value at their designed abstraction level. One way to resolve the in-house model development problem is to use standards as much as possible, as they have at least been adopted by international communities. Improving the translation mechanisms for acquiring standards into OWL, and developing a consensus on semantic best practices needed to effectively implement and integrate semantic models are ongoing topics beyond the scope of this paper.

In a recent paper we proposed the approach being used in this project, namely to integrate the standards associated with the Smart Grid and Smart Building to provide a system-agnostic information model (SAIM) and to do it in a manner that integrates models into functional abstraction layers (Hodges 2017, Mayer 2017, Koh 2017). The layering approach has also been proposed in (Xu 2004), and larger communities are beginning to see the need to grow interoperable domain models (e.g. the NIST Industrial Ontologies Foundry, Kulvatunyou 2018), and the IEC, which are talking about how to enable semantic interoperability using standards.

PLATFORM APPROACH / ARCHITECTURE

The platform, which we call EPIC (after the California Energy Commission program) is depicted in Figure 1.

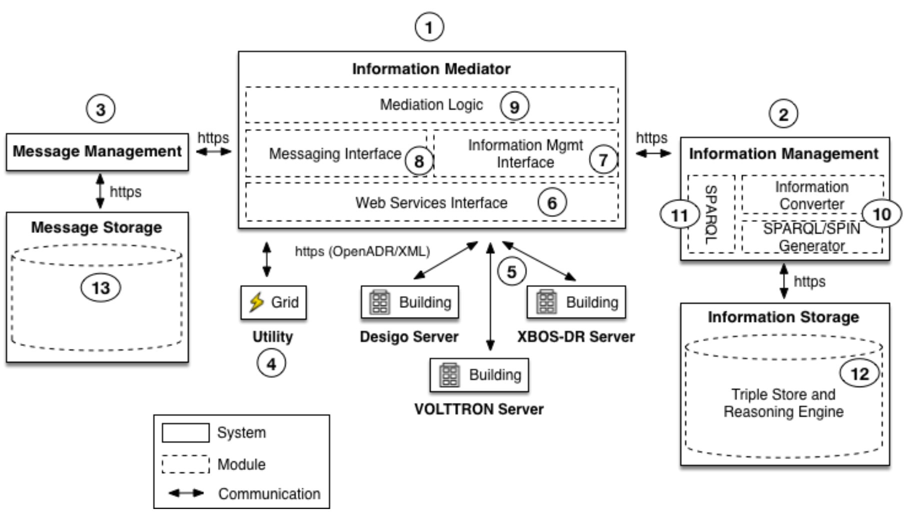


Figure 1. EPIC architecture.

The three major components of this system (shown as **1-3** in Figure 1) are implemented using web services so that they can reside on separate machines (though in the current version they reside on an Amazon cloud instance). The primary component, the Information Mediator (at **1**), serves as a proxy for all interactions and dispatches as necessary to the Information Management system (at **2**) and the Message Management System (at **3**). The Information Mediator interacts with external entities (Utility, at **4**) and BMS such as the XBOS (at **5**[1]) using the OpenADR protocol via a publish-subscribe messaging pattern. All content shared by the utility or BMS is translated into what we call the System Agnostic Information Model (SAIM) so that later negotiation (and content negotiation) can be supported.

SMART GRID / SMART BUILDING MODELS

The goal in supporting interactions between the grid and BMS is not just to support data interoperability (very straightforward) but to support semantic interoperability between unlike systems and to do so without implementing $O(N^2)$ adapters to the various entities that might engage in collaboration in the process. This is what gives rise to the EPIC System Agnostic Information Model (SAIM). Moreover, we do not believe that many institutions would adopt the use of ad hoc models, so we try to use existing standards and standards-compliant models as much as possible. We do this using a functionally-layered approach as shown in Figure 2.

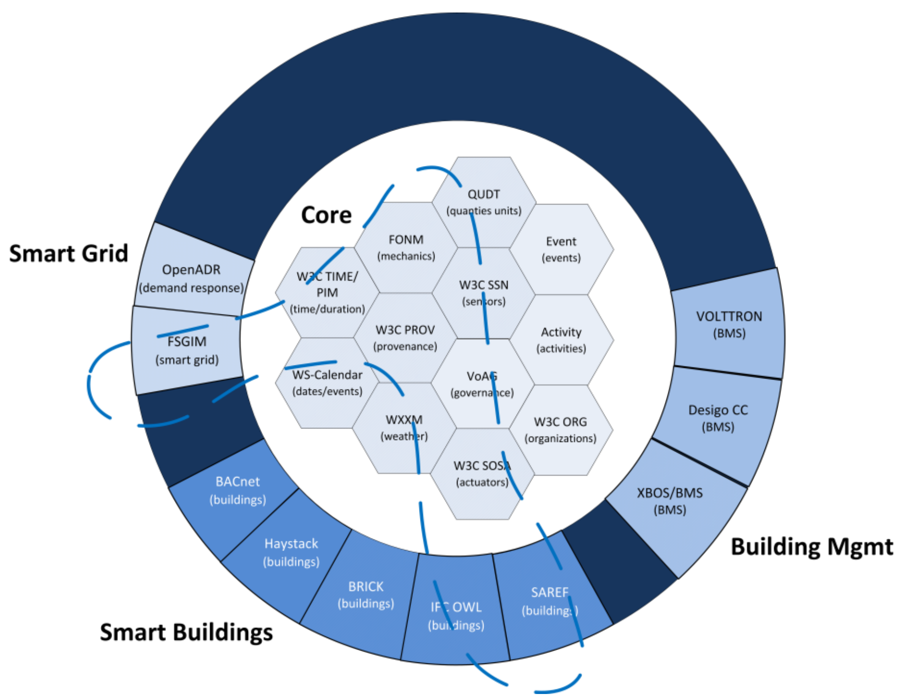


Figure 2. Model layering - increasing specificity radially.

[1] In the current project, only an adapter to BRICK has been developed. In a parallel project an adapter to Siemens Desigo CC has been partially developed.

Figure 2 shows a conceptual aggregation of semantic models into groups (annuli) defined by their degree of specialization. The outer annulus represents more specialized domain models, such as Smart Grid, Smart Buildings, and Building Management, which can be cross accessed by traversing through more general (or cross domain) models in the inner circle (i.e., Core). The figure makes no claim as to how these models are integrated; it only suggests that a path from any of the outer-annulus domains to any other outer-annulus domains can be affected through interoperability with the core. In fact, Figure 2 is only one such visualization of standards integration. In another visualization there are any number of annuli built on top of each other by degree of abstraction, where a specific application is seen as a slide of all annuli, from the innermost or upper ontology to the outermost domain-specific ontologies.

MODEL INTEGRATION

Essential to growing a standards-based semantic domain model for building interoperability is the integration of building automation system models such as XBOS, which uses BRICK (Balaji 2016) or VOLTTRON (Akyol 2012), both of which use variants of a tag-based information model but implemented so differently that direct interoperability is not possible. There are two approaches that can be used to drive integration: (1) one in which legacy models such as these are embraced and the integration is used to map across ontologies rather than to migrate data to the new model, and (2) one which is used to migrate both models and data and replace the originals. In our work we are implementing the former approach. In (Hodges 2017) we discuss our integration approaches (and associated issues) in greater detail, but here we identify the integrations we have performed to aid in the development of a system-agnostic information model for Smart Grid and Smart Building, one of which is shown in Figure 3.

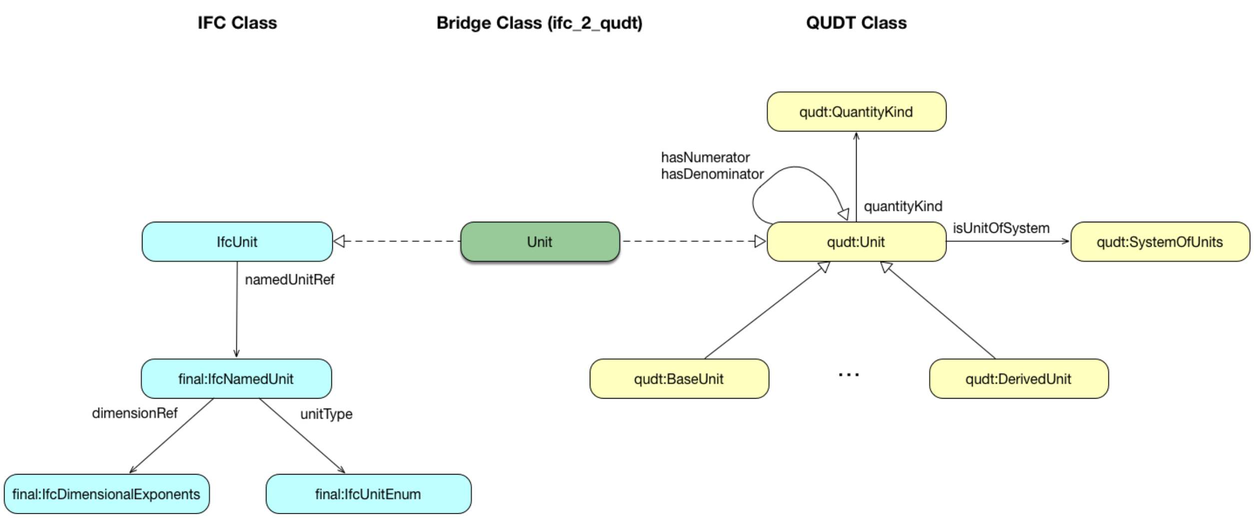


Figure 3. IFC to QUDT Unit class mapping.

This diagram shows the initial phase of a mapping between the unit portion of the IFC and QUDT curated ontologies. In this phase subject matter experts have looked at the two ontologies and have determined appropriate class mappings along with potential conflicts at the property or restriction level. In this case, a single Unit class (green) was proposed as subclassing the IfcUnit and qudt:Unit classes as there was no conflict with other property restrictions.

The same exercise can take place across all of the ontologies deemed necessary for the kind of integration desired, as shown in Figure 4.

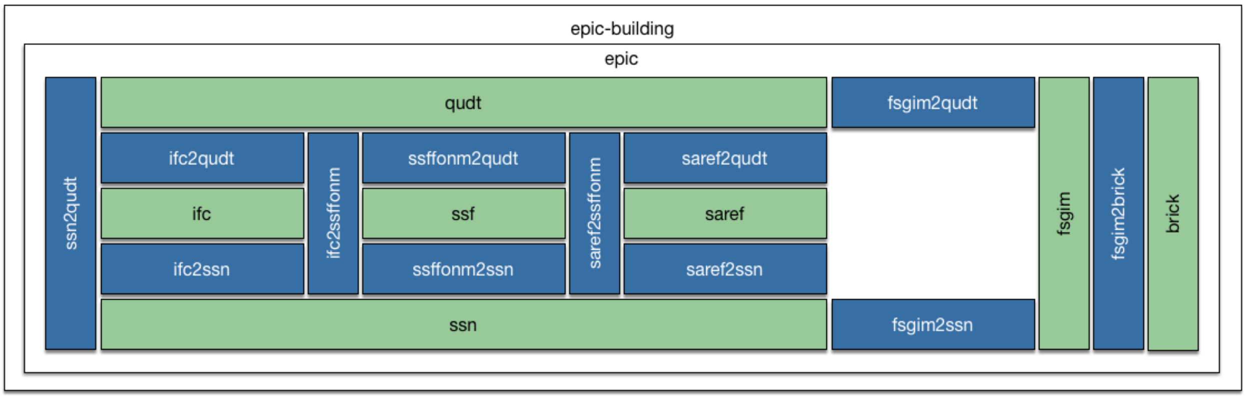


Figure 4. Bridge and adapter mappings.

Figure 4 illustrates 7 ontologies (qudt, ifc, ssf, saref, ssn, fsgim, and brick, in green) which are a part of this common model, along with the pairwise integrations between them (in blue). The integrations follow the example shown in Figure 3, though some are [much] more involved than the one depicted in Figure 3.

The result of these integrations is the ability to traverse from a legacy model such as BRICK, as shown in Figure 5.

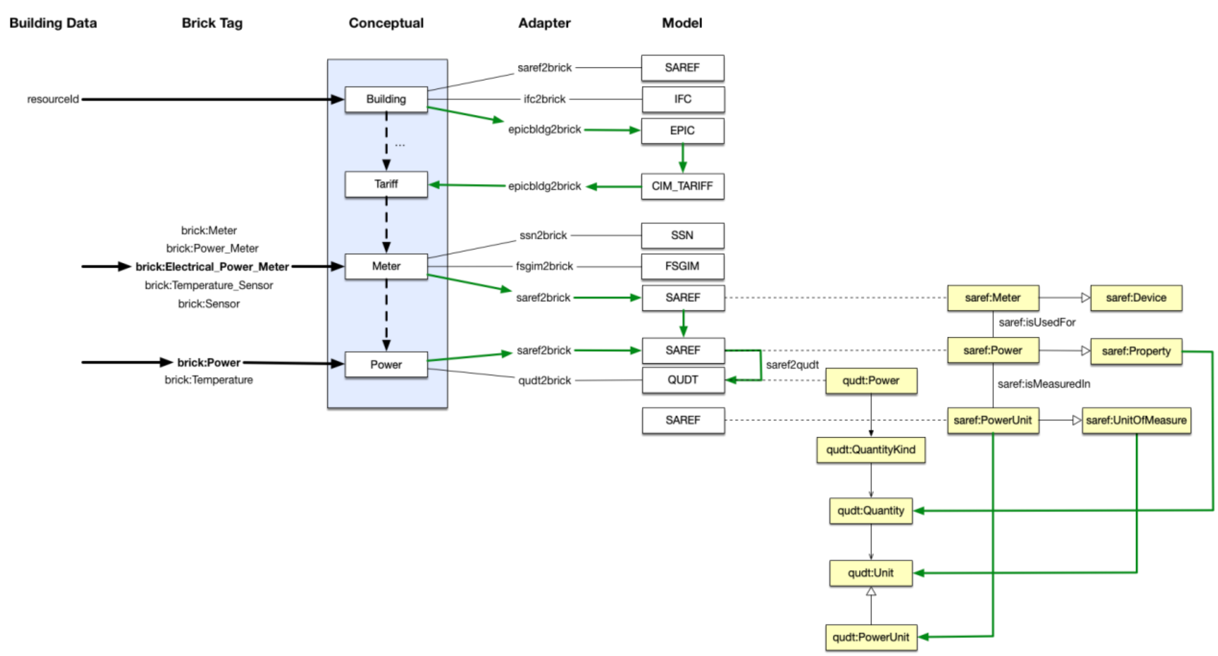


Figure 5. Mediator building to building mapping through SAIM.

Figure 5 depicts a path from supplied building identification data (at **1**), and meter data which is associated with Brick tags such as brick:Electrical_Power_Meter (at **2**) into the various SAIM models. The green line shows how brick meter data can be associated with SAREF and QUDT models to access Quantity and Unit structured models, and with the CIM_TARIFF model to access the contract tariff for the building in question. This information can then be used to perform analysis and optimization on energy usage compared to the pricing and contract tariff.

VISUALIZER

A visualizer was developed to expose some of the functionalities and data generated in the EPIC system. It adopts a dashboard layout to help users conveniently visualize the communication between the utilities and the buildings. Users can monitor the current prices and demands as well as retrieve historical data. The data are presented on the plots to showcase the time-of-use pricing hike during an event and how the buildings respond by adjusting demand accordingly.

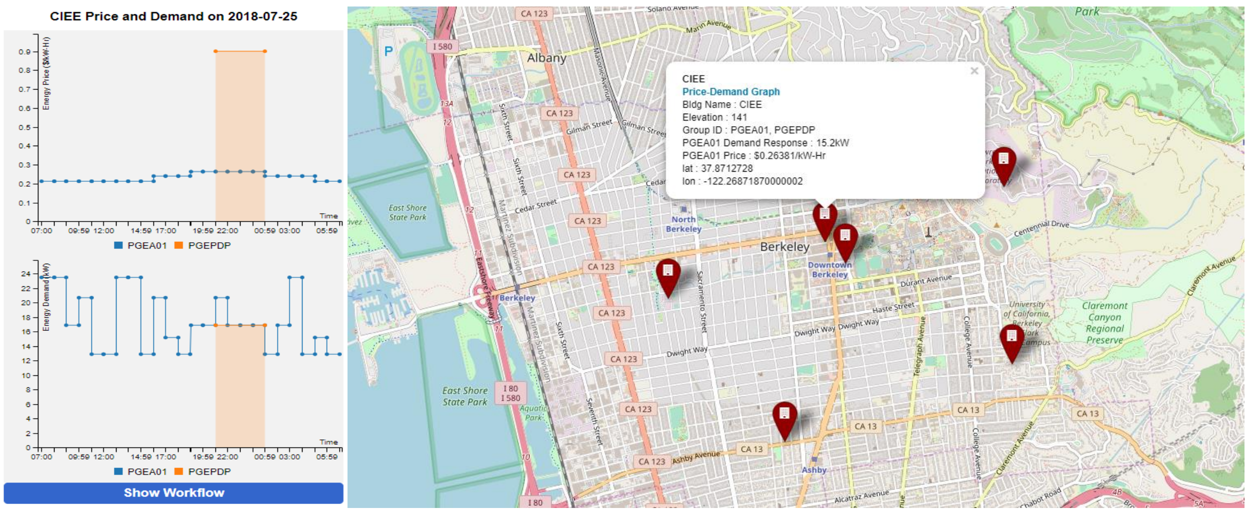


Figure 6. EPIC System Visualizer

CONCLUSION

A platform was presented that supports round-trip interactions between the grid utility and BMS using a standards-based, system-agnostic information model. Several issues underlying and complicating the successful integration of standards, to produce a viable domain model for energy and building management, were presented. Most notably the lack of consistency in ontology development and best practices, and equally challenging being the difficulty of developing mappings across ontologies where gaps or conflicts might exist. Nonetheless, a viable system-agnostic information model has been developed and has been in a pilot study using 23 buildings in northern and southern California.

