Technology & the Architect

Empowering the Contemporary Design
Process with Digitally Semantic Information

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I would like to dedicate this work to my family, those still with me and those I've lost during this project.

To my Aunt Shirley who was a dedicated believer in education and academics, you will be missed.

To my Uncle Shawn, whose mustache was always crooked and whose sense of humor, while strange and ridiculous, never failed to put a smile on my face; you will be missed.

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Abstract

The research presented in this paper takes a stance amidst two fields of study: that of Architecture and that of Computer Science/Information Technology. Beginning with a brief positioning of this dichotomous work in philosophy, this paper goes on to hypothesize that, for the purposes of efficient digital workflows and collaboration, Architecture must develop an ontology capturing the developed semantic knowledge of the discipline. Without delving into the technical details too deeply, this thesis analyzes several ontological examples, both offline and published online, in order to address the current state of affairs pertaining to questions of efficient information-sharing in the Architecture, Engineering, Construction and Operating (AECO) industry. Focusing on the proposal for a network of semantic web technologies to support knowledge-based interoperability solutions, this project addresses the question: what should an ontology meant to facilitate data-sharing — but developed on the premise of knowledge-sharing — be for AEC?

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Preface

As a young person raised in both the fantastical and boundless leaps of the 90's, and the digitally changed environment of the 2000's, I can freely admit to a needy and bottomless fascination with the information technology of our age.

I have always had a relationship with technology. As a young person, I have been the go-to technical voice in my family. When the home computer needed work, I took it apart and rebuilt it. When the home network was buggy, I rewired and defined it. When the home entertainment system was being installed, I wired it for surround sound and connectivity.

In a family where both parents had trouble even using the cable remote, I did the research and procurement, trouble shooting, installations and updating, and hardware upgrades. The rapidly growing technologies available for public consumption were my designated responsibility, and carrying into post-secondary, this relationship with technology served me well.

Studying architecture meant learning the traditional theories and methodologies while also learning to work in the contemporary landscape of practice in the information age. Design tools for image and video editing went hand in hand with other communication skills such as writing and research tools. Eventually, this dichotomous relationship between an education in theory and in relevant technologies grew to encompass software for architectural design and building information modeling.

I have studied and worked with many of these tools, and eventually began to lend my voice to the technical fields of technology and information in the built environment. I've worked with researchers and technical experts from all over the world, and come to understand that an architect is responsible for much more in this contemporary age of information.

The following thesis reflects this perceived relationship between the architect and his or her tools in contemporary practice. The objective was to push myself beyond the theories and methodologies of traditional architecture and address the changed role of the Architect in the rapidly evolving and changing context of the Information Age.

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Introduction

Technology and the Contemporary Architect

Our age is not a technological age because it is the age of the machine, it is an age of the machine because it is the technological age¹.

Within the ever-expanding realm of digital design and construction, it is not difficult to feel overwhelmed. Contemporary building projects present a unique challenge for those looking to apply the traditional centralized, tightly-knit, highly-invested, and closed management of information for a project.² Many building design and information technologies exist, including digital design, recording, technical reviews, and life-cycle management, to name a few. At their core, these technologies rely on the communication and management of information for the manipulation and outcomes for which they are designed.

The Architecture, Engineering, Construction and Operating (AECO) industry generates an endless outpouring of information that often leaves simple exercises and processes glutted by an overwhelming amount of data. This same data, however, can prove vital for many later purposes. A common challenge is to determine what is enough or what is too much information.

Thesis Questions

This thesis presents the results of an investigative effort to define, and contribute to, the future of the architectural discipline in an increasingly digital information-driven age. With advancements in the digital built environment, research has

¹ (Heidegger 1972)

² (Torma, n.d.)

identified the importance of shared conceptualization in addressing the industry challenges of increased interoperability and efficiency. As a community, architecture has seen the definition of a socially constructed, conceptual model of reality take place over centuries of practice³. In the search for solutions to the challenges presented by interoperability and efficiency, standardized and central data-models have been proposed many, many times.⁴

The trouble is, the central and standardized data-structure is an “all-or-nothing” solution that relies on its adoption by all the communities of practice inherent in the AECO industry for its own success. The industry is fragmented and the largest consequence is the difficulty to communicate and collaborate between these communities who hold vastly different views of the world. If collaborative interoperability and efficiency is key, recent research indicates that an approach that seeks to weave these many views together to form a cohesive structure built of many smaller parts would be more beneficial than a “one-fits-all” approach⁵.

Thus, given the need for a shared conceptualization from each community of practice, and thereby Architecture, a fundamental gap in contemporary architectural methodology has been identified. During the development of the digital domain of the built environment over the past several decades, shared conceptualization has been defined by computer-interpretable logic defined in a predominantly standardized or proprietary way, based on product or object data and authored by Developers. Though many research initiatives have existed and

³ (Rezgui et al. 2011)

⁴ (Solihin, Eastman, and Lee 2016)

⁵ (Rezgui et al. 2011; Pauwels, De Meyer, and Van Campenhout 2010; Pauwels, Zhang, and Lee 2017; Bizer, Heath, and Berners-Lee 2009)

made large contributions to advancements, it has been suggested that the field of disciplinary conceptualization, and therefore process-driven data defined by semantic logic, has gone largely uninvestigated. Essentially, a more user-defined and driven approach would be largely more beneficial.

Technology is in fact changing the way that we perceive, order and change the world around us. As such, it is both dangerous and beneficial. The benefit can be made possible by maintaining the authenticity of our perception and our action in the use of technology. Comparatively, the danger might be considered the continuation to action with technology with no thought for the authenticity of the world views that have engendered them.

Considering this ambiguity, this thesis began with two fundamental questions:

1. *Why do we need a shared conceptualization and multi-disciplinary conglomeration of data-structures authored by respective communities?*
2. *How could we build a digital and shared conceptualization (ontology) for the architectural discipline?*

Beginning with a survey of past methodologies in interoperability and progressing through current solutions to the frontier of research pertaining to the subject, this thesis will serve to argue that an architecturally-conceived-, and shared-, conceptualization of information is necessary to build a semantically-rich data-model for future interoperability solutions.

Digital design technologies enable the management of relationships between data-components (like building elements) beyond the object-level information in previous product or object based design. Information about important

methodologies like design philosophy, intent and process can be captured in digitization. A digital building model can therefore contain much more than a simple list of building components and locations; most importantly for an architecturally, semantically-rich building model, it can also contain the myriad of relationships that are intended and conceived between those objects by the architect.

Digital workflows in architecture have also evolved past this object-based and parametric 3-D modeling of the early 2000's⁶. Workflows exist for technology use-cases ranging from design to lifecycle management, and by combining these various information needs with the geometric properties of previous 3D technologies, a range of new 'dimensions' can be associated with virtual building models.

While digital technologies for the AECO industry like building information modelling (BIM) are still not fully adopted in Canada at the level of the local and smaller firms,⁷ the international research and development community has been working towards next steps for adoption. This evolution in the Canadian context has been much slower than elsewhere in the world. Countries like Norway, Finland and Denmark — for example — have become leaders adopting digital technologies for AECO.⁸

The pressing question in research and development is no longer “can we model it”; modelling in-and-of itself was never a final goal. The true value of digital

⁶ (Eastman et al. 2011)

⁷ (Poirier, n.d.)

⁸ (Hooper 2015)

technologies in the AECO industry is in fact the efficiency with which, and the degree of quality to which, one can create, record or manage information, and then later collaborate through it.

If the key to the process is information and the management of such, then the fundamental issues identified earlier remain. The ‘average’ architect has neither the choice of, nor the power over, the way in which the information that he/she generates is understood, linked, or later used. A shared conceptualization authored by the discipline (to theoretically take its place amongst many others) will be necessary to truly maximize the potential and future of the digital domain of the built environment. In comparison with the traditional practice —where an architect was both “Master Builder” and keeper of the overall project vision — architects now have less control and influence. They have largely lost control over the technologies that are used to communicate architectural intentions.

The newest generation of digital technologies in the AECO industry harness a concept that has been explored in the Computer Science Industry for decades. Termed the ‘Semantic Web’, linked data technologies can take information, at the most elemental — or instance-based — level and connect it instantaneously to other information or devices through a common “ontology” or shared system of definitions.

It is proposed that a solution to the industry challenges (of collaboration, interoperability and efficiency) lies within disciplinary or community dictated data-structures that can re-capture and reflect authenticated meaning,

perceptions, relationships and knowledge. Unfortunately, the architectural discipline is not currently equipped to deliver such a data structure⁹.

Methodology

Over the past two decades, the AECO industry has seen a plethora of tools, information exchange systems, and interoperability solutions developed for digital project delivery¹⁰. In this fast-paced environment, we often find ourselves working with and testing a variety of tools and technological solutions before the ramifications or flaws have been addressed fully. Information is created, delivered and managed in an ever-changing environment of un-authenticated structures. Where one project is completed in one workflow, another is developed in another; in this context, a vital component of the built environment is information.

Each new generation of tools and solutions begins a new period of struggle to ensure the relevancy of the information engendered by the legacy of previous generations. With this struggle at the forefront of current research in AECO technology, this thesis has approached the challenge of continued and efficient information-sharing with the objective of maintaining relevancy and ensuring future usefulness and evolution for the industry.

In this context, the following methods were used for the development of the discussion of this thesis:

⁹ (Ouellette, n.d.)

¹⁰ (Kolarevic 2003)

1. The surveying of contemporary research pertaining to workflows for the creation, delivery, exchange and management of information;
2. The surveying of current solutions for open and neutral information-sharing;
3. The surveying of current research pertaining to the linked-data argument for information-sharing; and
4. The surveying and analysis of current examples of shared-conceptualizations.

The tools investigated for these research methods are respectively as follows:

1. Literature Survey;
2. buildingSMART International's IFC4 specification and standard;
3. Literature Survey; and
4. Off-line conceptualizations (Succar's Conceptual Hierarchy¹¹), and published Ontology Web Language conceptualizations (ifcOWL¹², the BIM Guides Project¹³, and the Getty Vocabulary Program Ontology¹⁴) using Protégé 4 by Stanford University.

¹¹ (Succar 2013)

¹² (Pauwels and Terkaj, n.d.)

¹³ (Beange and Pauwels, n.d.)

¹⁴ (The Getty Research Institute/OnoText Corporation 2014)

Thesis Structure

The following chapters represent a significant amount of time and effort spent in the spirit of understanding a field of study outside traditional architectural research methods.¹⁵ From disciplinary workflows to the proposed web ontology language (OWL) notation, this thesis has meant the cultivation of another layer of disciplinary knowledge beyond what is typically considered crucial to an architectural professional. As such, this thesis has been structured to follow those incremental steps taken in the development of that knowledge in the hopes of providing an additional and rigorous justification for its conclusions.

Each chapter represents a summary of these steps taken during the research and progression of this understanding, leading eventually to the position that an important layer of disciplinary understanding has not been communicated in data structures currently in use for the AECO industry. The chapter structure of the thesis is as follows.

¹⁵ (Groat and Wang 2013)

The Mutating Architect

As a historically multi-disciplinary and polymathic discipline, architecture in Canada has played a vital role in the design and contract administration stages of building projects. This profession is changing, and so too are the skills and knowledge necessary to practice.

This chapter briefly identifies and discusses the ramifications of rapidly growing and advancing technologies for the discipline of Architecture.

The Question of Digital Work Flow

Digital AECO technologies have enabled advanced design tools and improved the individual tasks required of various disciplines. However, so far they have not developed to a point where they have had significant impacts on the processes and workflows in the delivery of projects¹⁶.

Several approaches exist to address the challenges of integration across individual disciplinary and/or model-use workflows. This chapter briefly identifies and discusses the various model-uses and workflows presently used for project delivery, along with three major categories of integration approaches identified in the industry¹⁷.

The Question of Digital Information

Several AECO interoperability technologies have been developed internationally, however this thesis will focus on those developed by buildingSMART International (bSI), formerly the International Alliance for Interoperability (IAI).

The central technology developed by bSI is IFC (Industry Foundation Classes¹⁸), a middle-ware common data schema used to represent the data engendered by digital technologies such as BIM. The IFC schema is meant to facilitate the exchange of information within digital technology workflows, however a common use in practice has been its requirement as a deliverable for its informal use as an archive format.

¹⁶ (Torma, n.d.)

¹⁷ (Torma, n.d.)

¹⁸ (buildingSMART International 2016b)

This chapter identifies and discusses the key benefits and gaps in interoperable technologies and approaches; namely IFC (along with BCF and MVD) and the centralized model approach.