REFERENCES

Akyol, B., Haack, J., Ciraci, S., Carpenter, B., Vlachopoulou, M. & Tews, C. (2016). "VOLTTRON: An Agent Execution Platform for the Electric Power System." Proceedings of the 3rd International Workshop on Agent Technologies for Energy Systems.

ANSI/ASHRAE/NEMA. (2016). "Facility Smart Grid Information Model." Technical report. ANSI/ASHRAE/NEMA Standard 201:2016.

ASHRAE. (2016). "BACNet." Technical report. ASHRAE Standard 135:2016.

Balaji, B. et al. (2016). "Brick: Towards a Unified Metadata Schema For Buildings." Proceedings of the 3rd ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings. ACM.

Hodges, J. (1993). "Naïve Mechanics: A Computational Model for Representing and Reasoning about Simple Mechanical Devices." Ph.D. Dissertation, UCLA.

Hodges, J., Garcia, K. & Ray, S. (2017). "Semantic Development and Integration of Standards for Adoption and Interoperability." Computer, 50(11), 26-36. IEEE.

Hodgson, R. (2012). "The Quantities, Units, Dimensions, and Datatypes Ontologies." <http://qudt.org>. Qudt.org.

IEC/PAS. (2014). "OpenADR." Technical report. IEC/PAS Standard 62746-10-1:2014.

ISO. (2014). "Industry Foundation Classes." Technical report. ISO Standard 16739:2013.

Kitamura, Y., Sano, T., Nama, K. & Mizoguchi, R. (2002). "A functional concept ontology and its application to automatic identification of functional structures." Advanced Engineering Informatics. Volume 16, Issue 2.

Koh, J., Ray, S. & Hodges, J. (2017). "Information Mediator for Demand Response in Electrical Grids and Buildings." 11th International Conference on Semantic Computing (ICSC).

Kulvatunyou, B., Wallace, E., Kiritsis, D., Smith, B. & Will, C. (2018). "The Industrial Ontologies Foundry Proof-of-Concept Project" The APMS 2018 International Conference Advances in Production Management Systems.

Mayer, S. and Hodges, J., Yu, D., Kritzler, M. & Michahelles, F. (2017). "An Open: Semantic Framework for the Industrial Internet of Things." Internet of Things. January. IEEE Intelligent Systems.

Poveda-Villalon, M., Nguyen, Q.D., Roussey, C. & De Vaulx, C. (2018). "Ontological Requirement Specification for Smart Irrigation Systems: A SOSA/SSN and SAREF Comparison." Proceedings of the 9th International Semantic Sensor Networks Workshop. Monterey, CA.

W3C. (2015). "OWL Web Ontology Language." Technical report. World Wide Web Consortium.

Xu, B., Wang, P., Lu, J., Li, Y & Kang, D. (2004). "Bridge ontology and its role in semantic annotation." Cyberworlds, 2004 International Conference. 329-334.

Using Linked Data to facilitate smooth and effective workflow in a federated model environment

Leif Granholm, M.SC. (Eng)[1], and Seppo Törmä D.Sc. (Tech)[2]

[1]Trimble Solutions Oy, Metsänpojankuja 1, 02130 Espoo, Finland, +358400440608, leif.granholm@trimble.com
[2]VisuaLynk Oy, Holmanpää 3B, 02240 Espoo, Finland, +358503160979, seppo.torma@visualynk.com

ABSTRACT

BIM has had a major impact on the design of new buildings but it has so far had little effect on workflows in construction projects. In this paper we present how BIM enhanced with linked data can provide comprehensive workflow support with natural data ownership and governance, granular online data sharing, and change management based on notifications downstream and change requests upstream. Linked data is used to link object instances in different models and many of the links can be created automatically as byproduct of design progression using a reference modeling paradigm for BIM software.

INTRODUCTION

BIM was originally understood as a single coherent centralized model representing a building. Recently that view has evolved into a concept of a federated model where every discipline - and often each phase within a discipline - create their own self-contained models whose data can then be combined in different ways for coordination and other purposes. However, it can be argued that BIM can and should be understood even more broadly as the transformation from human-understandable documents to machine-understandable data. This requires that data published and shared is expressed in a machine-readable format - such as IFC - instead of traditional human readable documents, such as drawings, schedules and natural language text.

The whole information management process should become digital, including the consumption of data. A brief executive summary of BIM could be *automating reception and consumption of data*. A major consequence of using structured data is the separation of content and presentation, which means that a consumer decides how the data will be presented and used. In a traditional document based process the producer of data decides this.

Figure 1 shows a part of an example workflow. Tasks are shown with their precedence relations and also their resources and information produced are indicated. Information created at the earlier tasks is needed in the execution of downstream tasks, and consequently a solution for information sharing is required. Traditionally it was based on the exchange of drawings, more recently on exchange of BIM files, and nowadays increasingly on access to online data in the models. Whatever the solution, it is important to take into account that the results of activities may need to change, perhaps multiple times: there can be new requirements, new versions of architectural models, corrections that are needed to structural model, and so on. Consequently, parts of the workflow must be re-executed later on, perhaps limited to a small portion of the previously shared information.

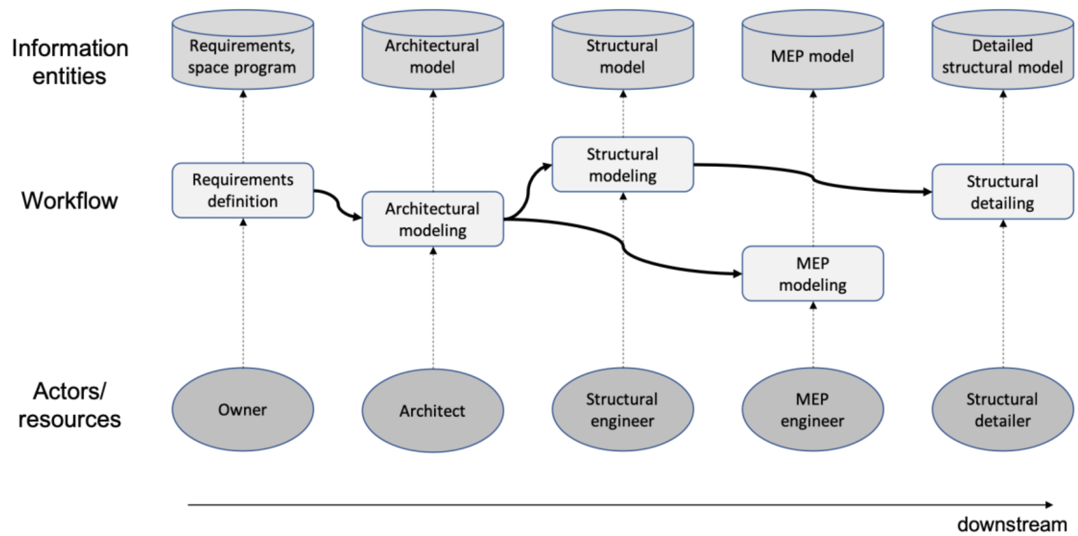


Figure 1. A part of an example workflow indicating the resources and results of tasks

In smooth and effective workflows all tasks should be able to access and utilize the information resulting from previous tasks in a focused manner - as a compact set of relevant data - and in a format that can be efficiently processed with appropriate tools. Drawings typically contain focused information but unfortunately not in a machine-understandable format. BIM models, on the other hand, are machine-understandable but usually not well-focused to support change management workflows. When some objects in one model are changed, effective change management requires the understanding what objects in other models might be affected. This can be achieved by cross-model links between objects using principles described in Berners-Lee (2006) and Bizer (2009).

This paper addresses the questions of how to solve the problems of digitalization of construction workflows and argues that a technology that allows flexible publication, access and linking of data is an important part of the solution. The technology is based on standard representations, online access to data, reference modeling, link generation supported by BIM tools, change notifications downstream and change requests upstream. The concrete realization can be based either on Linked Building Data representations (Beetz 2009, Törmä 2013, Törmä 2014, Hoang 2016I) or centralized BIM collaboration systems.

MANAGING WORKFLOWS

This chapter presents the concept of workflow management in an inter-organizational setting based on granular sharing of data published online, the design process based on the use of reference model and cross-model linking and change management processes in the workflow.

Organizing Principles

As Figure 1 suggests, the workflows in construction often cross organizational boundaries. Different tasks typically require specific types of resources, expertise and tools; each task is are naturally allocated to an actor with proper capabilities. From the perspective of workflow management, an important question is what information each task consumes, what information it produces, and how these two are related. In the following these are discussed as the incoming information, outgoing information, and linking information (Figure 2).

Incoming information. Almost all tasks - whether in design or construction stages - have at least some incoming information flows. In Figure 2, the task "Structural modeling" has two incoming information flows, the requirements model and the architectural model. The outgoing information of that task, a structural model, should conform to the contents of these incoming models. The central questions with incoming information relate to the effective access to the information - that all relevant information and no irrelevant information will be received - and the changes to the information over time. The task may need to be executed many times when the incoming information changes, and there should be effective ways to determine whether the changes affect the task and to what extent.

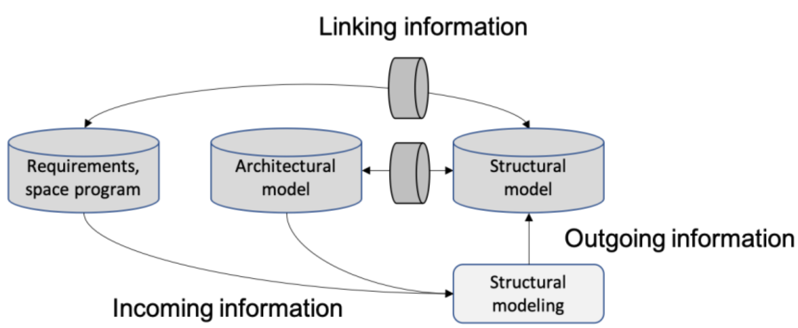


Figure 2. Incoming, outgoing and linking information of task "Structural modeling"

Outgoing information. When a task produces information as its result there are natural questions of ownership and responsibility of that information. In contrast to the early concept of BIM-based design - where the idea was to merge all BIM models together into a single unified model - in the workflow management approach presented in this paper each model remains separate for several reasons. The ownership of a model is explicit and defines who is allowed to modify it during change management workflows. A model can only be modified by the assigned designer who understands the rationale of the existing design and who has the proper expertise and tools to make the changes without breaking the design.

This concept has additional benefits over a single merged model. Firstly, intellectual property rights remain the same as with documents; consequently there is no need to change processes or business models to fully utilize BIM. Secondly, any model intelligence - for example, internal solutions developed for parametrized design - does not need to be shared with other parties in the project, since published data need only contain a snapshot with same information content as documents. Thirdly, full audit trail of the information can be recovered simply from the saved versions of datasets. Moreover, it allows the control of the access of the information based on the concept of digital sovereignty, as presented in Otto (2016).

Linking information. The outgoing information produced by a task is usually derived from incoming information, and is dependent on the contents of that information. This dependency can be determined at different points of time: during the creation of the dependent information, following its creation, or when the information is utilized. The information about the dependencies are called links, and they can be stored for later uses in specific linksets. When incoming information changes, the changes can be projected over the linkset to the outgoing information, to indicate to areas that are likely to be affected by the changes.

Links can be generated with a variety of methods. They could be specified manually or derived automatically based on graph matching algorithms. The third option explained below in more detail is to supply BIM design tools with interactive link generation capabilities.

Data Sharing

To proceed swiftly, workflow tasks should be able to receive all relevant and no irrelevant information from incoming information in a commonly usable format. However, in traditional BIM practice it has not been straightforward to achieve this. To provide smooth support for workflow management, especially taking into account the need to efficiently react to frequent changes, the following principles have been adopted: online publication of data, granular access to data, standard data formats, and access to objects' links.

Online publication of data. Whether on the Web or in a centralized cloud-based service, up-to-date data of previous models should be available for the consuming tasks and applications. Online availability of data can give a lot of flexibility to the contents that are shared. Same model information can be published at different levels of detail, and if desired, links to further data can be provided into unlimited level of detail. Models can be also published as use case specific sets or as deliverables corresponding to contractual milestones.

Granular access to data. The consuming tasks or applications should be able to access the data in a granular manner, even just one object at a time if needed. This means that replies to requests must support data formats that allow for the representation of individual objects, including links to further objects. The granular access is essential to keep the processing in consuming applications efficient and focused.

Standard data formats. The data should be returned in standard data formats. In the case of BIM, this means IFC or its derivative ifcOWL (Beetz, 2009) in the Linked Building Data approach. At the level of data serialization, Linked Building Data offers various alternatives ranging from XML and JSON to specific formats such as Turtle and N3. IFC itself is normally serialized either in the Step File Format or ifcXML, but neither of these allow a granular serialization of models. However, various APIs of BIM platforms can provide a objects descriptions in JSON or XML, that can be usable although not completely standardized formats.

Access to objects' links. When information about an object is accessed, it should be possible to either include the links of the objects in the reply, or to provide a related request that returns the links of the object. There are many variations of how the applications that access information about objects can be made aware of the related links. There can be an separate linking service that returns the links when accessed with the identifier of the object. In a centralized service there can be a default database for such links which makes it possible to include links to object descriptions transparently. Another approach is to use backlinking (Hoang, 2016); when a link is created, the target of the link is notified which allows it establish an (remote) inverse link to the referring object.

Reference Models and Link Generation

Since the focus in BIM has so far been on data production, the mechanisms to support data consumption in the downstream of a workflow are relatively undeveloped, especially in a multivendor environment. However, at Trimble there has been several years of development on some principles concerning structured machine-readable data that have proven to work well in daily use of Tekla Structures.

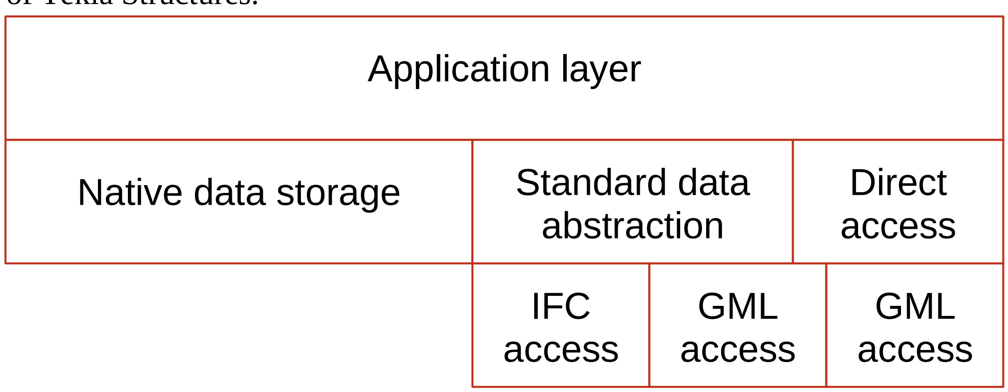


Figure 3. An example of a multikernel architecture

This concept is called a multikernel architecture (Figure 3) that maintains a clear separation between native and published data. Each application can have its internal native schema for creation, storage and management of data. The native schema is typically optimized for the specific functionality of the system. The application can publish and receive data in standard formats, such as IFC. When receiving data, application does not convert it back to its native schema but instead uses it together with native data. In a sense, the application has two geometric kernels that can run in parallel and can interact with each other. Multikernel architecture works much better than the alternative in which the received published model is imported and converted into a native format.

The multikernel software architecture concept - as implemented, for instance, in Tekla Structures - can be used to provide support for design work based on a reference model. The structural engineer can load a published version of the architectural model in Tekla Structures that renders it based on its IFC geometry. The designer can create the objects of a structural model as reference to the corresponding architectural objects. Some design tasks can even be supported by further automatization that enables the conversions of architectural objects into corresponding structural entities.

The functionality so far missing from this support it the link creation and publication. The event when a new object is created and positioned in a structural model is the correct point to suggest a link between the structural object and co-located architectural object. The links could be easily exported after the model has been completed as pairs of GUIDs, together with the nature of the relationship and enriched with metadata such as the time and user.

Change Management

When changes happen to a dataset produced in the workflow, the differences of the new version of the dataset with respect to previous version need to be identified. Methods for this have been studied in Oraskari (2015). Using the difference between two model versions, and linking to each downstream model, the possibly affected objects in the latter model can be identified. The result can be used to create a change notification to the responsible party of the model, which can start a ripple of change actions in the subsequent models.

When a information creation task ends up in a situation that needs changes from upstream models, it can create a change request using BCF messages (BIM Collaboration Format). BCF makes it possible to pinpoint the desired change using the view to the BIM model as the explanation of an existing problem.

The cornerstone of the concept is that all actors create their own data that is based on data from other (previous) actors that is then published in a standard format to be used both upstream and downstream in the value chain. This new data is owned and managed by the creator and cannot be changed by anybody else. Changes downstream and change requests upstream are facilitated by linking information between models.

IMPLEMENTATION TECHNOLOGIES

Two collaboration technologies to facilitate the workflow concept presented are reviewed: Linked Building Data and a Common Data Environment (CDE) to serve a federated model.

Linked Building Data - Web of Data technologies specified by Web Consortium allow the online publication of and access to structural data. The set of standards from globally unique identifiers (URIs) and graph-based data representation (RDF) to ontology description language (OWL) and query language (SPARQL), have been applied to the representation of building data with the ontology version of IFC, called ifcOWL and converters that can translate IFC data to Web-oriented graph format (ifcRDF).

In the Linked Building Data approach, the models are published online on the Web. Each of the identified objects has a URI which can be used to retrieve a description of the object in the RDF format, using the concepts of IFC as available in ifcOWL ontology. The online publication makes the model data accessible in a granular manner for all users over construction workflows, naturally taking the access control restrictions into account. The data can be accessed to the extent it is necessary: one object or a collection of related objects. It can be easily consumed by applications, as there are many tools to parse RDF data and the volume of data retrieved can be kept reasonable. The Linked Building Data approach enables in a natural manner the linking of objects across different models. Since the URI identifiers are globally unique and retrievable, links across can be created as ordinary RDF triples. However, the practices, methods and tools to actually create them those links that should exist between objects is a large open area of development.

Common Data Environment (CDE) - CDE (British Standard Institute 2013) is an emerging technology that has its roots in traditional servers in a client-server scenario. They contain the traditional database functions associated with client-server architecture amended with features from document management systems and cloud-based functionality for documents and models. Development has been rapid in recent years with the following main areas of development:

- Integrated Web-based viewers that can use both BIM and GeoSpatial data.
- API and built-in functionalities to support application development on CDEs.
- Support for BCF and workflow, issue management, and status management.

It seems that CDEs will be the main way the information is conveyed in the AEC industry. CDEs are the natural place to implement the linking functionality outlined above. The focus in BIM is shifting from data creation software to data consumption software; a large part of that software will be developed on the CDE platforms. All major BIM software vendors already have their own platforms on the market and under continuing development. It is therefore likely that no single platform will gain a monopoly in the market, and not even in a single project. Interoperability between the platforms is consequently of paramount importance. This can happen on two levels, interfaces directly between the platforms or through applications or middleware. The interoperability should be implemented using open standards, such as IFC and Linked Data.

DISCUSSION

Many parts of the workflow concept presented in this paper have so far been implemented. For data sharing, a Linked Building Data environment was implemented in a DRUMBEAT project (Hoang, 2016) and Trimble has implemented Trimble Connect, a Common Data Environment with workflow management support. The DRUMBEAT platform supported the backlinking based link management. Solibri Model Checker has been used for link generation between architectural, structural and MEP models. The reference modeling support has been implemented in Tekla Structures using the multikernel architecture. It has also support for BCF for notifications. The diff computation of Oraskari (2015) has also been implemented and tested with a large variety of models.

In the future research the different pieces of functionality need to be combined into a integrated solution for complete workflow support.

REFERENCES

Beetz, J. 2009. Facilitating distributed collaboration in the AEC/FM sector using semantic web technologies, PhD Thesis, Eindhoven University of Technology.

Berners-Lee, T., 2006. Linked Data – Design Issues, W3C, vol. 2009, no. 09/20.

Bizer, C., Heath, T. & T. Berners-Lee, 2009. Linked data-the story so far, International Journal on Semantic Web and Information Systems (IJSWIS), vol. 5, no. 3, pp. 1–22.

British Standards Institution 2013. PAS 1192-2:2013 - Specification for information management for the capital/delivery phase of construction projects using BIM.

Hoang, N. V., & Törmä, S. (2017). DRUMBEAT platform—a web of building data implementation with backlinking. In eWork and eBusiness in Architecture, Engineering and Construction: ECPPM 2016. CRC Press.

Oraskari, J., & Törmä, S. (2015). RDF-based signature algorithms for computing differences of IFC models. Automation in Construction, 57, 213-221.

Otto, B., Auer, S., Cirullies, J., Jürjens, J., Menz, N., Schon, J., & Wenzel, S. (2016). Industrial data space: digital sovereignty over data. Fraunhofer White Paper.

Törmä, S. Semantic Linking of Building Information Models. IEEE 7th International Conference on Semantic Computing. IEEE, 2013, pp. 412–419.

Törmä, S. (2014) Web of Building Data - Integrating IFC with the Web of Data. eWork and eBusiness in Architecture, Engineering and Construction: ECPPM 2014; Mahdavi, A.; Martens, B.; Scherer, R., Eds. CRC Press, pp. 141–148.

Ontology-Based Building Information Model Design Change Visualization

Ning Wang, SM.ASCE[1], and Raja R.A. Issa, PhD, JD, PE, F.ASCE, API[2]

[1]Ph.D. Student, M.E. Rinker, Sr. School of Construction Management, University of Florida, Gainesville, FL 32611-5703; e-mail: n.wang@ufl.edu
[2]Rinker Professor and School Director, M.E. Rinker, Sr. School of Construction Management, University of Florida, Gainesville, FL 32611-5703; e-mail: raymond-issa@ufl.edu

ABSTRACT

The use of Building Information Modeling (BIM) has become popular in the architectural, engineering, construction and Operations (AECO) industry, and BIM has been used in the lifecycle of projects. As more data is added to a BIM model, the complexity and data volume of the model increases. Further, many design changes are made to a building information model during design and construction phases, and it is difficult to extract and visualize the changed objects. Research on the use of ontology in BIM is also limited. The purpose of this study therefore is to use an ontology to visualize revised objects in BIM models. This research uses the Industry Foundation Classes (IFC) format, a widely-supported open standard for building information models. The changed objects in the BIM model are extracted by comparing the revised model to the original model, and a model report of the design change is provided. A prototype program using a sample IFC model is developed to validate the system. The results indicate that the proposed methodology is valid for the extraction and visualization of design changes in BIM models.

INTRODUCTION

Building Information Modeling (BIM) is a collaborative process in the architectural, engineering, construction and Operations (AECO) industry. Because it is collaborative, data interoperability is key. According to Gallaher et al. (2004), inefficient data interoperability costs the construction industry more than $15.8 billion annually. Industry Foundation Classes (IFC) is one of the most popular BIM data exchange formats for data interoperability and has been widely used in the AEC industry. However, current BIM applications do not support IFC perfectly (Jongsung and Ghang 2011). The size and complexity of IFC models increases as information is added (Jongsung and Ghang 2011; Zhang and Issa 2013). In addition, design change in BIM is considered a dynamic feature of construction projects (Juszczyk et al. 2016). BIM models and IFC models must often be modified as design changes in construction projects are made. Redesigning IFC models is almost evitable in construction projects. Even though BIM can provide valuable information supports for construction practitioners, due to design errors and project design changes, BIM design changes cannot be avoided. Construction practitioners are required to track IFC model changes during the lifecycle of a construction project (Shi et al. 2018). However, construction managers often face the overwhelming task of managing different versions of BIM models (Brittany et al. 2013). Although the vendor-specific software BIM 360 has a model change visualization function, the method was designed for vendor-based Revit files rather than open-source IFC files. Currently, the work of tracking design changes in IFC models is time-consuming and complicated.

This research aims to provide a methodology of visualizing changed 3D building elements in BIM models to track design changes. To achieve this goal, a comparison algorithm for use with two IFC models is required, as is an extraction method. In the literature review, the authors examine different extraction and comparison algorithms. Following the review, a methodology is developed for the comparison of a revised IFC model with the original IFC model and for the extraction of the changed building elements to several new IFC models for visualization. An ontology appropriate for the IFC schema and hierarchy tree was used. In accordance with the proposed comparison and extraction algorithms, the authors developed a python-based prototype application to validate the methodology. IfcOpenShell, an open-source IFC-parsing python library, was implemented to develop the prototype application. The result indicated that the proposed methodology is valid to visualize design changes in IFC models.

LITERATURE REVIEW

Industry Foundation Classes (IFC). As more efforts are made in BIM data interoperability and specifications, many BIM standards have been proposed such as in bSDD (buildingSMART Data Dictionary), OmniClass, COBie (Construction Operations Building Information Exchange), and other XML-based schemas (Sacks et al. 2018). Industry Foundation Classes (IFC) is the most popular BIM data exchange format in use in the AEC industry. BuildingSMART International (formerly International Alliance for Interoperability, IAI) proposed IFC as the international standard (ISO 16739). IFC is based on the ISO-STEP (Standard for the Exchange of Product model data) EXPRESS data modeling language (buildingSMART 2019). The advantages of the IFC specification are that they are open-source and easily accessible. The information in an IFC model can be seen, checked and freely modified without any license restrictions. For these reasons, the IFC specification has become the most popular BIM data exchange medium. BuildingSMART has published many versions of the IFC specifications such as IFC2x3 TC1, IFC4 Addendum 1, and IFC4 Addendum 2. Although IFC4 Addendum 2 is the latest released version, IFC2x3 TC1 is the latest stable version of the IFC specifications. IFC2x Edition 3 Technical Corrigendum 1 defines the IFC instance names, Globally Unique Identifiers (GUIDs), referenced instances, and property names in the IFC file (see Figure 1).

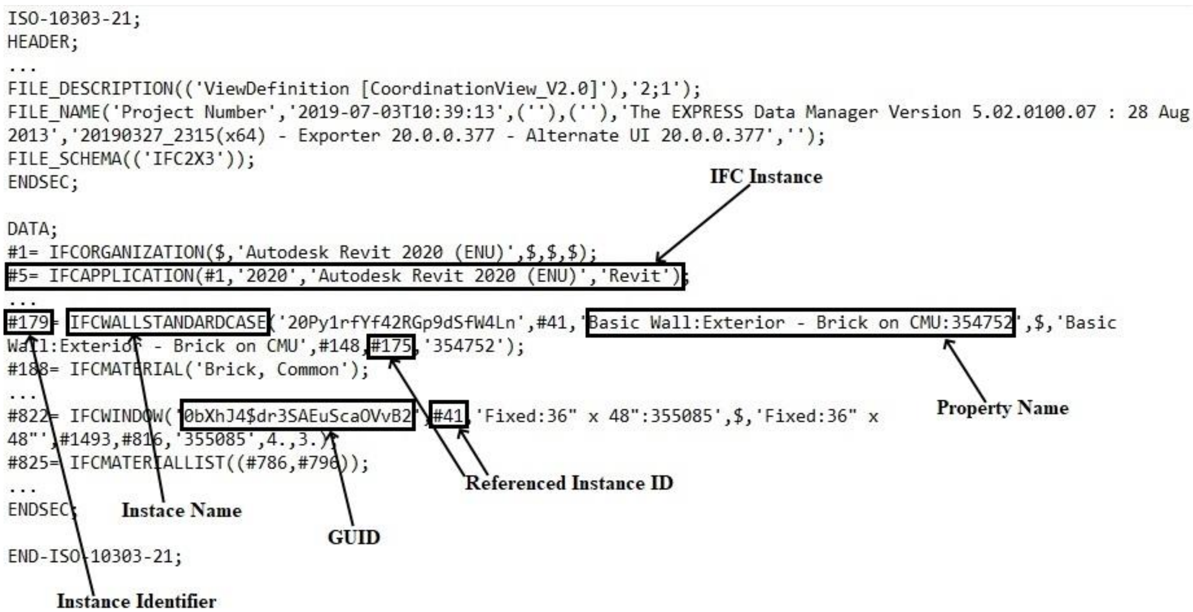


Figure 1. Basic Terms of IFC Instance in IFC2x3 File

Comparison of BIM Models. Ghang et al. (2011) proposed comparison criteria for identifying the rate of similarities and differences between two IFC files. The comparison metrics, based on GUID and other referenced values of the IFC instances, were used to provide the comparison report. However, this methodology was developed mainly on a syntactic-level rather than a semantic-level building information comparison. Brittany et al. (2013) developed a Navisworks Plug-in for tracking the number of 3D objects Ducts changes in several versions of BIM models. This automated tool, however, focused on the number of changes of objects instead of the changes of objects themselves. A framework (Fangxiao et al. 2014) of integrating change management and BIM was developed on BiMserver to update IFC models by change request. Shi et al. (2018) proposed a method and software called *IFCdiff* to identify the differences between two IFC models for model changes tracking. Their approach compared the two IFC files through an analysis of the IFC hierarchy structure and IFC content to find similarities and differences. However, their methodology focused on a syntax comparison instead of a semantic comparison, and differences in geometry and attributes were not reflected in their approach.

Extraction from BIM Models. An IFC file contains a large amount of information about the building and the construction such as geometry and attributes of building elements. Extracting relevant information from BIM models is time-consuming work (Jongsung et al. 2013; Nepal et al. 2013; Zhang and El-Gohary 2015). Jongsung and Ghang (2011) proposed two algorithms for extracting information from an IFC model. Algorithm 1 extracted the requested data, and Algorithm 2 eliminated unrequested data from the IFC model. Based on that research, Jongsung et al. (2013) developed another algorithm to extract a partial model from an IFC model not based on IFC schema. This algorithm, however, only extracts selected building element types and selected objects within one building area. In other research, Nepal et al. (2013) proposed an ontology-based methodology for information extraction regarding the construction domain from BIM models. Zhang and Issa (2013) proposed an ontology-based partial BIM model extraction methodology which implemented an ontology API to extract objects from the BIM model. Objects and the relationship between objects were considered in the extraction algorithm. Semantic natural language processing (NLP) techniques have also been implemented to extract logic-based semantic information from BIM models to support automated compliance checking (Zhang and El-Gohary 2015).

Ontology. According to Studer et al. (1998), "an ontology is a formal, explicit specification of a shared conceptualization." An ontology can provide a standard description for things within a knowledge domain. An ontology modeling process converts concepts and the relations between concepts into a formal ontology within one knowledge domain (Zhang and Issa 2013).

Creating an ontology involves defining and describing vocabularies and relationships in a knowledge domain. In most research on construction ontology, RDF and OWL are the languages adopted to solve interoperability problems. RDF and OWL, defined by XML schema, were proposed by the World Wide Web Consortium in 1999 as ontology languages within semantic web technology. OWL, built on RDF (RDF/XML), can provide more descriptive expression for data interoperability than RDF (W3C 2012). Figure 2 showed the hierarchy structure of *IfcRoot* in Protégé, an OWL language modeling software. This study implemented OWL as the ontology modeling language.

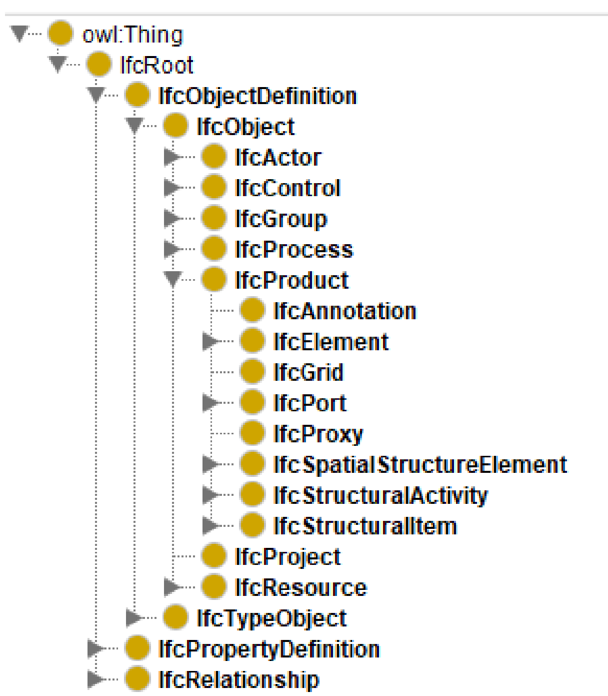


Figure 2. Hierarchy Structure of *IfcRoot* in Protégé

METHODOLOGY

To achieve the research goals, a comparison algorithm for extracting and visualizing 3D objects was developed (see Table 1). In this research, the extraction of 3D objects involves extracting the *IfcBuildingElement* (under *IfcElement*) in the IFC files. To compare each *IfcBuildingElement* in the IFC files, the selection of the identifier of each *IfcBuildingElement* is important. The instance identifier number can change depending on the total instance numbers in the IFC model (Ghang et al. 2011). GUID is a system-independent identifier used to track objects in BIM models (Sacks et al. 2018). GUID remains consistent in the instances of the *IfcBuildingElement*. Therefore, this research implemented GUID as the first comparison criterion for the revised IFC model and the original model. If the GUID is new in the revised IFC file, the *IfcBuildingElement* will be extracted from the revised IFC model as an added 3D object. The deleted *IfcBuildingElement* will also be extracted from the original IFC file, if the GUID does not exist in the revised IFC model. The visualization of each extracted model can be conducted separately and in combination.