The Argument for Linked-D

Though integration methods have thus far solved many of the information exchange challenges between tasks and workflows, the myriad of solutions presently used in the process are instantaneous in nature and still require human interpretation, manual work and repetitive sub-tasks for the transformation of information at process-initiation and conclusion. This inefficient and tedious implementation of data-sharing in practice comes from the nature of information conversion itself. As identified in the previous chapters, existing approaches are struggling with maintaining two, presently conflicting, objectives; the semantic richness, and therefore usability (or quality) of the information engendered from the process, and the efficiency with which the process is performed.

Some efforts, such as ifcOWL¹⁹ are working to address the issue of ongoing and real-time (vs. instantaneous) information exchange, while maintaining semantic richness or quality. The issue that this work aims to identify is that this solution is largely created, documented and interpreted from a computer- and developer-perspective, rather than from a community- or discipline- authenticated perspective.

¹⁹ (Beetz, van Leeuwen, and de Vries 2009; Pauwels, De Meyer, and Van Campenhout 2010)

Conclusion

With the evolution of thinking within this thesis came the identification of a key gap in the interoperability and integration of information in the AECO Industry. As concluded earlier, the largest gap in digital technologies for the architectural discipline remains the logic used to define information, and the attention paid to documentation of important processes. Semantically speaking, meaning, relationships and definitions have been derived largely by a un-verified human-computer interpretation. Languages like EXPRESS, OWL, XML and SPARQL remain incomprehensible for the average architect and as such, require a platform from which to view and validate the captured information. If these languages remain illegible to the architects who are creating them inadvertently through a user interface for use in a shared data environment, is the architect simply a user of information rather than a creator? In this chapter, I have worked to understand the various languages and reasoning logic used for these formats. If the originating software is the geometric visualization of the information generated by AECO Industry processes, and the exchange formats are the computer-readable capture of that information, where is the open platform for human interpretation (based on common disciplinary knowledge maturity)?

The Mutating Architect

“Across all practices and disciplines [] a rich ecology of technology threatens to overwhelm at the same time that it exhilarates and empowers.”²⁰

As an infamously autonomous discipline and echelon of persons of great intellect and inspiration, Architects have historically applied their talents in a cross-disciplinary fashion. However, many contemporary Architects maintain a seemingly self-directed and dictated relationship with Information Technology. Interest in the products and possible objects — rather than the entirety of their engenderment — has left many in the position of a “user” rather than a “creator”. This has become an ongoing struggle for the discipline of architecture.²¹

As architects, we thrive on creative processes. Most of all, we thrive on creative authority. However, in the context of digital tools for the AECO industry, this creative authority is no longer ours.

On the one hand, there are those leaps and bounds in the creative process being made by experimental research in both academia and industry²². Though the products and objects generated by these innovative processes are creative in the extreme, doesn't the “use” of technologies created by others still categorize these brave experimentalists as users? Whether creatively exploring the frontier of digital technologies or using a standardized product as instructed, architects are restricted by the technologies conceived by others. This is a fundamental challenge to the adoption of digital technologies in architectural design. I argue

²⁰ (Burke and Tierney 2007)

²¹ (Moe and Smith 2012)

²²

that architects have the potential to work around this challenge through an understanding of logic- and language-based semantics and data-structure for shared conceptualization.

In the context of digital technologies, semantics can be considered in three ways;

1. in the logic defining the computer interpretation of information (as seen in computer languages like C++);
2. in the logic defining language in human interpretation (as seen in the meanings and definitions of words, expressions etc.);
3. as the combination of both human and computer interpretation (as seen in semantic web technologies).

For the purposes of this thesis, semantic will be used in consideration of this third meaning.

Within each integration and interoperability strategy, one of the largest challenges has manifested as the consequences of forcing information from one data-structure to another in a restrictive, standardized way²³. These restrictive but neutral data-structures are often generated from a generalized industry purview, and by nature, restrict the ability to exchange or manipulate the important semantic information generated by many specialty processes.

In light of this challenge, several international researchers have begun to identify the importance of this discipline- and community- specific semantic information

²³ (Torma, n.d.)

and discuss the methods that might be used to capture it during that most vital exchange process²⁴.

To propose a first step in crossing the void between the traditional skills and methodologies of architecture and those required to take a more active role in the development of our own disciplinary tools, the focus of this thesis is on the building blocks of any digital tool; information management and knowledge structuring.

Regardless of which tool an architect uses, the structure and semantic definitions that translate data to usable information is ever present. These structures and semantics vary greatly from one tool to another, and most have been created by principles and sensibilities only superficially familiar with architectural practice. There are many architects who have chosen to work with software development for exactly this reason, and in order to provide a valuable conduit through which to translate architectural end-user needs and methodologies to software development. One such Architect, Jeff Ouellette, had this to say regarding the state of this relationship between the architectural discipline and software development:

Jeff Ouellette
Vectorworks

“Architects typically aren’t informed consumers. The AECO Industry is restricted to software, processes and functionalities that are dictated mostly by the impetus to compete between vendors; the process for architecture as a discipline to get the functionality and capability that they need from their software or workflow is extremely slow, simply because [as a whole,] architects don’t know how to ask for, or demand, what they need. To me, this is one of the

²⁴ (Torma, n.d.; Pauwels, Zhang, and Lee 2017; Rezgui et al. 2011)

fundamental issues with digital technologies in the AECO Industry. The products are being designed by developers based on what they **think** is needed, and for the most part, this results in a slower up-take in the technological advancement of the industry than you've seen in others.”²⁵

Among many efforts to synthesize a common data-structure for the industry, this work focuses on one in particular: the Industry Foundation Classification schema in EXPRESS format, using STEP technologies, also known as IFC, and its translation to semantic web technologies.

²⁵ (Ouellette, n.d.)

The Question of Digital Work Flow

The need for interoperability is widely recognized by industry²⁶. The Industry Alliance for Interoperability (IAI), now buildingSMART International, has been developing an industry tool since 1994. Originally pulling together 12 industry partners from the United States, the IAI developed a solution for interoperability on two key principles: definitions and relationships²⁷. The Alliance called their solution Industry Foundation Classification (IFC) and employed industry stakeholders from all 12 constituent companies to define and relate the terms of their interoperability solution.