Table 1. Model Change Extraction and Visualization Determination

Original Model Object GUID	Revised Model Object GUID	Attribute/Geometry	Instances Status
Exist	Exist	Not Changed	Not Extracted
Exist	Exist	Changed	Extract & Visualize
Exist	Not Exist	NN	Delete & Visualize
Not Exist	Exist	NN	Add & Extract & Visualize

*Each model objects visualization can be conducted separately and in combination.
*NN=Not Needed

The challenge of developing the comparison algorithm was in the comparison of the geometry and attribute information of the *IfcBuildingElement*. For an attribute comparison, this research implemented the property name of the *IfcBuildingElement* as the criterion. For a geometry comparison, the referenced values regarding the geometry information were identified to compare the *IfcBuildingElement* in the two IFC models. The modified *IfcBuildingElement* was extracted from the revised IFC file. Based on the above comparison and extraction algorithm, this research proposed a methodology to visualize the design change in the BIM model (see Figure 3). After the *IfcBuildingElement* was extracted from the original and the revised IFC models, the ontology-augmented IFC model was built to contain semantic information about the *IfcBuildingElement* in the output IFC files. *IfcProject* information was required for the extraction from the original and the revised IFC models to build a relationship of *IfcBuildingElement*, *IfcBuilding*, and *IfcBuildingStorey* (see Figure 4). Upon the extraction of the ontology-augmented IFC models, the visualization of the added, deleted, and modified 3D objects was performed.

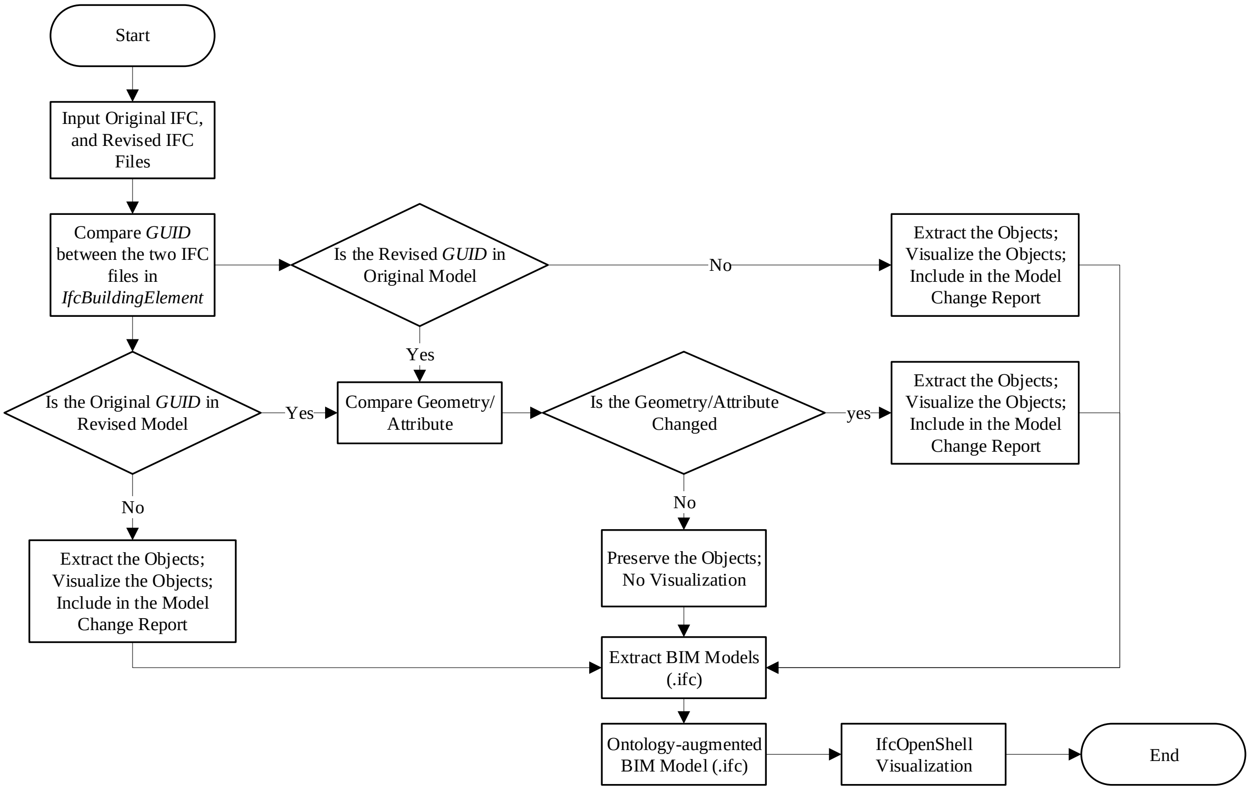


Figure 3. Methodology of Extraction and Visualization for IFC Model Change

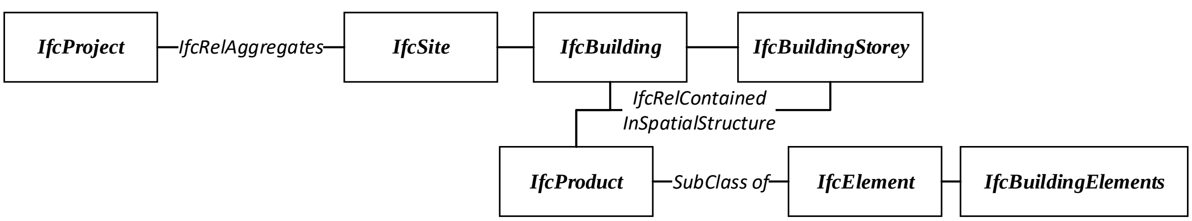


Figure 4. Relationships between *IfcProject* and *IfcBuildingElement*

Prototype Application. A python-based Prototype Application based on the proposed visualization methodology was developed (see Figure 5). For the extraction and visualization function, the prototype application was built on IfcOpenShell to copy the required *IfcBuildingElement* to the new IFC files. The test IFC models were exported from Autodesk Revit 2020.

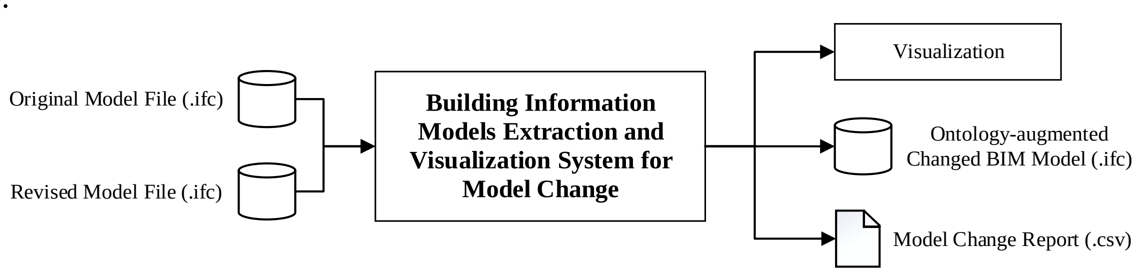


Figure 5. Python Prototype Application for BIM Model Design Change Visualization

VALIDATION AND DISCUSSION

The research implemented two sample IFC models (samples A & B) to test the proposed prototype application (see Table 2 and Table 3). The computer used to validate the prototype was an Intel i7-9700 CPU of 3.00 GHz with 16.0 GB RAM memory. For the smaller IFC models, the visualization time of the prototype was within one minute, while the visualization of the larger IFC model took over 10 minutes. The proposed prototype can visualize the extracted objects (see Figure 3) either from the original or the revised model to visually identify the differences between the IFC models (see Figure 6). The added model (solid) can be visualized with the original BIM model (transparent) to track design changes.

Table 2. Original, Revised, and Output Information of IFC Model Sample A

Model Information	Original Model	Revised Model	Added Model	Deleted Model	Modified Model
Number of *IfcBuildingElement*	8	10	4	2	6
File Size	40 KB	51 KB	8 KB	5 KB	12 KB
Visualization Response Time	0.70s	0.72s	0.54s	0.54s	0.57s

Table 3. Original, Revised, and Output Information of IFC Model Sample B

Model Information	Original Model	Revised Model	Added Model	Deleted Model	Modified Model
Number of *IfcBuildingElement*	940	948	16	8	782
File Size	10 MB	11 MB	49 KB	72 KB	3 MB
Visualization Response Time	50.65s	51.54s	2.48s	2.78s	20.77s

The results indicate that the proposed methodology is valid to visualize the changed 3D objects in the IFC models. The python-based prototype application quickly responded to track the design changes by comparing the original IFC file to the revised IFC file. However, the proposed methodology of visualizing has some limitations in its comparison algorithm. For the attribute comparison, the property name within the IFC instances was used as comparison criteria. The placement of the *IfcBuildingElement* is not taken into account in the geometry comparison algorithm. The *IfcCartesianPoint* geometry information of the *IfcBuildingElement* was used to compare the two IFC models.

CONCLUSION

Previous methods of tracking design changes in IFC models were time-consuming and vendor-specific. This study proposes a new methodology for visualizing the changes of 3D building elements based on open-source IFC models. The results indicated that the proposed prototype is valid for the tracking of design changes in BIM models; it also responded quickly generated responses to comparison requests. The ontology-based BIM model design change visualization system will assist construction practitioners by quickly identifying the changed building elements within a large and complex BIM model. The proposed comparison algorithm, however, has some limitations. In future work, the authors will further refine the proposed methodology and prototype application with more semantic information extraction from BIM models. Future versions of the comparison algorithm will cover the placement and relevant detailed property information of the building elements.

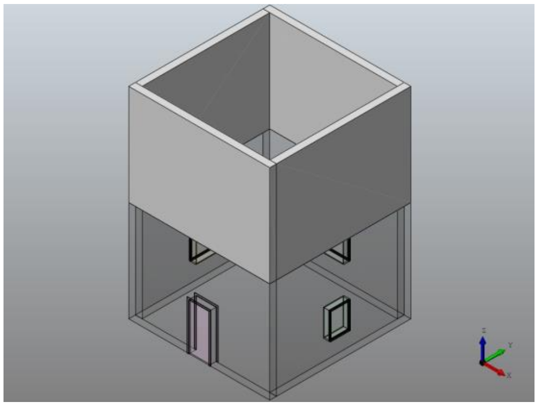


Figure 6. Visualization of Design Changes of Sample IFC Model in Prototype Interface

REFERENCES

Autodesk Inc. (2019). "BIM 360 Change Visualization." <https://www.autodesk.com/bim-360/bim-collaboration-software/design-collaboration/change-visualization/>.

Brittany, G., A., I. R. R., Rui, L., and Le, Z. (2013). "A Tool for Automatically Tracking Object Changes in BIM to Assist Construction Managers in Coordinating and Managing Trades." *Computing in Civil Engineering (2013)*, Proceedings, 500–507.

buildingSMART. (2007). "IFC2x Edition 3 Technical Corrigendum 1." <https://standards.buildingsmart.org/IFC/RELEASE/IFC2x3/TC1/HTML/>.

buildingSMART. (2019). "Industry Foundation Classes (IFC)." <https://technical.buildingsmart.org/standards/ifc>.

Fangxiao, L., Karim, J. A., J., A. C., and Dinghao, W. (2014). "A Framework for Integrating Change Management with Building Information Modeling." *Computing in Civil and Building Engineering (2014)*, Proceedings, 439–446.

Gallaher, M. P., O'Connor, A. C., John, L., Dettbarn, J., and Gilday, L. T. (2004). "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry." *National Institute of Standards and Technology*, U.S. Department of Commerce Technology Administration, Gaithersburg, MD.

Ghang, L., Jongsung, W., Sungil, H., and Yuna, S. (2011). "Metrics for Quantifying the Similarities and Differences between IFC Files." *Journal of Computing in Civil Engineering*, American Society of Civil Engineers, 25(2), 172–181.

IfcOpenShell. (2019a). "IfcOpenShell-python: A python module based on IfcOpenShell." <http://www.ifcopenshell.org/>.

IfcOpenShell. (2019b). “IfcOpenShell Academy.” <http://academy.ifcopenshell.org/>.

IFCwiki. (2019). “IFC - Industry Foundation Classes.” <http://www.ifcwiki.org>.

Jongsung, W., and Ghang, L. (2011). “Algorithm for Efficiently Extracting IFC Building Elements from an IFC Building Model.” *Computing in Civil Engineering (2011)*, 713–719.

Jongsung, W., Ghang, L., and Chiyon, C. (2013). “No-Schema Algorithm for Extracting a Partial Model from an IFC Instance Model.” *Journal of Computing in Civil Engineering*, 27(6), 585–592.

Juszczyk, M., Tomana, A., and Bartoszek, M. (2016). “Current Issues of BIM-based Design Change Management, Analysis and Visualization.” *Procedia Engineering*, The Author(s), 164(June), 518–525.

National Institute of Building Sciences. (2019). “BIM Definition.” <www.nationalbimstandard.org>.

Nepal, M. P., Sheryl, S.-F., Rachel, P., and Jiemin, Z. (2013). “Ontology-Based Feature Modeling for Construction Information Extraction from a Building Information Model.” *Journal of Computing in Civil Engineering*, 27(5), 555–569.

Sacks, R., Eastman, C. M., Teicholz, P. M., and Lee, G. (2018). *BIM handbook : a guide to building information modeling for owners, designers, engineers, contractors, and facility managers*. Hoboken, New Jersey : John Wiley & Sons, Inc., 2018; Third edition.

Shi, X., Liu, Y. S., Gao, G., Gu, M., and Li, H. (2018). “IFCdiff: A content-based automatic comparison approach for IFC files.” *Automation in Construction*, 86(June 2016), 53–68.

Studer, R., Benjamins, V. R., and Fensel, D. (1998). “Knowledge Engineering: Principles and methods.” 25, 161–197.

W3C. (2009). “OWL Web Ontology Language Guide.” <https://www.w3.org/TR/owl-guide/>.

W3C. (2012a). “OWL 2 Web Ontology Language Primer.” <https://www.w3.org/TR/2012/REC-owl2-primer-20121211/>.

W3C. (2012b). “Web Ontology Language (OWL).” <https://www.w3.org/OWL/>.

Zhang, J., and El-Gohary, N. M. (2015). “Automated Extraction of Information from Building Information Models into a Semantic Logic-Based Representation.” *Computing in Civil Engineering 2015*, 173–180.

Zhang, L. (2012). “Ontology-based web services framework for building information modeling.” University of Florida, Gainesville, FL.

Zhang, L., and Issa, R. R. A. (2013). “Ontology-Based Partial Building Information Model Extraction.” *Journal of Computing in Civil Engineering*, 27(6), 576–584.

Blockchain and the Built Environment: Automated Design Review Process

Nawari. O Nawari, Ph.D., P.E., F.ASCE,[1] and Shriraam Ravindran, M.Sc.[2]

[1]School of Architecture, College of Design, Construction & Planning University of Florida; e-mail: nnawari@ufl.edu

[2]Ph.D. student, School of Architecture, College of Design, Construction & Planning University of Florida; e-mail: shr1raam@ufl.edu

ABSTRACT

Blockchain is a technology concept that originated from the first cryptocurrency known as Bitcoin and was soon noted to have a much wider range of applications beyond serving as the platform for digital cryptocurrency. A blockchain (BC) is essentially a decentralized and an immutable ledger that records every transaction made in the network. The implementation of decentralized technology in any industry would result in augmented security, enforce accountability, and could potentially accelerate a shift in workflow dynamics from the current hierarchical structure to a decentralized, cooperative chain of command by encouraging trust and collaboration. This paper present examines the potential integration with the BIM process in advancing the automation of the design review process. Moreover, the study explores how employing distributed ledger technology (DLT) could be advantageous in the automating the design review process by reinforcing network security, providing more reliable data storage and management of permissions, ensuring change tracing and data ownership. The paper evaluates the potential application of blockchain technologies such as Smart Contracts in cybersecurity, data ownership and other aspects, as well as enhancing the framework for automating the design review process with a demonstration using Hyperledger Fabric.

INTRODUCTION

The blockchain is a digitized, decentralized public ledger of data, assets and all pertinent transactions that have been executed and shared among participants in the network. While it is most associated with digital cryptocurrencies such as Bitcoin, blockchain is viewed as an emergent technology that could potentially revolutionize and transform the current digital operational landscapes and business practices of finance, computing, government services, and virtually every existent industry (Crosby et al., 2015; Crosby M, 2016). The chief hypothesis behind blockchain is the creation of a digital distributed consensus, ensuring that data is decentralized among several nodes that hold identical information and that no single actor holds the complete authority of the network.

A Decentralized Ledger Technology (DLT) is a peer-to-peer network generally incorporates a decentralized consensus mechanism, distributing the computational workload across multiple nodes present throughout the network, facilitating the nodes to create connections, and they ensure the connections stay alive, while also ensuring every node in the network receives and transfers out data (Nakamoto 2008; Wang, Yingli, Jeong Hugh Han 2018; Zheng et al. 2017).

This mechanism excludes the likelihood of a system failure or a complete network blackout. DLT usually achieve this by integrating a decentralized consensus structure before the blockchain initiating transaction operation. The network participants agree in advance and decide on a consensus mechanism appropriate to their requirements. Every endorsing node in the network runs the same consensus algorithm, thus, the system does not need any third-party administrator to oversee the transaction operations (Brakeville and Perepa 2016).

Blockchain can address accessibility and visibility of the data in a secure and efficient manner since the ledger is distributed (Brakeville and Perepa, 2016; Clack *et al.*,2016a; Frantz and Seijas *et al.*, 2017). It facilitates setting different levels of privacy as every participant is essentially a stakeholder and no single participant has full administrative privilege. Thus, formulating and enforcing consensus is crucial to the blockchain operation, with terms to data updates, error-checking, and collective decision-making. The selection of which BCT to uses

Smart contracts are contracts programmed with the blockchain that automatically executes upon the fulfillment of certain conditions. , removes the requirement of a third-party intermediary for overseeing the transaction in real-time (Dhawan, 2016; Bhargavan *et al.*, 2016; Clack *et al.*, 2016a, 2016b; Seijas, Thompson and McAdams, 2017). T

Hyperledger Fabric is a platform for generating distributed ledger blockchain systems, supported by a modular design, offering a flexible digital framework that delivers high levels of confidentiality, and scalability. It is designed to support pluggable implementations of different components and accommodate the complexity and details that exist across the economic ecosystem. The Hyperledger blockchain aims to be a general-purpose, enterprise-grade, open-source DLT that features permission management, pluggability, enhanced confidentiality, and consensus mechanism and is developed through a collaborative effort.

BIM is at the forefront of digital transformation in the AEC industry, encouraging collaboration and trust, and simplifying data exchange. BIM models present a comprehensive design and construction model of the building that can include all aspects of the facility such as architectural components, structural elements, and MEP design areas. Further, several built-in plug-ins in BIM platforms like Autodesk Revit enable the simulation of external site conditions, geography, weather, as well as carry out energy analysis, building energy modeling, structural analysis, etc. In the future, BIM development will eventually aim to unify all design and analysis tools in one platform. However, the current BIM process has several limitations such as no archival of BIM model change and modification history, difficulties in assigning responsibilities and liabilities, insufficient cyber-resilience and cybersecurity, and lack of legal framework detailing model data ownership and legal contractual issues (Eastman et al. 2011; Ahn et al., 2015)

Employing BCT in the BIM process can address several issues that are currently phasing the BIM implementation in the AEC industry. For instance, these include cybersecurity, reliable data storage and management of permissions, change tracing, and data ownership. This paper proposes a framework that is based on integrating HLF and the automation of the design review process in a BIM workflow.

GOALS AND OBJECTIVES

The primary purpose of this study is to examine the BCT and its integration with the BIM workflow to enhance the automation of the design review process. The objectives include a) review Hyperledger Fabric (HLF) and its potential applications in BIM workflow, b) propose a framework for integrating HLF and the Automation of the Design Review process to enhance the cyber-resilience and security, data storage and management of permissions, and data ownership.

METHODOLOGY

The study approach is based on an organized review and evaluation of the HLF, and the potential of its integration with BIM workflow to improve the security and efficiency of the design review process. This includes the retrieval of the relevant data from the literature sources assessing the quality of the content, and synthesizing the data to develop a framework for integrating the HLF with the automation of the design review process.

HYPERLEDGER FABRIC

Hyperledger is a collaborative effort founded by the Linux Foundation in 2016 to advance cross-industry BCT. It aims at the development of distributed applications written in standard general-purpose programming languages (Andreoulakis et al, 2018). It is a cross-industry open standard platform for blockchain that seeks to transform the technique business transactions are conducted universally.

HLF is one of the blockchain projects within Hyperledger. Like other BCT, it has a distributed ledger, uses Smart Contracts (SC), and is a system by which participants manage their transactions. In HLF, SC is known as chaincode. It is executable code, deployed on the network, where it is invoked and validated by peers during the consensus process. The common programming language used in developing chaincode is Go, Ruby, Java, and NodeJS (Hyperledger, 2018).

The fundamental differences between HLF and other blockchain systems are that it is private and requires permissions (Nawari and Ravindran 2019). In contrast to an open permission-less system that allows unknown identities to participate in the network, the nodes of an HLF network join through a trusted Membership Service Provider (MSP). Moreover, Hyperledger Fabric has the ability to create channels, allowing a subgroup of participants in the network to establish a separate ledger of transactions (Nawari and Ravindran 2019). This is an especially important option for BIM workflow where subcontractors can exchange data within the only subgroup of the network. For example, the structural engineer of record of the project can exchange information with steel connection subcontractors only while still being part of the HLF network and sharing those transactions with the rest of the nodes (Nawari and Ravindran 2019).

AUTOMATED DESIGN REVIEW PROCESS

Regulations are normative text prescribed by governing entities to enforce constraints to design and engineering processes and manufacturing based on existing conditions, and function as the defining text for laws, codes, specifications, standards, etc. Automating design review and compliance processes in the AEC industry would benefit the industry, saving time, money, labor, and minimizes scope for risk and human errors. While much of the decision-making and consideration of the code is dependent on the experience of the reviewers, automation could at least enforce the upper and lower limits and report results instantaneously. Translation of various clauses and statements into computable language presents a major challenge in achieving automation (Eastman et al. 2009; Nawari 2018). However, following an ideal framework to develop a tool that successfully accounts for all regulations through the accurate interpretation of formal language and model data exchange could be pivotal in increasing efficiency and upholding safety standards in any AEC projects. Automating design review and compliance processes in the AEC industry would greatly benefit the industry in terms of increasing productivity, minimizing resource consumption and reducing the scope for human errors.

Nawari (2019) developed the Generalized Adaptive Framework (GAF) that aims at attaining a computable model with the clear syntax to accurately characterize building code requirements, to reduce model complexity and develop a unified format to exemplify building regulations and building information modeling to automate design review and compliance processes. However, the compliance checking process must be secure with reliable data storage and management of permissions, change tracking, and collaborative. Thus, this study proposes a framework that integrates the HLF and the GAF to improve the security and efficiency of the automatic design review process in a BIM workflow

PROPOSED FRAMEWORK

The proposed framework aims to use HLF to implement an automated the Design Review Process based on the Generalized Adaptive Framework (GAF) (Nawari 2019). Figre 1 below delineate an overview of the integrated HLF and GAF framework to automace design review and compliance checking process. The four main elements of the framework are the GAF, Smart Contracts (Chaincode), membership services, and ordering services.

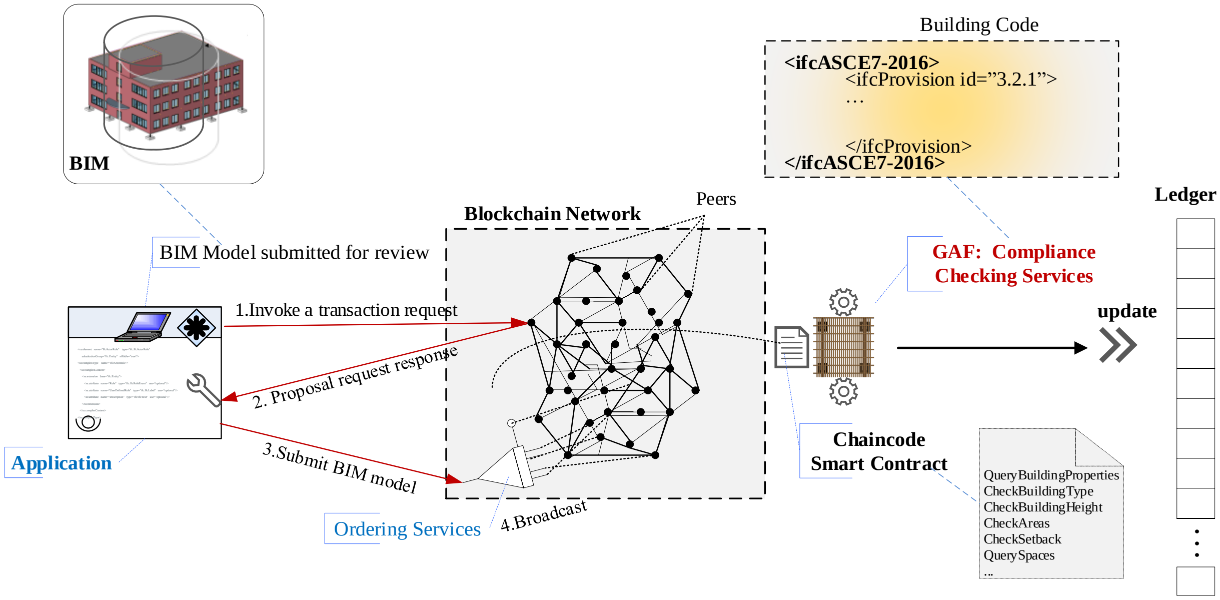


Figure 1. Overview of the Integrative HLF + GAF Framework for automating design review Process

The HLF is based on a permissioned blockchain network that provides security to protect data exchanges between members of entities who share a mutual goal but have intellectual properties that they need to secure while exchanging information. The proposed framework has a modular architecture. The main modules are depicted in figure 1 and include:

(a) Membership services: A membership service provider (MSP) allocates cryptographic identities to peers participating in the network, and maintains the identities of all nodes in the system . This module serves to create a root of trust during the network formation.

(b) Ordering services: A service that broadcasts the state updates to peers in the network and establishes consensus based on the order of transactions via, the Ordering Service Nodes (OSN), or orders that establish the total order of all transactions in the Fabric. The ordering services in HLF represent the consensus system. The ordering service groups multiple transactions into blocks and outputs a hash-chained sequence of blocks containing transactions.

(c) Chaincode (Smart Contract) services: It is an application-level code stored on the ledger as a part of a transaction. The chaincode runs transactions that may modify the data on the ledger. A chaincode is installed on network members' machines, which require access to the asset states to perform read and write operations. The chaincode is then instantiated on particular channels for specific peers.

(d) GAF: The GAF represents the business logic that is written as a chaincode. The GAF has algorithms that can be expressed and executed in JAVA programming objects to extract, access and link BIM and regulations data to report the results of the design review process.

CONCLUSION

The Blockchain is a growing digital technology which is characterized bys a decentralized, full-lifecycle traceable public ledger of transactions for all participants, and security and privacy of the network that is based on consensus algorithms. Due to these characteristics, Blockchain has gained recently widespread traction in various fields.

HLF is a blockchain that is principally suited for developing the automation of design review process in BIM workflows, due to its ease of programming (using SDK), flexibility, user-defined smart contract (chaincode), robust security, identity features, and modular architecture with pluggable consensus protocols. The the proposed integrative BCT+BIM framework aims to provide secure, reliable automaion process of the design review and compliance checking in BIM workflow. The chaincode technologies (also known as Smart Codes) available in HLFs are promising technologies for advancing the security and efficiency in the AEC industry, particularly for the compliance checking process. Furthermore, the HLF can address many of the current concerns facing the BIM workflow, such as data security, privacy, the speed of transactions, and change tracing and permission management that arise from using centralized BIM work processes. Future research will focus on expanding the integrative framework to include other issues related problems such as data ownership and legal issues.

REFERENCES

Ahn, Yong Han, Young Hoon Kwak, and Sung Joon Suk. 2015. “Contractors’ Transformation Strategies for Adopting Building Information Modeling.” *Journal of Management in Engineering* 32(1): 05015005.

Bhargavan, Karthikeyan et al. 2016. “Formal Verification of Smart Contracts.” *Proceedings of the 2016 ACM Workshop on Programming Languages and Analysis for Security - PLAS’16*: 91–96.

Brakeville, Sloane, and Bhargav Perepa. 2016. “Blockchain Basics: Introduction to Business Ledgers Get to Know This Game-Changing Technology and IBM’s Contribution to It.” : 1–6.

Clack, Christopher D., Vikram A. Bakshi, and Lee Braine. 2016a. “Smart Contract Templates: Essential Requirements and Design Options.” : 1–15. http://arxiv.org/abs/1612.04496.

———. 2016b. “Smart Contract Templates: Foundations, Design Landscape and Research Directions.” : 1–15.

Crosby, M., Nachiappan, Pattanayak, P., Verma, S., and Kalyanaraman, V. 2015. *Blockchain Technology: Beyond Blockchain*.

Crosby M. 2016. “BlockChain Technology: Beyond Bitcoin.” *Applied Innovation Review (AIR)*: 6–19.`

Dhawan, Mohan. “Analyzing Safety of Smart Contracts.”

Eastman, C., Jae min Lee, Yeon suk Jeong, and Jin kook Lee. 2009. “Automatic Rule-Based Checking of Building Designs.” *Automation in Construction* 18(8): 1011–33.

Frantz, Christopher K, and Mariusz Nowostawski. 2016. "From Institutions to Code: Towards Automated Generation of Smart Contracts."

Nakamoto, Satoshi. 2008. "Bitcoin: A Peer-to-Peer Electronic Cash System." *Www.Bitcoin.Org*: 9.

Nawari, N. 2018. *Building Information Modeling: Automated Code Checking and Compliance Processes*. Boca Raton, Florida.: CRC Press, Taylor & Francis Group, LLC.

Nawari, N., 2019. "A Generalized Adaptive Framework (GAF) for Automating Code Compliance Checking." *Buildings* **2019**, *9*(4), 86; https://doi.org/10.3390/buildings9040086

Seijas, Pablo Lamela, Simon Thompson, and Darryl McAdams. 2017. "Scripting Smart Contracts for Distributed Ledger Technology." *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* 10323 LNCS: 631–32.

Wang, Yingli, Jeong Hugh Han, and Paul Beynon-Davies. 2018. "Understanding Blockchain Technology for Future Supply Chains: A Systematic Literature Review and Research Agenda." *Supply Chain Management: An International Journal*.

Zheng, Zibin et al. 2017. "An Overview of Blockchain Technology: Architecture, Consensus, and Future Trends." *Proceedings - 2017 IEEE 6th International Congress on Big Data, BigData Congress 2017*: 557–64.

BIM Framework for Sustainability in Saudi Arabia

Fatma Hasanain MIA[1] and Nawari O. Nawari[2], Ph.D., P.E., F.ASCE2

[1]Ph.D. student, University of Florida, College of Design, Construction & Planning, School of Architecture, P.O. Box 115702, 1480 Inner Road, Gainesville, FL 32611-5702; email: fhasanain@ufl.edu
[2]University of Florida, College of Design, Construction & Planning, School of Architecture, P.O. Box 115702, 1480 Inner Road, Gainesville, FL 32611-5702; email: nnawari@ufl.edu

ABSTRACT

Improving the performance of existing buildings has provided a broad market for the green renovation of US building stock currently estimated at 76 billion square feet. Building Information Modeling (BIM) has had a remarkable impact on the building industry by enhancing productivity and document accuracy. The integrative nature of BIM technology renders it an ideal tool for implementing sustainable strategies into the renovation and retrofit of existing structures. The intent of this research is to determine what functions of BIM could be utilized to implement sustainable design principles in new and existing structures in Saudi Arabia by exploring the nature of the relationship between BIM platforms and sustainability. The study sought to establish a framework for sustainability in Saudi Arabia.

In recent times, Saudi Arabia's market gasoline prices have dropped dramatically, necessitating the kingdom to establish its 2030 vision. The 2030 vision aims to make Saudi Arabia an ideal sustainable society by reducing its reliance on petrol, creating more sustainable buildings, and using renewable energy resources. Due to the lack of a national rating system in the kingdom, LEED will be used as a guideline to formulate a unique rating system suitable for Saudi Arabia and supports the kingdom's 2030 vision.

This research aims to provide a BIM framework to achieve the envisioned sustainability goals and implement sustainable design principles in Saudi Arabia. Further, the study aims to develop a new rating system for Saudi Arabia that is fully integrated with BIM platforms.

Keywords BIM, Sustainability, Green buildings, Sustainable Buildings, Rating System, Saudi Arabia, 2030 Vision.

INTRODUCTION

Even though green buildings are created in many countries worldwide, they do not have the same popularity and acceptance in Saudi Arabia. This gap has been apparent by the lack of guidelines and regulations that encourages green buildings and sustainability in the country. Due to the lack of a national green building rating system in the Kingdom of Saudi Arabia, LEED is used as a rating system, but it does not apply to the Saudi Arabian infrastructure. The Saudi Vision 2030 has set ahead the roadmap for future generations to prosper and live their lives in a steady economic state where both the private and public sectors join hands to enhance the country's income and natural resources.

Recently the Architecture, Engineering, and Construction (AEC) industry started to implement BIM in their practices. BIM has tremendous capabilities and positive influence on green building certifications. Various countries worldwide started to require green building certification for projects as a mandatory procedure; the utilization of BIM in all built projects will be a standard protocol shortly. Consequently, BIM will continue to grow at a steady pace and it will be utilized as a tool for construction practices and sustainable design.

BACKGROUND

After the discovery of oil in Saudi Arabia, petroleum became a vital industry. Since the 1980s the economy of Saudi Arabia boomed and has been developing at a dramatic pace due to the massive revenues from oil exports. According to Mubarak, even though Saudi Arabia was once an undeveloped country the oil wealth led to various project developments, modernized the country and led to low unemployment rate (1999). Recently Saudi Arabia's petrol selling prices have dropped dramatically making it necessary for the kingdom to establish it's 2030 vision. The 2030 vision aims to make Saudi Arabia an ideal sustainable society by reducing its reliance on petrol, creating more sustainable buildings, and using renewable energy resources. When creating a perfect sustainable society there must be equal access to nutrition, healthcare, clean water, shelter, education, energy, economic opportunities, and employment.

The EIA indicated that even though Saudi Arabia is the world's largest producer and exporter of petroleum liquids, it is also considered to be the largest consumer of petroleum liquids in the Middle East (2013). Rahman and Khondker mentioned that Saudi Arabia faces green gashouse emissions since its economy is based on oil and in which the energy sector is entirely dependent on fossil fuels (2012). Investing in renewable energy sources and the use of public transportation is discouraged (Rahman & Khondaker, 2012). Saudi Arabia is ranked 61st in the Climate Change Performance Index of 2014, which is last position on the index (Burck, et.al, 2013). Therefore, it is crucial for Saudi Arabia to reduce its environmental footprint and enhance its building sustainability (Taleb & Pitts, 2009).