IFC has now developed to its 4th iteration using STEP technology and EXPRESS format. While this data-structure had done much to increase the ability for software and participants in the industry to speak with one another, interoperability remains one of the biggest challenges facing the AEC industry today. With increasing process capabilities, the sheer volume and variety of information requiring exchange in workflow and for delivery has steadily increased. Research and development has continued to struggle with implementing a standardized data-structure amidst the veritable jungle of software-proprietary native structures. Some have concluded that the single data-model to standardize them all is simply too restrictive and inflexible of a solution.²⁸

²⁶ (buildingSMART International 2016a)

²⁷ (1994)

²⁸ (Rezgui et al. 2011; Pauwels, De Meyer, and Van Campenhout 2010)

In order to discuss the challenges and recent research developing around interoperability, it is important to understand the context. Data exchange in the early 2000's was only possible through custom-built translators specific to applications or through manual translation — where the receiver of the information rebuilds the structure in the receiving application²⁹. Definitions of objects, products and terms, as well as their relationships, each to the others, were requiring constant translation between structures and languages.

As a neutral and open data schema, IFC was developed to address this need for an exchangeable format that would reduce excessive translation and allow for a standardized communication of information from one format to another. The IFC format has its limits, however. While it does provide a method for truly neutral exchange, it does still require software vendor buy-in, industry up-take, and knowledgeable users for expansion or efficient use. It requires clear guidance and documentation for its specific purposes and use-cases, relying on the accurate understanding of the users exporting and importing it for the completeness and accuracy of its data.

Thus, before the importance of IFC and interoperability can be addressed, it is important to summarize the fundamental need based on a brief analysis of high level contemporary workflows in the AEC Industry. Discussed internationally, model use-cases represent the many purposes that building information, engendered during the lifecycle of a building, can be leveraged to serve. The buildingSMART alliance®, a council of the National Institute of Building Sciences (NIBS), has been working since the mid-2000's on a structure

²⁹ (Venugopal et al. 2012)

describing the many range of projects defining the collective use of information pertaining to the built environment.

Defining the industry as four essential aspects of the life-cycle of the building (summarized in Figure 1: Summary of the National Institute for Building Science's BIM Tetralogy, © buildingSMART Alliance., many model use-cases have been described under the categories of design, procurement, assembly and operation (which form the constituent components of the buildingSMART logo). Many of these use-cases are more feasibly envisioned as spanning multiple phases and elements of information management during the building life-cycle.

Figure 1: Summary of the National Institute for Building Science's BIM Tetralogy, © buildingSMART Alliance.

In any given building's lifecycle are a myriad of projects, and in each project, is a myriad of workflows whose best results are achieved in collaboration, each with the others. Within each workflow are again a myriad of design and authoring tools, whose best results are also achieved in collaboration, each with the others.

If each tool allows for the creation of a partial dataset or model that represents its particular contribution to the project overall, a disciplinary workflow is commonly misunderstood as the *singular* exchange between a collection of constituent parts and the authority collecting those parts (see Figure 2: Common (mis)understanding of Model exchange workflow).

Figure 2: Common (mis)understanding of Model exchange workflow.

In other terms, many believe that a digital information workflow is linear, and that the exchange of information, as dictated in the formation of the deliverable product, or in the delivery of the finished product itself, is a singular occurrence. Neither of these assumptions are at all accurate. A true information workflow, enabled by — or realized only by — an open and neutral format for the exchange, might look more similar to Figure 3: More accurate depiction of data exchange and delivery..

In this graphic representation of the workflow, each node represents a constituent part of the workflow, or of the final product. The lines represent the necessary information exchanges between workflow or disciplinary players. It is

important to note that these exchanges are necessary between most, if not all, the nodes and that they are often bi-directional for purposes of change-management and issue detection.

The nature of the information exchange is therefore repetitive, off-line and requires an equally repetitive process of export/import translation. This constant requirement for translation to-, and from-, neutral and open formats like IFC is exactly the premise upon which several collaboration solutions have been developed.

Currently, there are several such solutions. Firstly, as seen in Figure 3, is the point-to-point exchange. This method is most-effective for small information-scale projects, where the total number of exchanges is limited to a manageable number.

Figure 3: More accurate depiction of data exchange and delivery.

Secondly, as seen in Figure 4, is a centralized data repository approach. This method of collaboration is most-effective for delivery teams that can work in an integrated environment, where exchanges can be reduced in number by direct communication between the many workflow contributors, eliminating the need for participant to participant exchange for change- and issue-management. A centralized repository can be implemented on a secure and closed network, or via a cloud solution.

Figure 4: Example of a centralized data repository.

Neither of these methods address the restrictions that information exchange places on simultaneous workflows. The file can only be sent, or synced, once completed and exported/imported. This is the fundamental challenge for collaboration and information exchange in contemporary digital AECO workflows. However, before the solution can be discussed, it is important to understand how instances (data, object or model) are related.

The Question of Digital Information Exchange

While reviewing material for this thesis, many sources were found to be voicing concerns about the reiterative and repetitive exchange process necessary for IFC data models³⁰. The concept of working from one central building information model is becoming increasingly popular and efforts to find a solution to the challenge of efficient interoperability has been an ongoing discussion for world leaders in the research and development in the digital built environment³¹.

In many of the existing frameworks that exist for project delivery, this commonly idealized concept of the “central” model would prove to be a very difficult proposition; issues pertaining to risk, liability and process engineering would arise alongside the many other more technical issues like hardware and protocols.

A common challenge in any project using digital technologies for a deliverable is the change request. To give an example, an architecture team has delivered the conceptual model to other participants for an owner’s new commercial building. This conceptual model included objects or open-space volumes for purposes of replacement with objects developed by the designated authority (structure by the structural engineer, services by the mechanical/electrical engineer etc.). The owner decides, part way through the process, that he/she would in fact prefer an atrium space at the building’s core after all. This changes triggers the reiteration of the exchange process across all the design stage workflows.

³⁰ (Pauwels, De Meyer, and Van Campenhout 2010; Van Berlo et al. 2012; Rezgui et al. 2011; Torma, n.d.)

³¹ (Van Berlo et al. 2012)

Some delivery frameworks would require that the entirety of the conceptual model be changed and delivered again. Other more advanced processes have enabled interoperable middle-wares like the BIM Collaboration Format (BCF)³² and the Model View Definition (MVD)³³ to capture and exchange smaller defined data-sets between project members. These frameworks that define exchange processes and requirements are called Information Delivery Manuals (IDM's)³⁴.

Thus, if the delivery of a digital design and construction project is characterized by the contracting of many different companies, firms and authorities, the ability to work efficiently is extremely important. This ability to work efficiently is directly correlated to collaboration and data-sharing capabilities of the multi-disciplinary team.³⁵ However, this point of convergence for all information flowing during a building's lifecycle combines the semantics and syntaxes of several disciplinary interpretations, and is the breeding ground for misunderstanding. For example, a common misunderstanding of the centralized model, arises from the meaning of the term 'model' itself³⁶. Because this term combines several disciplinary interpretations, it is crucial to maintain a correct understanding and control over this interpretation.