Due to the decline in oil supply in Saudi Arabia, and due to the abrupt decrease in oil selling prices, the kingdom is looking into new ways to diversify its economy and its energy future. The kingdom's 2030 vision aims to minimize Saudi Arabia's reliance on oil. Saudi Arabia has embarked upon a new economic journey, towards diversification and long-term prosperity. The Saudi Arabia Renewable Energy Investment Forum (SAREIF), will seek to accelerate the kingdom's renewable energy deployment program – a key component of economic transformation and the kingdom's 2030 vision (Jurgenson & Bayyari, 2016). Another important factor regarding the vision is using the country's natural resources such as the sunlight and wind. Improving the country's energy efficiency by just 4 percent a year could save the equivalent of 1 million barrels a day of crude by 2030 (Mosly, 2015).

Currently, the rate of green buildings in SA is relatively slow compared to other countries due to the lack of a national green building rating system; therefore, a BIM-based metric can accelerate the process of obtaining more green buildings in the Kingdom.

RESEARCH OBJECTIVES

The main goal of this research is to examine how BIM currently function concerning sustainable practices and develop a BIM-based framework for sustainability in Saudi Arabia (SA) to achieve the kingdom vision for 2030. The objectives include 1) review existing methods and frameworks to measure sustainability, 2) propose a rating system for the kingdom of Saudi Arabia (KSA), 3) identifying the critical elements of the 2030 vision 4) integrate the findings into a BIM-based Metric for Sustainable Built Environment in Saudi Arabia.

LITERATURE REVIEW

Sustainability

In today's world, sustainability is one of the most talked-about and less understood scholarly concepts. Even though it is a well-established term, there some general and vague understanding of sustainability especially in places where environmental origins of sustainability come second (Lew et al., 2016; Marchese et al., 2018). In such fields the simplest definition of sustainability is "to maintain the status quo and to not disappear"– seems to be serving the purpose

(Lew et al., 2016; Sayer et al., 2004). There are about 200 definitions of the concept of sustainability and most commonly used one is defined by the World Commission on Environment and Development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: the concept of needs, in particular the essential needs of the world’s poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment’s ability to meet the present and future needs” (Lengar & Pearce, 2017). This common definition of sustainable development with some minor alteration is widely used in various fields. As example sustainability is defined as “the capability of maintaining over indefinite periods of time specified qualities of human well-being, social equity, and environmental integrity” (Leach, et al., 2010).

Even though, the World Commission’s definition of sustainability focuses on the importance of the economic, social and environmental responsibility (Lizarralde et al., 2015), Green building certification as well as sustainable construction in developed countries concentrates on carbon reduction as well as energy consumption with paying very little attention to the social aspects of sustainability (Kibert, 2007; Lizarralde et al., 2015). Assessment tools in regards to sustainability are often being judged for marking boxes without considering the relation between the variables of intervention and the consequences (Lizarralde et al., 2015). Therefore, sustainability in the built environment and green building rating systems in general, are considered “an exercise of efficiency” (Reed, 2007) that serve as a technical solution to save issues created by the system itself (Lizarralde et al., 2015).

In the Architectural, Engineering, and Construction (AEC) industry, sustainability relies on “the paradigm shift in the usage of available resources to meet societal needs and aspirations, over time” (Kibert et al. 2002). The concept of “need vs. limits” is considered a major part to achieve this paradigm change. According to Lengar and Pearce, each part of the comparison provide ideas to improve sustainability in the built environment. For example, enhancing technologies to stay within the limits imposed by the environment as well as better handling or reducing human needs. BIM must be implemented in order to better enhance sustainability in the built environment and meet human needs (2017).

Green Building

Green building design is defined as the practice of building structures and implementing procedures resource-efficient and environmentally responsible for their entire life cycle. According to the EPA Green buildings are also defined and known as high-performance building, sustainable building and green buildings (2014).

Leadership in Energy and Environmental Design (LEED) is a voluntary green building rating system developed by the United States Green Building Council (USGBC) to assess building's performance and promote sustainability. The theoretical framework of LEED is based on a critique of contingencies inherent to various definitions of sustainability and an analysis of the new politics that are emerging through the discourse of sustainability (Cottrell, 2010).

Recently many countries around the world have pursued sustainability. Both the general public and world governments are pursuing sustainability due to the worldwide environmental disasters and negative impact caused by manmade activities and pollution. The World Business Council for Sustainable Development (WBCSD) indicated that the building sector by itself is accountable for about 40% of the world's energy use. As a result, this has caused various countries to focus their attention on producing more sustainable buildings that have a minimal negative effect on the environment and its surrounding. Green LEED-certified buildings represent a significant component of sustainability, as their creation is intended to decrease natural resource consumption through energy and water conservation (Mosly, 2015). Even though Saudi Arabia is one of the world's wealthiest countries, its sustainability applications in the construction sector are limited and the number of green LEED-certified buildings within the country is remarkably small.

An essential foundation for promoting sustainable green building development is the creation of a system that assesses green buildings. For instance, in 1990 in the UK introduced the Building Research Establishment Environmental Assessment Method (BREEAM) and few years later the United States Green Building Council created LEED (Leadership in Energy and Environmental Design). According to Zafar, several other countries followed the same steps. It has been evident that in these countries the public, investors, and owners are pushing towards certified green buildings. Green buildings bring numerous advantages besides contributing to sustainability. For example, green buildings have fewer maintenance costs, enhanced durability, low operation costs, increased occupants' comfort and lower development costs (2017).

Green Building Rating Systems in the Middle East and North Africa (MENA)

In addition to LEED and BREEAM multiple green building rating systems are used worldwide. Nowadays, In the MENA region sustainability is a top priority. The United Arab Emirates (UAE) and Qatar, as well as other countries, established their own green building rating system to promote sustainability (Zafar, 2017). Below is a list of the green building rating systems in MENA:

a) Global Sustainability Assessment System used in (Qatar)
b) Pearl Rating System used in (Abu Dhabi)
c) ARZ Building Rating System in (Lebanon)
d) The Green Pyramid Rating System in (Egypt)

Saudi Vision 2030

In June 2016 the Saudi Vision 2030 was approved and announced by King Salman by King Salman Bin Abdulaziz the custodian of the two holy mosques (Government of Saudi Arabia, 2016). The goal of the 2030 vision is to move the Kingdom's economy away from its sole dependence on oil export (Hashmi, 2016). The vision includes specific targets, certain objectives and obligations to be accomplished by the private and public and non-profit sectors in the Kingdom. Several of ambitious goals of the Saudi Vision 2030 include:

1. Cutting the Kingdom's overall non-oil government revenue from SR 163 billion ($43.5 billion) to SR 600 billion by 2020, increasing further to SR 1 trillion by 2030
2. Increasing the private sector's contribution from 40% to 65% of GDP; and
3. Raising the Kingdom's share of non-oil exports in non-oil GPD from the current 16% to 50% (Almasoud, 2016)

The Saudi Vision of 2030 collaborated with the National Transformation Plan (NTP) 2020 to include a new enhanced determination for efficiency, planned tax increases, providing major roles to private divisions starting with privatization of airport ground service and operation., and strategically executed spending cuts. (Hashmi, 2016). According to Almasoud, the NTP 2020 aims to accomplish the Saudi Vision 2030 through four major pillars that will make this plan attainable. The four pillars are privatization, governance, investing in human capital and Economic Diversification (2016).

Supporting the NTP four pillars are the following goals:

- Reduce depend on oil
- Review the performance of ministries and combat corruption
- Achieve maximum efficiency
- Develop sectors like tourism and enhance the Hajj and Umrah operations
- Create more jobs for Saudi nationals
- Utilize resources to support future projects (Hashmi, 2016).

In addition to that, the vision demonstrates an effort to enhance all aspects of the Saudi population's development and wellbeing in addition to protecting and preserving the environment and its natural resources. The vision also seeks to protect the environment by enhancing the effectiveness of waste management, reducing ally types of pollution, establishing major recycling projects, rehabilitating and safeguarding beaches and natural reserves and islands and making them accessible to everyone, promoting the optimal use of water resources by utilizing renewable and treated water as well as eliminating desertification (Government of Saudi Arabia, 2016). The government, as well as local engineering bodies, started working together to establish the concept of sustainability and how it can be applied which is crucial to the success of the execution.

Oil in Saudi Arabia

Petrol has made Saudi Arabia a rich and a prosperous country economically. Since the 1930s Saudi Arabia had a radical economical growth due to having the highest petrol stock in the world. Consequently, this innovated the country to become one of the most rapidly developing countries in the MENA region (Al Surf, 2014). The revenue generates per barrel of oil for Saudi Arabia had more than doubled from $0.22 in 1948 to $1.56 in 1973 (Mubarak, 1999). The price continued to soar to $10 and higher in 1974 following the Arab oil embargo. Oil revenues continued to climb and by 1982 had reached over $30 per barrel. The peak of oil revenue occurred on December 1979 when the price was at $121.28 per barrel and June 2008 at $141.32 per barrel. Government oil revenue made massive leap from $4.3 billion to $101.8 billion between 1973 and 1980 (Conca, 2015). The plentiful income from oil revenue gave Saudi officials the resources to implement major changes to the economy. Today the price of oil has experienced a large drop, the price of barrel of oil today typically ranges below $60 and it is no expected to rise above $100 any time soon (Conca, 2015). Saudi Arabia's need to diversify its economy and step away from its dependence and reliance on oil is due to this drop-in oil revenue.

LEED Certified Buildings and Green Building Codes in Saudi Arabia

Multiple obstacles exist in Saudi Arabia slowing the adoption of LEED-certified buildings. Some of the are: the climate in Saudi Arabia is not favorable to the typical sprawl of Western suburban development, lack of public awareness, lack of stakeholder interest, low levels of investment in sustainable buildings, lack of financial incentives, and lack of government regulations on sustainable buildings. In addition to that design firms lack the knowledge to design and create sustainable buildings that suite the Saudi Arabian culture (Mosly, 2015).

In Saudi Arabia, there is currently no mandatory building codes nor regulations that features the principles of a sustainable built environment in the country. According to Karam, many researchers argued that it is essential to set a comprehensive set of green building standards and codes to widely spread sustainable practices and reduce water and energy consumption (2010) (Karam, 2010).

Recently the Saudi government created the Saudi Green Building Forum (SGBF), which is responsible for developing regulations and laws that encourage green building initiatives, supporting "the collection of standards and systems for green building, disseminating green building information, engaging stakeholders and promoting green building concepts and cultural awareness of green building among citizens through workshops, conferences and publications. The U.S. Green Building Council's LEED building rating system is recognized in projects in Saudi Arabia, and SGBF is the sole authorized Education Delivery Partner for LEED" (Karam, 2010).

Building Information Modelling (BIM)

BIM is defined by the Whole Building Design Guide (WBDG) as "a digital representation of physical and functional characteristics of a facility which serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward" (WBDG 2012). Autodesk, on the other hand, defines BIM as the "integrated process built on coordinated reliable information about a project from the design through construction and operations" (Autodesk 2009) up to the end of life for the facility and the American Institute of Architects (AIA) defines BIM as "a digital three-dimensional model linked to a database of project information, combining all information from the design inception to the facility management" (AIA, 2014). Although, various definitions of BIM exist the below are essential BIM features:

- Use of BIM as a combination of products/tools which produces three dimensional models, with enhanced visualization, and that is rich in information pertaining to the project.
- Use of BIM as an integrated process which enables the flow of information between stakeholders up to and including the management/operations of the facility.
- A combination of product and process that helps stakeholder decide about the building over the life cycle.

Due to its ability to serve stakeholders, BIM has multiple definitions. In addition to that BIM allows collaboration between designers, owners, architects, contractors, and other building specialists. BIM has rich information that is necessary for sustainability and green certification aspects that can be used in different phases of the project by stakeholders (Azhar et al. 2008; Mahdavinejad and Refalian 2011; Siddiqui et al. 2009). Miller (2010) also indicated that BIM is utilized to enhance sustainability in built environment. For instance, in a green building the amount of energy consumed can be measured. In the BIM model various design options for sustainability can be easily traced and implemented. Additionally, advanced visualization methods such construction animation of green buildings, 3D renderings as well as solar studies can be utilized (Azhar et al. 2011). Visualization is one of BIM's main advantages; in addition to its improved visualization BIM presents great "calculation ability of the model to quantify the savings to a certain extent, thereby resulting in improved design insights, risk mitigation, 4D and 5D analysis, clash detection, prefabrication, systems coordination, widening the search for solutions, improved integration in decision making, differentiation of objective and subjective judgment, and maintenance." As a result, these help project team members to establish a cohesive holistic analysis, eliminate waste, reduce cost escalation and solve interdisciplinary issues. BIM is not solely considered a graphical tool, it is also a comprehensive information modeling program that can have various advantages in regards of life cycle assessment, sustainability, energy efficiency, construction waste and rainwater harvesting (Lengar & Pearce, 2017).

The use of BIM for designs purposes in the construction industry has seen tremendous growth due to its potentials to improve collaborations among project stakeholders. It contains information and data essential in defining product development standards and approvals. This is important, as models developed using BIM provides several effective solutions and potential applications in almost every stage of development. This makes it different from Computer Aided Designs (CAD) as its operations are based on an internalized system of integrated information while CAD operates on external sources of information. To this, Krygiel and Nies (2008) affirmed that BIM contains the planning, construction and operation information of a building as opposed to CAD which only contains two-dimensional drawings. This is one of BIM's advantage over CAD as it manages all graphics information, and operates within a controlled environment, eliminating any miscommunication such as data redundancy. BIM's main concept centers around this. BIM main concepts were described by Krygiel and Nies (2008) to include capabilities to:

- Develop project design, construction, and maintenance management strategies,
- Integrate and manage the flow of graphical data with information data, and process description.
- Decentralize individual tasks into complex processes; transforming individual processes into teams.
- Rapidly and effectively perform life-cycle operations of building projects.

BIM offers the ability to accomplish rigorous functions concurrently as it provides potential benefits with its application in the AEC industry.

METHODOLOGY

This research follows a mixed approach that is both qualitative and quantitative. This study requires both primary and secondary data. To achieve the research objectives, the qualitative data collection methods used will include a semi-structured interview, an online survey for the public, two Delphi rounds, and three case study analysis. The research targets input from experts in the construction field in Saudi Arabia, primarily because of a lack of public awareness. The public at this point in time is unaware of the matter being studied. The quantitative data collection methods used include surveys and questionnaires, correlation coefficient, linear regression, and chi-square and results will be numerical and quantified in order to obtain the required result. This research work employs the following outlined method for the purpose of obtaining the results. Data about the 2030 vision of the KSA will be analyzed and contrasted with the existing rating system in the Middle East. A new BIM-based metric will be developed based upon the data analyzed to assist in attaining the KSA 2030 vision.

The diagram below depicts the methodology process. It includes scope identification, the selection of relevant articles, abstracts assessment, excluding irrelevant articles, determining the sustainability parameters, and finally, developing a BIM Framework to measure KSA 2030 vision attainment levels.

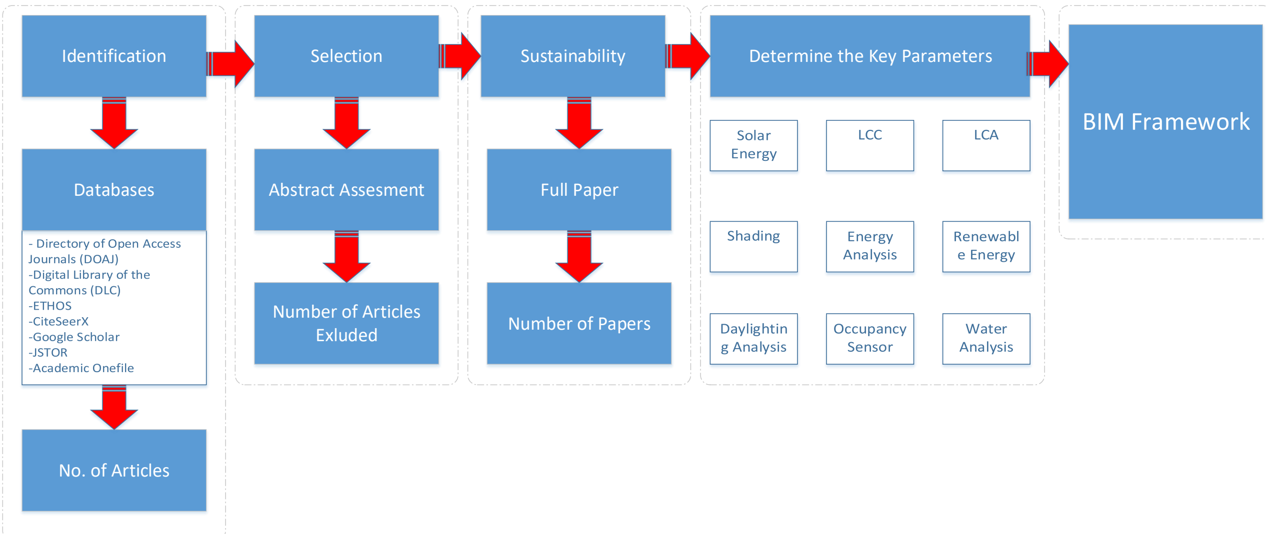


Figure 1. Methodology Process.

PROPOSED BIM FRAMEWORK

The proposed framework targets nine themes to be measured to determine the level of attainment of the KSA 2030 vision. This framework is implemented in Autodesk Revit to give a quick assessment of a new or existing building of its contribution to achieving the KSA 2030 vision (see figure 2). Figure 2 delineates an overview of the user interface of the proposed BIM-framework.