On the one hand is the interpretation of the 'centralized model' approach in which a single ***building model*** is kept at the center of the process and maintained by an over-seeing authority. In this approach, every participant and

³² (buildingSMART International 2016c)

³³ (buildingSMART International 2016e)

³⁴ (buildingSMART International 2016d)

³⁵ (Isikdag and Underwood 2010)

³⁶ (Pauwels, De Meyer, and Van Campenhout 2010)

therefore every application, should rely on this central building model to achieve the interoperability of information and efficiency desired throughout the design and construction process. After several years of implementation and development, however, it has been indicated that this approach merely improves the communication process by supplying the means to construct a building information model, but does not improve the interoperability of this information between the many other applications used for analysis, calculation and visualization³⁷. This building model and its limited interoperability with these other applications is precisely the objective of IFC.

By converting a BIM model to IFC, this highly sought after interoperability is meant to be available between all participants. However, many issues remain within IFC implementation. Information translated between native and IFC formats risks distortion and loss. In addition, IFC format remains essentially an exchange format. It is not easily manipulated by the many end-using participants in the design and construction process. Though several applications have been developed in recent years to address this manipulation of the IFC schema, the common user, and in the case of this thesis, the Architect, does not have the technical knowledge of data-sharing necessary to implement an open and non-proprietary process within which the centralized model can be used as envisioned.

³⁷ (Pauwels, De Meyer, and Van Campenhout 2010)

It has been argued that poor data-sharing practices have been the result of a fundamental gap in the industry.³⁸ Between the two players in the development of tools for the domain of the digital built environment, Developers and users, the knowledge and understanding of data-sharing is mostly one-sided and reliant on the Developer. Data distortion and loss is an inherent part of the semantic and syntactic differences between the many data structures of the digital domain³⁹. For the common architect, this fundamental flaw in the process is an invisible barrier that prevents interoperability between those same applications and data structures. The common architect does not know the exact mapping of his/her information from one schema (application) to another; to make matters worse, the common workflow requires that *many* schemas (applications) be mapped, each to the others.

For this reason, despite the many benefits that have resulted from both BIM and IFC, neither should be considered the final destination in the quest for highly efficient collaboration and data-sharing. Both technologies have strength in the process; BIM has enabled a multitude of disciplines to visualize a building design in 3D, while IFC has provided a neutral and open data structure for the purposes of mapping exchanges between BIM environments. However, since the birth of both technologies in the 1990's, many more computer-aided tasks and workflows have been developed for the built environment that make exchange much more complex. As a result, IFC models are typically exchanged just like any other

³⁸ (Rezgui et al. 2011)

³⁹ (Pauwels, De Meyer, and Van Campenhout 2010)

model in the design and construction process, leaving the same challenge as seen in the ***building model*** approach of multiple models being managed in parallel.

This leads us to the other interpretation of the centralized model; in the ***data model*** approach, the IFC schema is implemented as a central database. Though this solution is currently under investigation and faces its own array of challenges, it is already proving to be a successful alternative to the combined BIM and IFC model approach.⁴⁰

⁴⁰ (Beetz, van Leeuwen, and de Vries 2009)

The Argument for Linked-Data

Of the many interoperability strategies that exist, the apparent central concern is an effective and parallel workflow. Among these presently existing strategies for interoperability is the proposed shift towards semantic web data and knowledge sharing. Key motivators for this shift have been identified by Pauwels et al.⁴¹ as the following:

- 1) a desire to overcome the interoperability issue among software tools used in diverse disciplines, or at least improve information exchange processes;
- 2) a desire to connect to various domains of application that have opportunities to identify untapped valuable resources closely linked to the information already obtained in the AEC domains; and/or
- 3) a desire to exploit the logical basis of these technologies, which is currently undisclosed in the AEC domains.

These motivators identify two key concepts; the desire for more flexible and disciplinary-specific information and knowledge sharing, and the desire for the mapping of the various structures and interpretations that exist in the varied AECO communities and technologies. This second desire is tantamount to the argument of this thesis, for the simple reason that no single all-encompassing data-structure could hope to address the sheer volume and variety of the software — and discipline — specific structures that presently exist.

⁴¹ (Pauwels, Zhang, and Lee 2017)

Shared conceptualization, or an **ontology**⁴², of this rich semantic tradition could represent an extremely advantageous addition to the entirety of the building lifecycle. In his article “Architecture’s Next Ontological Innovation,” Patrik Schumacher discusses the intersections between recent technological innovations in architecture and philosophy. He believes that:

The “truth” (pragmatic efficacy) of an ontology cannot be universally asserted, but only evaluated discipline by discipline.⁴³

As a discipline based in both an interpretive philosophical and engineering-based scientific methodology, Rezgui et al.⁴⁴ identify their definition of what such an ontology approach should be like.

In such an approach, we try to interpret, accommodate and model what is, rather than trying to change reality to fit a single model. This inevitably results in different ontologies for different communities, but the challenge then is to find ways to allow those communities to collaborate effectively with one another whilst maintaining their existing, efficient, effective separate world- views. The implication is that we are forced to shift our emphasis from developing a standard representation of a single “reality”, towards providing mechanisms for supporting communication between differing perceptions of reality, focusing our attention on the overlaps at the boundaries and the specific conceptualizations that are required for such communication to happen.

⁴² The definition for ontology is essentially a dichotomous one; firstly it is the branch of metaphysics dealing with the nature of ‘being’, and secondly it is a set of concepts and categories in a subject area or domain that shows their properties and the relations between them. For the purposes of this thesis, an ontology is defined as the shared conceptualization of ‘being’ that is organized in a set of concepts and categories (or classes) that shows their meanings (or properties) and the relations between them (or links).

⁴³ (Schumacher 2012)

⁴⁴ (Rezgui et al. 2011)

These varied, and sometimes differing, perceptions of reality have given rise to equally varied and differing data structures. Thus, in such an approach, Rezgui et al. are calling for a network of community — or disciplinary — knowledge mapping that would capture the variety of data-structures in such a way as to create parallel, but individual, ‘links’. This ‘linking’ of data would effectively maintain the characteristics of any native data-structure, while permitting the ongoing linkage of specific instances to other such structures. To put it plainly, a single instance could exist simultaneously in a wide variety of data-structures.

Semantic Web Technologies

The application of semantic web technologies can be understood in two ways⁴⁵:

1. the translation of human-readable documents and objects to contain more machine-oriented semantic information; and
2. the translation of machine-oriented information to a human-readable structure that captures human-defined semantic relationships for documents and objects.

It is this approach that has seen usage of semantic web technologies notably increase in the AECO Industry since its advent as a concept for the web in 1999, and since its first proposals to transform EXRESS schemas into ontologies for the domain sometime in the early 2000’s.⁴⁶ Though recently embraced by buildingSMART International, this solution remains widely misunderstood by industry practitioners. Its fundamental premise is interoperability through inter-domain linkage and logical inference; meaning interoperability through a common data structure built up of- and leveraging- meshed links to native data-

⁴⁵ (Bizer, Heath, and Berners-Lee 2009)

⁴⁶ (Pauwels, Zhang, and Lee 2017)

structures, permitting both advanced- and native- logic and reasoning. Before discussing its adoption in the AEC industry, however, it is important to define what is meant by ‘semantic’ and ‘semantic web’ technologies.

The word ‘semantic’ is defined as: of, relating to, or arising from, the different meanings of words or other symbols.⁴⁷ With regards to technology, the word ‘semantic’ is best compared to an abstraction layer above existing data, objects and values and connects it to other content and processes; it represents a computer-readable meaning derived from mathematically represented relationships and reasoners.⁴⁸ When then applying ‘semantic technology’ to the web, the term is best defined as using the web to create links (URI’s) between data from many different sources to pull it into one loaded space. These data-sets or links may be as diverse as databases maintained by two organizations (such as buildingSMART International and the Getty Research Institute, as introduced later) or simply linking two heterogeneous data-sets in a single system that historically have not interoperated easily in the past (such as differing design authoring BIM softwares)⁴⁹. Ontologies (the published form of semantic web technologies, usually in RDF format) are vital components of linked data and allow for the visualization, manipulation, advanced querying and publication of data-structures.

In the case of buildingSMART’s ifcOWL interpretation, such a common data structure could be achievable by translating the EXPRESS schema into semantic web technology notations such as the web ontology language (OWL), whereby

⁴⁷ (Random House Dictionary 2016)

⁴⁸ (Noy and McGuinness 2001)

⁴⁹ (Bizer, Heath, and Berners-Lee 2009)

additional structures could be linked to process data in a parallel and automated fashion among many structures. As seen in the IFC4_ADD1.ttl file appended to this thesis submission, the IFC4 structure has been automatically generated from the EXPRESS schema using the IFC-to-RDF converter developed by one of the ontology's creators.⁵⁰ This process was described at length in an article similarly written by Pauwels and Terkaj for the purposes of recommending and using his converter for an ontology endorsed as a buildingSMART International standard.⁵¹

With the adoption process begun, issues pertaining to reiterative IFC exchanges, and parallel workflow synchronization are addressed by Pauwels et al. What remains to be seen, however, is an understanding of how such an ontology could be used to bring together the various specialized and semantically-rich data-structures of the many disciplines within the AEC Industry. A common complaint in buildingSMART International circles, especially within the International User Group (IUG) forums, the significant absence of both IFC and ifcOWL documentation is both concerning and counter-productive, reinforcing this thesis in its earlier conclusion that general professionals of many disciplines are meeting with a barrier to adoption and process-evolution that represents a gap between developer and user logic.

After a significant literature review, several reasons for the implementation of an ontology have been identified (though do not represent an exhaustive list, as the technology is still evolving):⁵²

⁵⁰ (Pauwels and Terkaj, n.d.)

⁵¹ (Pauwels and Terkaj 2016)

⁵² (Noy and McGuinness 2001)

1. To share common understanding of the structure of information among people or software agents;
2. To enable reuse of domain knowledge;
3. To make domain assumptions explicit;
4. To separate domain knowledge from other [functional and] operation[al] knowledge; and
5. To analyze domain knowledge.

It is important to note that these reasons and benefits should exist simultaneously for both developer and user groups, facilitating rigorous communication and authentication each for the other.

Of the myriad of ontologies that have been developed in recent years, perhaps the most pertinent is the *Getty Vocabularies Program Ontology*⁵³. In this project, the Getty Research Institute is “making data about art, architecture, and other cultural heritage objects available as Linked Open Data (LOD). This applies to the metadata about the objects, their creators, patrons, associated places, style, work type, and other terminology concerning their description, history, scholarly research, and conservation.”⁵⁴

For research and discussions pertaining to culture and heritage, this ontology is extremely valuable. An important distinction to make regarding its application to the domain of architecture, however, is that this ontology is developed surrounding historic and contemporary styles, names, and dates. This ontology might be selectively used by heritage architects, for example, in their efforts to both record, impart and conserve important historic information pertaining to a

⁵³ (The Getty Research Institute/OnoText Corporation 2014)

⁵⁴ (The Getty Research Institute 2016)

specific project or site. Vice versa, if the Architect then further enriches the data with further discoveries, results or research, the Getty Institute could similarly use this enrichment or evolution of their data and re-integrate it with their database. While such an ontology is certainly important in examples such as heritage conservation, it does not necessarily describe the information that a new build architect would consider important in the larger AECO Industry context.

In short, an ontology could provide invaluable links to content readily available (and rigorously authenticated) to describe architectural information like style and terminology; as such, this thesis recommends that a future development of such a practice-focused architecture ontology should link to — and load — the research and data-sets developed by the Getty Research Institute. For a more detailed example of how semantic web technologies might be implemented on a hypothetical project, see the end of this chapter.

Components of Ontologies

To discuss the benefits, possibilities and flexibilities that ontologies would afford the AECO Industry, it is important to break down the structure of the semantic web technology in question. In this section the specific notation and components of the Web Ontology Language (OWL) implemented in the *Protégé 4* application⁵⁵ developed at Stanford University is the platform chosen for this thesis.

⁵⁵ (Stanford Center for Biomedical Informatics Research, n.d.)

Classes

OWL classes are:

1. Interpreted as sets that contain individuals/instances;
2. Described using mathematical descriptions that clearly state requirements for classification in the set;
3. Organized into super- and sub- class hierarchies (also known as taxonomies); and
4. Defined in relation to other classes (super- or sub-).