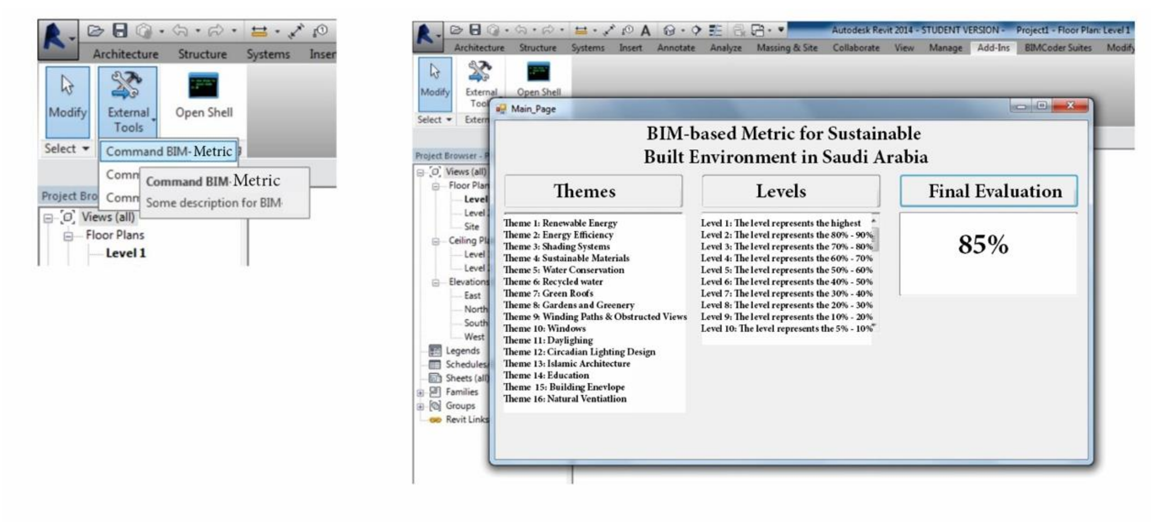


Figure 2. BIM-Framework for Sustainability in KSA.

CONCLUSION

The KSA supply of gasoline is not sustainable at the current rate. Thus, the Kingdom established its 2030 vision to address this issue. The vision aims to make KSA a sustainable society and reduce its reliance on fossil fuel. Even though green buildings are created in many countries worldwide, they do not have the same acceptance and popularity in Saudi Arabia. This gap has been observed by the absence of policies and regulations that promotes sustainability and green buildings in the country. Due to the lack of a national green building rating system in the KSA, LEED is used as a rating system but it does not apply properly to the Saudi Arabian climate, culture, and infrastructure. The Saudi Vision 2030 has set ahead the roadmap for future generations to prosper and live their lives in a steady economic state where both the private and public sectors join hands to enhance the country's income and natural resources.

Building Information Modeling (BIM) can greatly assist in establishing a cohesive building performance analysis to assure having an enhanced sustainable building design. It is evident that using BIM plugins to conduct a sun path analysis, life cycle assessment as well as carefully analyzing things such as solar, ventilation, heat gain, and energy efficiency and energy demand in buildings are important ways to enhance sustainability and encounter economic saving. Furthermore, the study aims to develop a new BIM framework to estimate the level of attainment of the KSA 2030 vision. Future research is recommended to assess the BIM framework to support multiple analysis functions and testing tools that can assist architects, engineers, and contractors with sustainable integration initiatives in the built environment.

REFERENCES

Almasoud, S. (2016). Transforming Saudi Arabia: National Transformation Program 2020 Approved Retrieved from LONDON, UK: http://www.shearman.com/~/medial/Files/NesInsights/Publications/2016/06/Transforming-Saudi-Arabia-National-Transformation-Program-2020-Approved-PDF-061016.pdf

AIA (2014) Integrated Project Delivery: An Updated Working Definition AIA California Council, Sacramento, CA [online]. Available from: http://www.aiacc.org/wp-content/uploads/2014/07/AIACC_IPD.pdf.

Asadi, E., da Silva, M.G., Antunes, C.H., Dias, L. and Glicksman, L. (2014) Multi-objective optimization for building retrofit: A model using genetic algorithm and artificial neural network and an application. Energy and Buildings. 81 pp. 444–456.

Burck, J., Marten, F., & Bals, C. (2013). The Climate change Performance Index: Results 2014.

Conca, J. (2015, July 24). U.S. Winning Oil War Against Saudi Arabia. Retrieved December 09, 2017, from https://www.forbes.com/sites/jamesconca/2015/07/22/u-s-winning-oil-war-against-saudi-arabia/#231a59a81678

Cottrell, M. (2010). Guide to the LEED® Green Associate exam.

Hoboken: John Wiley & Sons, Inc.

EIA. (2013). Overview: Saudi Arabia. U.S. Energy Information Administration (EIA) viewed 12/03 2014. Retrieved from http://www.eia.gov/countries/cab.cfm?fips=SA

EPA. (2014). Basic Information: Definition of Green Building. United States Environmental Protection Agency, viewed 3/9 2015. Retrieved from http://archive.epa.gov/greenbuilding/web/html/about.html

Government of Saudi Arabia. Saudi Arabia's Vision for 2030. 2016. Available online: http://vision2030.gov.sa/en . [Google Scholar]

Gray, R. & Bebbington, J. 2001. Accounting for the Environment, Sage.

Hashmi, N. (2016). Saudi's Strategic Vision for 2030. Retrieved from Washington DC: National Transformation Program 2020. (2016). vision2030.gov.sa/sites/default/files/NTP_En.pdf

Jurgenson, S.; Bayyari, F.M.; Parker, J. A comprehensive renewable energy program for Saudi Vision 2030. Renew. Energy Focus 2016, 17, 182–183. [Google Scholar] [CrossRef]

Karam, S. (2010). Special report: Can Saudi Arabia fix its housing time bomb?, Reuters. Retrieved from http://www.reuters.com/article/2010/08/26/us-saudi- real-estate-idUSTRE67P2CQ20100826

Krygiel, E. & Nies, B. 2008. Green BIM: successful sustainable design with building information modeling, Wiley. com.

Kibert, C.J., Sendzimir, J., and Guy, B.G. (2002). Construction Ecology Nature as the basis for green Buildings, 1st Edition, Spon Press, New York, NY.

Kibert, C. J. (2007, November). The next generation of sustainable construction. Building Research and Information. https://doi.org/10.1080/09613210701467040

Langar, S., & Pearce, A. R. (2017). The Role of Building Information Modeling (BIM) in the implementation of Rainwater Harvesting Technologies and Strategies (RwHTS). Journal of Architectural Engineering,23(1).

Leach, M., Stirling, A., & Scoones, I. (2010). Dynamic sustainabilities: technology, environment, social justice. Retrieved from https://www.taylorfrancis.com/books/9781136541674

LEE, N. & GEORGE, C. 2013. Environmental assessment in developing and transitional countries: principles, methods and practice, Wiley.

Lew, A. A., Ng, P. T., Ni, C. C., & Wu, T. C. (2016). Community sustainability and resilience: Similarities, differences and indicators. Tourism Geographies, 18, no. 1, 18–27. Retrieved from https://www.tandfonline.com/doi/abs/10.1080/14616688.2015.1122664

Lizarralde, G., Chmutina, K., Bosher, L., & Dainty, A. (2015). Sustainability and resilience in the built environment: The challenges of establishing a turquoise agenda in the UK.

Mosly, I. (n.d.). Barriers to the Diffusion and Adoption of Green Buildings in Saudi Arabia. Retrieved December 09, 2017, from http://www.ccsenet.org/journal/index.php/jms/article/view/54413

Mubarak, F. A. (1999, June 1–7 1999). Cultural adaptation to housing needs: A case study, Riyadh, Saudi Arabia. In IAHS Conference Proceedings.

Nguyen, T., Shehab, T. & Gao, Z. 2010. Evaluating sustainability of architectural designs using building information modeling. The Open Construction and Building Technology Journal, 4, 1-8.

Rahman, S., & Khondaker, A. (2012). Mitigation measures to reduce greenhouse gas emissions and enhance carbon capture and storage in Saudi Arabia. Renewable and Sustainable Energy Reviews, 16(5), 2446-2460. http://dx.doi.org/10.1016/j.rser.2011.12.003

Taleb, H., & Pitts, A. (2009). The potential to exploit use of building-integrated photovoltaics in countries of the Gulf Cooperation Council. Renewable Energy, 34(4), 1092-1099. http://dx.doi.org/10.1016/j.renene.2008.07.002

Zafar, S. (2017, March 04). Green Building Rating Systems in MENA. Retrieved from https://www.ecomena.org/green-building-mena/

Digital Twins of Urban Buildings with a Data and Computing Web Platform

Xuan Luo[1] and Tianzhen Hong[2]

[1]Building Technology and Urban Systems Division, Lawrence Berkeley National Laboratory, Mail Stop 90R3147C, 1 Cyclotron Rd, Berkeley, 94720; e-mail: xuanluo@lbl.gov
[2]Building Technology and Urban Systems Division, Lawrence Berkeley National Laboratory, Mail Stop 90R3111, 1 Cyclotron Rd, Berkeley, 94720; e-mail: thong@lbl.gov

ABSTRACT

More than half of the world population lives in urban areas. U.S. cities consume 70% of primary energy, produces 80% of GDP, and are facing challenges of aging infrastructure, impact of climate change and extreme weather events. With the growing visibility to city data, virtualized paradigms and integrated platforms of urban systems can inform urban scale analytics, and therefore help city policymakers to evaluate district and city-scale energy efficiency issues and opportunities.

This demo will showcase an open and free data and computing web platform – CityBES, which uses CityGML-based 3D city models, simulates building performance to identify retrofit measures that can cut building stock energy use by 50%, and evaluates city-wide PV potential. CityBES visualizes 3D-GIS integrated building performance in dozens of metrics (e.g., energy, water, demand, cost, GHG, savings, and regulation compliance status) for each building at urban scale. There are three layers in the software architecture of CityBES: the Data layer, the Algorithms and Software layer, and the Use Cases layer. The Data layer includes the weather data, and the CityGML 3D city models. The Software layer capsules the simulation cores Commercial Building Energy Saver (CBES) which is built upon EnergyPlus and OpenStudio. The Use Cases layer provides examples of potential applications. The demo intends to introduce some of the applications and workflows of CityBES at the data level, regarding data integration, visualization and utilization. Functionalities include integrating building data from different resources to compile and visualize building performance related database, and to construct city-scale building energy models. Utilizing the models to link and interact with district utility data and sensor network data, the platform is able to simulate and predict the spatiotemporal energy fluctuations of cities.

BUILDING DATA INTEGRATION

CityBES leverages existing data from several sources that are compiled into a central database, including assessors' records, GIS data, and public building energy use disclosure data. The data sources are combined and integrated into CityGML files to represent 3D city models in the database. CityBES uses typical meteorological year weather data in EnergyPlus simulations, and allows user-defined weather data measured at local stations. For retrofit analysis, CityBES integrates more than 100 energy conservation measures (ECMs) with technical performance data as well as cost data. Economic data such as energy costs, investment costs, discount rate and payback years are also incorporated. The integrated database provides the majority of the data required for urban building energy modeling and performance analysis.

BUILDING PERFORMANCE DATA ANALYSIS AND VISUALIZATION

CityBES performs district- to city-scale building energy simulation, and provides performance analysis results in many applications, including energy benchmarking, urban energy planning, energy retrofit analysis, building operation improvement. CityBES renders a 3D view of the city building stock to visualize these performances. A suite of performance metrics of buildings can be visualized by color-coding the 3D view of the buildings, including site or primary energy use (absolute amount or per floor area), greenhouse gas emissions, whole building peak electric demand, Energy Star score, retrofit energy savings, weekly operating hours, energy use breakdown into end uses (lighting, plug-loads, cooling, heating, and process loads), and code and compliance status. Moreover, monthly utility data of the buildings can be used to fine tune the baseline model before retrofit analysis to estimate energy savings of ECMs.

DIGITAL TWINS OF URBAN BUILDINGS

Modeling the urban buildings integrated with city utility data and live measurement data from city sensor network, the CityBES platform has the potential to learn and connect the spatiotemporal information of the city. Spatiotemporal fluctuations of the city, in terms of building energy demands and consumption, are enabled through virtualization at the real-time intersection of Internet of Things. Analytical results can be used to evaluate and optimize urban system design decisions and development options. The digital twins of urban buildings, virtualized with CityBES, can help stakeholders understand dynamics of building stock changes, technology evolution and policy change related issues, such as evaluating city energy resilience considering the deployment of renewable energy, energy storage, electric vehicles, and advanced control strategies.

To conclude, CityBES offers insights into resource efficiency, environmental sustainability, and infrastructure resiliency, and provides predictive insights into the city’s smarter performance and growth, leveraging emerging opportunities in big data and artificial intelligence.

References:

Y. Chen, T. Hong, X. Luo. Development of City Buildings Dataset for Urban Building Energy Modeling, Energy and Buildings, 2018.

Y. Chen, T. Hong, M.A. Piette. Automatic Generation and Simulation of Urban Building Energy Models Based on City Datasets for City-Scale Building Retrofit Analysis. Applied Energy, 2017.

T. Hong, Y. Chen, S.H. Lee, M.A. Piette. CityBES: A Web-based platform to support city-scale building energy efficiency. Urban Computing, August 2016, San Francisco.

T. Hong, Y. Chen, M.A. Piette, X. Luo. Modeling City Building Stock for Large-Scale Energy Efficiency Improvements using CityBES. ACEEE Summer Study, 2018.

Data Integration and Innovation: The Future of the Construction, Infrastructure, and Transportation Industries

Ron Perkins[1], C. Douglass Couto[2], and Aaron Costin, Ph.D.[3]

[1] Jobsite Technology Group, LLC; e-mail: rperkins@jobsitetechgroup.com
[2] Former CIO at the Michigan Department of Transportation and Senior Fellow at the Center for Digital Government; dougco28@outlook.com
[3] M.E. Rinker Sr., School of Construction Management, University of Florida; e-mail: aaron.costin@ufl.edu

ABSTRACT

There can be no doubt of the impact emerging and innovative technology is making across the entire construction industry. From planning, design, construction, and facilities or asset management, these latest "tools" are becoming the norm. These technologies are also becoming more prevalent in the infrastructure and transportation industries. There are challenges to consider when adopting new software or hardware solutions, in which people can be the biggest hurdle. Business owners must be convinced the ROI is there and users must see that the learning curve is not so disruptive that it impacts the project schedule. There can also be reluctance to embrace technology designed to address a process that has "always been done that way." Nearly everyone agrees that IT makes sense and it is inevitable in the coming years. The questions that need to be addressed are *what to adopt and how to do it remain the primary concerns?* With examples from the transportation industry, this paper discusses the latest practices, challenges, practical solutions, and the outlook of information technology and data integration in the construction, infrastructure, and transportation Industries.

INTRODUCTION

With an ever-expanding list of devices and means of field data acquisition tied to project delivery systems, it is growing more important every day to automate or streamline as many of these data paths as possible. It is also essential to design an effective method to realize data integration and interoperability between the various information systems (Costin and Eastman 2019). Efficient interaction between devices and applications and reduces the time and effort needed for communication and information exchange among different stakeholders during the project lifecycle. Leveraging these technologies is critical because of the accuracy and efficiency they bring to the project. Incorporating this data into project workflow while maintaining integrity is only the first step in the process. Infotech[2], developer of AASHTOWare Project™, is one software developer that has a project going with Leica and HNTB to streamline the path for inspection data coming from the Leica rover and bringing that data into the Appia® construction administration

[2] https://www.infotechinc.com/

software used to manage the inspection data. Maintaining the data and adding functionality to manipulate or run analysis during project delivery is the stage where the greatest benefits will be achieved.

Considering the latest statistics from Dodge Analytics (2019), McKinsey Global Institute (2017), KPMG International (2019), and others, there is a sense for what is being referred to as the "Construction Disruption." It started with processes that were traditionally paper heavy and moved many of them to a digital workflow. Plan distribution, bidding, and invoicing have all migrated in that direction. The benefits include more efficient processes with a higher level of accuracy. According to Command Alkon[3], their eTicketing solution for concrete saves on average ten minutes per load, per day – that equates to an extra load can be obtained almost every day. This is just one of many examples throughout the AEC industry.

CURRENT PRACTICE

The KPMG International "Construction Disruption" study recognized three different adoption levels for construction firms: Innovative Leaders at the top 20%; Followers in the middle 60%; and the last 20% of firms are referred to as "Behind the Curve" (KPMG International 2019). This study further illustrates the fact that those Innovative Leaders are not only ahead of the curve with well-known technology such as laser scanning, rovers and drones, they are now leveraging that expertise in emerging technology like artificial intelligence (AI), Predictive Analytics and the internet of things (IoT.) The point here is that software and hardware dev cycles are increasing, not decreasing. This means that the longer it takes for many of the "Behind the Curve" firms to begin on this journey they grow further behind than they probably even know. That same study states that 70% of construction companies believe those who do not adopt digital ways of working will go out of business.