Classification, and in the case of an ontology, the first layer of structure, captures groups of instances for the purposes of defining ‘things’. Classes could also be referred to as concepts, whereby a concept is named, defined and contains individuals or instances that are inherently included by relationship to this class/concept.

In Figures 5, 6 and 7, the visualization shows the class hierarchy of the ontology in question. It is important to note that all classes belong to larger super-class ‘Thing’. This is an important distinction made in the logic of the ontology that allows for the queries, descriptions and relationships to be defined with descriptors like “any-thing like” or “some-thing that”.

Below is a very high-level visualization of the classifications made by bSI’s IFC schema. Within this visualization, it can be quickly observed that this classification system is based in computer science knowledge. For an unfamiliar viewer (of the architectural discipline, for example), the structure is neither

intuitive nor easily navigable. Naming, relationships and definitions are similarly counter-intuitive for a computer language illiterate viewer.

Figure 5: Visualization captured from a Protégé⁵⁶ window with IFC4_ADD1.ttl open.

In comparison, below is a high-level visualization of an ontology developed in collaboration with one of the ifcOWL creators, Pieter Pauwels, for the BIMGuides project under buildingSMART International’s International User Group. This data structure is reflective of a literature (rather than geometric or parametric)

⁵⁶ Protégé is a free, open-source ontology editor and framework for building intelligent systems. It is supported by a strong community of academic, government, and corporate users, who use Protégé to build knowledge-based solution in areas as diverse as biomedicine, e-commerce, and organizational modeling.

This work was conducted using the Protégé resource, which is supported by grant GM10331601 from the National Institute of General Medical Sciences of the United States National Institutes of Health. (Stanford Center for Biomedical Informatics Research, n.d.)

based dataset, but provides a much clearer idea for navigation of classifications and relationships. One might argue that the average end-user should never have to visualize their information and data-structures in this fashion. This thesis argues that quite the opposite should be true of the Architect. It is precisely this level of understanding that would facilitate the creation of a shared conceptualization and ontology (like Figures 5 and 6) for the architectural discipline and for use in the creation, distribution, collection and manipulation of architectural information.

Figure 6: Visualization captured from a Protégé window with *BIMGuides_Draft.ttl* open.

Below is a high-level representation of the Getty Research Institute's *Getty Vocabulary Program Ontology*. This ontology represents an interesting middle-ground between developer and user legibility. Several classes that are describing

data-sets that might never be necessary for a user are described in a less user-comprehensible naming logic. In comparison, other classes are quite clearly named using a significantly more user-friendly naming methodology.

Figure 7: Visualization captured from a Protégé window with *GVP_Ontology.ttl* open.

Properties

OWL properties are *binary* relations (one-to-one) on individuals/instances.

Properties can be visualized as the relationships between individuals/instances; they can take many forms, and for every form OWL has a property type.

Below is an example from each ontology referenced by this thesis. It is important to note that Protégé and OWL do not necessarily visualize properties in the same way. As such, though properties are discussed in this thesis as a single component of the ontology, and treated as such in the notation, the component is broken into three distinctive property tabs in Protégé (object, data and annotation properties). For the purposes of this thesis, only object properties will be discussed.

Figure 8: Visualization of Object Properties for the ifcOWL Ontology, and IFC4_ADD1.ttl file.

It is important to state that Figure 8 is an incomplete list of the properties described for ifcOWL, but sufficient for discussion purposes. It is again obvious that the ifcOWL ontology is not meant for development-illiterate users. This is troublesome, as the complexity is not proven to be necessary. In addition, no documentation is provided for the mapping and methodology of the schema definition, which has also proven to be a barrier to user up-take.⁵⁷

Figure 9: Visualization of Object Properties for the BIM Guides Project Ontology, and BIMGuides_Draft.ttl file.

At the other end of the spectrum for user-legibility is the ontology developed for bSI's *BIM Guides Project*. These definitions have been named with a logic and methodology that facilitates the human interpretation of the domain. This ontology is seen in Figure 9, above.

⁵⁷ (Beetz, van Leeuwen, and de Vries 2009)

Below is the ontology-case chosen as an example of the middle-ground in Figure 10; the *Getty Vocabulary Project (GVP) Ontology*. In this ontology, we see again an interesting blend of user- vs. developer- legibility in the naming methodology.

Figure 10: Visualization of Object Properties for the Getty Vocabulary Program Ontology, and file *GVP_Ontology.ttl*.

Individuals/Instances

Individuals or Instances represent the data-objects or values in the domain in which the ontology is described. At this level, the ontology is most useful.

Between the myriad of classifications and the described relationships existing

between individuals/instances, a wide variety of benefits could be possible, such as advanced query functions, visualizations and efficiently described values.⁵⁸

Below is an example of the bSI's BIM Guides Project Ontology –case, representing a trial run of work done experimenting with the translation of a data-set from an XML file. Here an individual/instance 'BIMGuide1' belongs to the class 'BIMGuide' and is described as seen below in Figure 11. Further experimentation in the project is expected to yield a result (in the specific case of this value) of an individual/instance 'Building and Construction Procurement Guide' belonging to the class 'BIMGuide' and described with replacements such as 'NATSPEC' (Institution1) and 'Free' (fee1).

⁵⁸ (Beetz, van Leeuwen, and de Vries 2009){Pauwels:2017hr}

Figure 11: Visualization of an Individual belonging to a Class and described by Properties in a Protégé window, from the BIM Guides Project Ontology and file BIMGuide_Draft.ttl.

Below is an example of the middle-ground ontology case, the GVP Ontology. Here the individual/instance ‘Vernacular’ belongs to the class ‘Concept’ and is described as seen below in Figure 12.

Figure 12: Visualization of an Individual belonging to a Class and described by Properties in a Protégé window, from the GVP Ontology and file GVP_Ontology.ttl.

A Proposed Approach

If viewed as a constantly evolving and maturing network of semantic perspectives and disciplinary voices as well as project information, the issue engendered by the “one-fits-all” central and standard structure will be avoided. Linked-Data allows for the rapid and flexible assembly of pertinent ontologies to provide a single resource or structure for the instigating purpose. Any given actor could elect from a variety of published data-sets from other project contributors or reusable sources such as:

1. Previous project examples from the actor’s own data-base;

2. Discipline-specific information for the project (mechanical, structural, design conceptualization, heritage conservation, geo-technical information etc.);
3. Administrative information (budgeting, scheduling, phasing, authority delegations, call-lists, clash detection, change tracking etc.);
4. Standardization information (code-compliance, planning requirements, performance requirements, commissioning etc.);
5. Simulation information (energy, light, seismic etc.); and
6. Consultation information.

Furthermore, these varied resources and structures can be updated in such situations as they are modified or matured by their various authors, thus preventing expiration of information or application. An important question when considering the necessary growth and evolution of available ontologies might perhaps be similar to the old adage ‘when is enough, enough or too much, too much’? With regards to AECO Industry applications, a simple solution that can be carried from existing workflows is the concept of phasing. However, the control of scope and the ability to find and select pertinent information is all a question of best-practices and standardization. It is important to remember that this thesis, and semantic web technology itself, does not recommend a single ‘one-fits-all’ ontology or source; rather the desired ontology or data-base for any given purpose should be assembled from myriad of unique and individual published sets available on the web. This solution is a tailored one, meant to work similar to a metaphorical shopping-cart; find, select, assemble and use.

To visualize what such an assemblage might look like, Bilal Succar describes his vision for such a network of ontologies and termed it the BIM Framework in his doctoral thesis, *Building Information Modelling: Conceptual Constructs and*

*Performance Improvement Tools*⁵⁹. Composed of five abstraction layers, each nesting into the next as seen in Figure 13, this vision represents a manifestation of a framework for the sharing of text-based information.

Figure 13: Succar's Vision of the BIM Framework, re-constructed from his Conceptual Hierarchy Figure (© Succar, 2014).

A digital built environment domain solution, however, would require the effective amalgamation and interoperability of several types of information. In order to do so, a more pertinent conceptualization of this network of ontologies might look more like Figure 14 when focused on the discipline of Architecture.

⁵⁹ (Succar 2013)

Figure 14: Proposed framework for an industry shared-conceptualization, focusing on Architecture (© Beange, 2016).

As we can see, the discipline of architecture would truly only contribute ontologies at the lowest two abstraction levels. Each level is defined by the sub-ontologies that it pulls together; in example, the BIM Guides Project- and GVP-ontologies would be acting at the Dictionary Level, as they collect definitions (text-based information) for concepts and terms, while ifcOWL would be acting at the Discipline and Use Levels, as it collects the information generated by the various disciplines, and can also house the finalized model.

In order to better understand this proposed implementation, an example as follows could be considered. In the case of the rehabilitation of a major central library, and considering all pertinent information that could be collected using this technology, the following figure represents shared information (up-load or down-load from published domains).

Figure 15 – Visualization of an assembled network of ontologies (or data-sets), © Wikimedia Commons 2015.

In this visualization, the network of ontologies is extremely complex, which when simplified might look more like Figure 16 below. In the example of a central library rehabilitation project, major information sources could include all of the example ontologies included in this thesis as well as many more. Cultural information supporting the heritage value of the building and site could be downloaded from the Getty Vocabulary Project, while geometries and parametrics could be downloaded from the project-specific ifcOWL ontology. A planning and standardization process could be established by downloading from

the BIM Guides Project ontology, and other important information could be feasibility downloaded from a discipline specific ontology like the one proposed by this thesis.

Figure 16 – Simplified visualization of a shared network of data-sets for any specified project.

Considering Figure 16, implementation for shared information might be as follows:

Administration	During the administration of the project, this actor may download pertinent requirements from a standards body, or legal processes from a previous project or guideline. They would upload communication records, meeting minutes, change requests/tracking, clash detection information and much more.
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Architect	In the case of the central library example, a firm might pull together the ready-made data-sets from the Heritage Conservation team, the Owner or Custodian requirement documentation and programmatic wishes, as well as from previous projects within its own archives for known details or specifications. A firm would also generate its own data based on its creative, or working processes.
Heritage	The heritage conservation actors, again in the case of the central library example, might pull together data-sets from sources like the Getty Vocabularies Project, Archives Canada, the library's own data, as well as generate its own data based on research and as-found recording.
Contractor	The contractor, in the example of the central library, would be pulling together data from administration regarding changes, the architect with regards to the verification of work or drawings, and the heritage conservation team with regards to new or experimental preservation techniques. The contractor would also generate their own data based on site-verification and change-tracking, as well as on-site decision verification.
Owner/Custodian	This actor would likely pull together information from stakeholder consultations, specialized disciplinary reports on the building and site's condition, perhaps the requirements

of an existing master plan and the conceptualizations brought forward by the architect. They would also generate their own data based on budgeting, scheduling and operational information, as well as perhaps act as the maintainer of the amalgamated final data-set.

In the case of the example given in Figure 16, the scope of included actors is small for reasons of scope in this thesis, however it is clear that real-time access to authenticated and verified information would be a very real asset for the interoperability of the process, and efficiency of project delivery.

Conclusion

Knowledge- management, engineering and solutions are not necessarily within the traditional repertoire of the professional architect. Though the research undertaken for this work has discovered that many architects have assumed a dichotomous role as both Architect and Developer, it is also true that the majority of professional architects are not necessarily prepared for the methods used to articulate their world-, and industry-, views for a digital domain for the built environment.

This leaves us with a vital question; how could such an articulation of a shared conceptualization take place? This thesis proposes that the creation of a prototype ontology for this purpose would be highly recommendable, but that it would also require the acknowledgement of the profession as a necessary addition to the polymathic tradition of Architecture. As such, first and foremost this thesis puts forward, and identifies, the ontology as a necessary step forward for the integration and effective interoperability of the architectural discipline in the digital domain of the built environment and AEC industry. As one possible part of a larger framework, ontologies built for the discipline of architecture would work in linked fashion to define the domain for computer and human alike.

Thus far, the question concerning the necessity of a shared conceptualization and multi-disciplinary conglomeration of data-structures has been addressed by identifying the various challenges presented by current interoperability solutions used in the AEC industry. Parallel research has resulted in similar conclusions

and additional technical experimentation, as identified in Venugopal et al.'s work⁶⁰ and that of Rezgui et al.⁶¹

With the advent of Linked-Data for the AEC industry, discipline- and specialization- specific ontologies will be extremely important to address the issues pertaining to synchronous and parallel work in the digital workflows and processes of the industry. However, the gap that such a network would fill is entirely reliant upon the ability of the varied disciplines and communities to each articulate the definitions and relationships inherent in their unique semantic perspectives. This ability to articulate semantic nuances will in turn rely on the familiarity of each respective discipline or community of practice with the formal methodologies of shared conceptualization authorship.

⁶⁰ (Venugopal, Eastman, and Teizer 2015)

⁶¹ (Rezgui et al. 2011)

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