The next level of innovation comes from hardware and software developers. Firms, such as Leica[4], have introduced faster and more accurate laser scanners, rovers, and total robotic stations. The use of drones has exploded with departments of transportation (DOT's), contractors, and inspectors working on construction projects. Virtual Reality and Augmented Reality (VR/AR) are now coming into the fold with leading-edge firms looking for better ways to communicate and collaborate more effectively with owner agencies, engineers, and other project team members. Building Information Modeling (BIM) has the potential to be the same catalyst it was in the vertical construction market. According to Federal Highway Administration (FHWA), BIM is a collaborative work method for structuring, managing, and using data and information about transportation assets throughout the lifecycle (FHWA 2020). More than 20 DOT's, including the Florida DOT, have joined the Transportation Pooled Fund – TPF-5(372) BIM for Bridges[5] initiative along with FHWA and software vendors. BIM has been a paradigm shift in the building

[3] http://commandalkon.com/getetickets/
[4] https://leica-geosystems.com/
[5] https://bimforbridgesus.com/

environment, so the transportation industry is developing ways to integrate these technologies and solutions for transportation and infrastructure projects. With several states now working on their Model as Contract programs, it is inevitable that anyone working on a transportation project is going to have to know how they interact with the model during the bid, build, and handover process.

THE IMPORTANCE OF DATA AND KNOWLEDGE MANAGEMENT IN TRANSPORTATION

The endgame of all this data is better lifecycle asset management, which is driving BIM and many of these other technologies. 3D modeling has been widely adopted across transportation and infrastructure projects and it is well known that Bentley was helping firms design in 3D long before Autodesk. The demand now is not just to help firms design better, but to have better visualization, improved communication, and more effective collaboration. These reasons are tangible benefits and should be considered when embracing 3D and the growing demand for model as the contract. What cities, states, and other owners and agencies are asking now is: *how can I better manage my assets, physical and digital, for the life of the asset?* In the transportation sector this does not just mean identifying guardrail location or streetlight condition anymore. The new assets will include sensors and cameras and other real-time data that are applied to what many refer to as Smart City technologies.

The advances in technology, applications, and our ability to deploy the array of innovative solutions has the potential to revolutionize the transportation industry. It should be noted all these solutions rely on abundance of data. Transportation organizations have relied on data for planning, design, building and maintenance of road and bridge infrastructures, as they understand that data is a valuable resource. As we gather more data about our transportation systems, we are now beginning to understand the importance of data as an enterprise asset that like other assets must be managed and developed to remain valuable. Also, the emerging technologies and the processes that will evolve as a result will challenge the next generation of employees. The American Association of State Highway and Transportation Officials (AASHTO) recognized the impact of this data surge forming the AASHTO Data Management and Analytics Committee and the Knowledge Management Committee. These committees were instrumental in consuming the work of the National Cooperative Highway Research Program (NCHRP) reports related to Information and Knowledge Management (KM) research projects. There were three core projects that provided a set of tools to transportation leaders about how to create better programs to support transportation systems and have formed a foundation for later research. The panels also adopted definitions of common terms to create a better understanding of these concepts.

- NCHRP Report 829, *Leadership Guide for Strategic Information Management for State Departments of Transportation* (NASEM 2016a). The guide provides a direction for creating a program, establishing policies, and implementing a strategy. It targets the c-level suite and division managers.

- NCHRP Report 846, *Improving Findability and Relevance of Transportation Information* (NASEM 2017). The guide addresses the need for cooperation between business units and the tools that are needed to help employees find the information they need.
- NCHRP Report 813, *A Guide to Agency-Wide Knowledge Management for State Departments of Transportation* (NASEM 2015a). This guide provides a course of action for developing an enterprise knowledge management plan and program.

The work continues as later research is adding to the necessary tools and addresses the emerging concerns around cybersecurity and privacy.

- NCHRP Document 221, *Protection of Transportation Infrastructure from Cyber Attacks: A Primer* (NASEM 2016b)
- NCHRP Report 754, *Improving Management of Transportation Information* (NASEM 2013).
- NCHRP Report 814, *Data to Support Transportation Agency Business Needs: A Self-Assessment Guide* (NASEM 2015b).
- NCHRP SCAN 12-04, *Advances in Transportation Agency Knowledge Management* (Halikowski et al. 2014).

These systems rely on trusted data sources for all aspects of the enterprise business activities. Those who use the data must be confident that the data are accurate. Around 1997, the Michigan DOT decentralized operations to bring delivery closer to their customers at the local levels. The reorganization required better improved sharing of data and better knowledge management. The chief information officer created a governance structure with a steering committee and designated data owners for each of the data elements. Data owners were the only people who could make changes/corrections to the data based on the guidance from the steering committee and their functional business knowledge. There was a time when people would shop the department for answers that supported a specific agenda. This was possible because every business unit were stewards of a unique data source.

The AASHTO Data Management and Analytics Committee (AASHTO 2013) was established to address the collection, processing, analytics, reporting, and sharing of data within a multimodal transportations organization to support the entire program and project lifecycles. The vision is for the data to help transportation leaders make better informed decisions such as allocating resources to support the project life-cycle-plan, build, operate, and maintain the Nation's transportation systems. The committee working with the other AASHTO committees and the US DOT data leadership promulgated seven core data principles (AASHTO 2013):

- Principle 1 – VALUABLE: Data is an asset; Data is a core business asset that has value and is managed accordingly.
- Principle 2 – AVAILABLE: Data is open, accessible, transparent, and shared; Access to data is critical to performing duties and functions, data must be open and usable for diverse applications and open to all.
- Principle 3 – RELIABLE: Data quality and extent is fit for a variety of applications; Data quality is acceptable and meets the needs for which it is intended.
- Principle 4 – AUTHORIZED: Data is secure and compliant with regulations; Data is trustworthy and is safeguarded from unauthorized access, whether malicious, fraudulent, or erroneous.
- Principle 5 – CLEAR: There is a common vocabulary and data definition; Data dictionaries are developed, and metadata established to maximize consistency and transparency of data across systems.
- Principle 6 – EFFICIENT: Data is not duplicated; Data is collected once and used many times, for many purposes.
- Principle 7 – ACCOUNTABLE: Decisions maximize the benefit of data; Timely, relevant, high-quality data are essential to maximize the utility of data for decision-making.

It is the growing consensus that that data is really "the currency" for adoption of the future technologies. With the mounting topics and research, data is at the heart of each. One could argue that data powered the models and innovative uses of these emerging technologies. There has been an ongoing debate about the role of Information Technology (IT) and Operational Technology (OT) in managing these technologies, in which both are needed for success. The information and communications technology (ICT) traditionally managed by a chief information officer (CIO) or chief technology officer (CTO) bring the skills, technologies, and processes to collect, store, and manage the data. The deployment of transportation technologies that support functional business activities works best when handled by those with business expertise. Another argument is that a balanced team would include ICT professionals who know the business operations and OT professionals who understand the challenges for managing the infrastructure needed to use functional data and information.

DATA INTEGRATION CHALLENGES AND SOLUTIONS

There are still significant challenges in accomplishing this streamlined data path (Costin et al. 2018). First is the human component. Attempts to force change in workflow presents a multitude of challenges from training and education to overcoming resistance from individuals who feel like: *if it's not broke why fix it?* Adding to that potential complexities and impact on project schedule, while staff members are working their way over the learning curve with new technologies or business processes and successful results could be difficult to obtain. Second, there are software and technology challenges. Moving data from devices to applications and then to other applications, also referenced as interoperability, also present a variety of challenges. Solutions including software vendors providing open application programming interface (API) and the use of neutral exchange standards, such as IFC, are being utilized to mitigate some of these challenges. However, often times competitive software companies do not make it easy to move data from their solutions into others in the hope that they hold the data captive and thus the user committed to their software suite as well. Third, the increase in data, IoT, and AI will expand the technology risks and exposure to cybersecurity attacks. We are witnessing transportation organizations being attacked by bad actors and those seeking to enrich themselves through ransomware attacks or worse simply disrupt our daily operations. There is also a risk associated with loss of services through natural disasters and other local events that impact critical ICT infrastructure. These issues are addressed when the organization develops their resilience plans. Critical technologies, data, information, and knowledge must be protected to assure continuity of the operations.

The Florida DOT is a leader in addressing the challenges for data and knowledge management and presented a model that addresses people, processes, and technologies. They are demonstrating the necessity of managing transportation technology and the associated data as an enterprise asset (FDOT 2019). Namely the Data Governance (001-325-064) establishes data governance as a priority, and the Enterprise Technology Governance (001-325-062) establishes a technology governance structure to effectively support the delivery of the Work Program, align technology and data, automate services, improve customer experiences, and bolster safety and connectivity on Florida roadways. The CIO/CTO community has successfully used this construct for deploying technology solutions. The Florida approach takes it to the next level to include both the IT and OT communities. Significantly, this model forces them to work together, identify the business needs, and address gaps in strategy, technologies, people skills, processes, and investments.

An important aspect of future deployment is also making information and data available when needed to allow for repeatable results when used by employees. The concepts associated with knowledge management provide these tools. Transportation organizations are concerned about the impact of an aging workforce that is also becoming more mobile. The result is a loss of knowledge when people move on to new chapters of their life through retirement or new career opportunities. AASHTO established the Committee on Knowledge Management (KM) to address these emerging issues (AASHTO 2019). A KM program can help a transportation organization manage the challenges of a transitional workforce. When considering the knowledge gained by employees working with and deploying the next generation of transportation technologies, a great deal can be lost during a transition. The KM Committee defines Knowledge Management as an umbrella term for a variety of techniques that retains the know-how of transportation employees. While there may be some application and technology considered in creating a KM program, the real driver is the knowledge that is in the employees' brain, and not the data in the system. When developing a KM program, the focus is on the people and the processes used by the organization with less emphasis on technology.

The Virginia DOT is a recognized early adopter of a KM program. They were faced with a huge loss of knowledgeable people due to a large bubble of retirements. The department needed to figure out how to transfer the knowledge that was about to leave. VDOT explains the difference between information management and knowledge management this way:

> "*If we only needed information to get things done, then institutions would just be manuals and procedures, but it takes more than information to perform a function, particularly one as complex as VDOT's. It takes people who not only know what to do and how to do it, but why to do it a particular way*" (Halikowski et al. 2014).

Michigan DOT morphed their knowledge and data programs along a lengthy timeline that started when they were migrating to client server technology (TRB 2016). They created data sources to support each of the department's business functions. Michigan DOT started their journey when faced with huge employee reductions and the requirement to build new management systems mandated by the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. While the act expired with most DOT's never starting these systems, Michigan chose to complete the central databases that became the single trusted source for data about the program. As the Michigan DOT continued to adopt new technologies for e-construction, they applied the concepts from their knowledge management program to be sure that the data and information captured from all parties involved with a construction project are given access to the knowledge and information (TRB 2016). People have access to the information they need to perform the many tasks associated with delivering a project.

CONCLUSION AND FUTURE OUTLOOK

The recent Commercial Real Estate study performed by Deloitte (Deloitte Center for Financial Services 2019) states that investors want companies to prioritize predictive analytics and business intelligence to make buildings future ready. The significance of this study is that it clearly illustrates the fact that the commercial construction market has moved on beyond BIM. Virtual Design and Construction (VDC) practices have become the norm in the vertical building industry. The Transportation Research Board (TRB) studies and those done by countless universities and others across the country all suggest that the horizontal market is following the path of vertical. This provides us with a glimpse into the future.

Many of these disruptive construction technology innovations are already here. There is a wealth of statistical data and studies that have been done whose data can be used to help construction businesses of all sizes determine their path and where the most ROI will come from. As mentioned before, the risk versus reward can only be measured by each organization. There is a benefit to wait and see and learn from the pioneers. There could also be a significant risk as those early adopters not only become more proficient with the technology others have yet to adopt but are also moving on the next phases to benefit their organization, their projects and their clients.

Throughout the process of adopting data integrated solutions and shifting from paper centric practices to digital solutions there are countless benefits. The most obvious are removing redundancies of multiple data entries by all parties involved in the data capture and usage cycle. The risk of human error when data is manually transferred from one system to another are always very high. Developing methods to acquire this data directly from the device that captured it, e.g. rovers, cameras, drones, etc., will not only all but eliminate the margin of human error it could also incorporate more metadata associated with the source file. Once the digital data has been captured, transferring that content from one system to another also becomes less of a challenge if neutral exchange standards are used. On October 9, 2019 The American Association of State Highway Transportation Officials (AASHTO) signed an Administrative Resolution AR-1-19 Title: "Adoption of Industry Foundation Classes (IFC) Schema as the Standard Data Schema for the Exchange of Electronic Engineering Data" (AASHTO Board of Directors 2019). Data standards are a necessity for successful BIM programs and the integrations being developed today. Firms like Infotech are forming strategic partnerships with academics, public sector committees, and other consultants to gain knowledge and develop strategies required to support the use of IFC.

As we move forward with the implementations of the technologies and processes discussed during the recent events and forums, we are compelled to address the ever-growing need for information, data, and knowledge management systems and processes. Without them, industry organizations will be overwhelmed and drowned in the data created. A good approach is to ask: *what question do these data answer and for whom do they serve?*

REFERENCES

American Association of State and Highway Transportation Officials (AASHTO). (2013). "AASHTO Core Data Principles: Data Management and Analytics." < https://data.transportation.org/aashto-core-data-principles/> Accessed February 20, 2020

American Association of State and Highway Transportation Officials (AASHTO). (2019). "Committee on Knowledge Management." < https://km.transportation.org/> Accessed December 20, 2020

AASHTO Board of Directors. (2019). "Adoption of Industry Foundation Classes (IFC) Schema as the Standard Data Schema for the Exchange of Electronic Engineering Data." Administrative Resolution AR-1-1. <https://highways.transportation.org/wp-content/uploads/sites/46/2019/10/Administrative-Resolution-AR-1-19-Adoption-of-Industry-Foundation-Classes-IFC-Schema-as-the-Standard-Data-Schema-for-the-Exchange-of-Electronic-Engineering-Data.pdf>

Costin, A., Adibfar, A., Hu, H., and Chen, S. S. (2018). "Building Information Modeling (BIM) for transportation infrastructure–Literature review, applications, challenges, and recommendations." Automation in Construction, 94, 257-281.

Costin, A., and Eastman, C. (2019). "Need for interoperability to enable seamless information exchanges in smart and sustainable urban systems." Journal of Computing in Civil Engineering, 33(3), 04019008.

Deloitte Center for Financial Services. (2019). “Commercial Real Estate Outlook: Agility is Key to Winning in the Digital Era.” <https://www2.deloitte.com/content/dam/Deloitte/uk/Documents/real-estate/2019-commercial-real-estate-outlook.pdf>

Dodge Data and Analytics. (2018). “Q4 2018 USG + U.S. Chamber of Commerce Commercial Construction Index.” <https://www.construction.com/toolkit/reports/q4-2018-commercial-construction-index>

Federal Highway Administration (FHWA). (2020). “Building Information Modeling (BIM) for Infrastructure.” <https://www.fhwa.dot.gov/construction/bim/>

Florida Department of Transportation (FDOT). (2019). “Documents and Publications.” Civil Integrated Managemet. <https://www.fdot.gov/cim/navigation/documents.shtm>

Halikowski, J., Burk, B., Dabling, L., Dexter, A., Ellis, A., Hammer, M., Michel, C., Oman, L., and Wilkinson, L. (2014). “Advances in Transportation Agency Knowledge Management.” NCHRP 20-68A, Scan 12-04 < http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-68A_12-04.pdf>

KPMG International. (2019). “Future-Ready Index: Leaders and Followers in the Engineerign and Construction Industry.” Global Constrution Survey 2019. < https://assets.kpmg/content/dam/kpmg/xx/pdf/2019/04/global-construction-survey-2019.pdf>

McKinsey Global Institute (2017) “Reinventing Construction: A Route to Higher Productivity.” McKinsey and Company. <https://www.mckinsey.com/~/media/McKinsey/Industries/Capital%20Projects%20and%20Infrastructure/Our%20Insights/Reinventing%20construction%20through%20a%20productivity%20revolution/MGI-Reinventing-construction-A-route-to-higher-productivity-Full-report.ashx>

National Academies of Sciences, Engineering, and Medicine (NASEM). (2013). Improving Management of Transportation Information. NCHRP Report 754. The National Academies Press, Washington, DC. <https://doi.org/10.17226/22504>

National Academies of Sciences, Engineering, and Medicine (NASEM). (2015a). A Guide to Agency-Wide Knowledge Management for State Departments of Transportation. NCHRP Report 813The National Academies Press, Washington, DC. <https://doi.org/10.17226/22098>

National Academies of Sciences, Engineering, and Medicine (NASEM). (2015b). Data to Support Transportation Agency Business Needs: A Self-Assessment Guide. NCHRP Report 814. The National Academies Press, Washington, DC <https://doi.org/10.17226/23463>

National Academies of Sciences, Engineering, and Medicine (NASEM). (2016a). Leadership Guide for Strategic Information Management for State Departments of Transportation. NCHRP Report 829. The National Academies Press, Washington, DC. <https://doi.org/10.17226/23480>

National Academies of Sciences, Engineering, and Medicine (NASEM). (2016b). Protection of Transportation Infrastructure from Cyber Attacks: A Primer. NCHRP Document 221. The National Academies Press, Washington, DC. <https://doi.org/10.17226/23516>

National Academies of Sciences, Engineering, and Medicine (NASEM). (2017). Improving Findability and Relevance of Transportation Information: Volume I A Guide for State Transportation Agencies, and Volume II Background Research. NCHRP Report 846. The National Academies Press, Washington, DC. <https://doi.org/10.17226/24804>

Transportation Research Board (TRB) (2016). “TR News: Applying Knowledge Management.” Number 305, September-October, p32. <http://onlinepubs.trb.org/onlinepubs/trnews/trnews305.pdf>