

# Foundational Research in Integrated Building Internet of Things (IoT) Data Standards

Towards a Scalable Data Acquisition Framework for the Smart Built Environment, i.e., Smart Buildings, Smart Communities and Smart Cities, that enables the utilization of the data housed in separate building systems for IoT innovative use cases

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Center for the Development and Application of Internet of Things Technologies (CDAIT)  
IoT Research Working Group

# ***Foreword***

*This research was reviewed, selected, and monitored by the Internet of Things (IoT) Research Working Group of the Georgia Institute of Technology (Georgia Tech) Center for the Development and Application of Internet of Things Technologies (CDAIT) (<https://cdait.gatech.edu>). It aims to fill an important gap in the IoT ecosystem. The Working Group is led by Kenji Takeuchi (Honeywell), Chair; Saud Khader (Verizon) and Jay Sexton (Georgia Tech), Vice Chairs. Other Working Group members are listed at the end of this report.*

*The report recognizes that while a vast amount of IoT data originates in a building environment, it is often overlooked. As a result, lack of inter-system connectivity is bound to impede the effective and efficient expansion of IoT.*

*In short, this work is about fostering data interoperability between building systems.*

*It is an important component of broader research efforts currently underway at the Georgia Tech Digital Building Laboratory whose goal is “Advancing Construction Through Digital Technology” (<https://dbl.gatech.edu/>).*

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*This research provides a helpful in-depth complement to the White Paper on IoT-Facilitated Citizen/User Engagement released by CDAIT in July 2018 that used Smart Cities as a use case for the deployment of IoT technologies (see [https://cdait.gatech.edu/sites/default/files/georgia\\_tech\\_cdait\\_thought\\_leadership\\_working\\_group\\_white\\_paper\\_july\\_9\\_2018\\_final.pdf](https://cdait.gatech.edu/sites/default/files/georgia_tech_cdait_thought_leadership_working_group_white_paper_july_9_2018_final.pdf)).*

*The views expressed in this Research Report are solely the authors’ collective own and do not necessarily represent those of Georgia Tech, the CDAIT company members, the individual members of the IoT Research Working Group, the University System of Georgia, or the State of Georgia.*

# **Foundational Research in Integrated Building**

## **Internet of Things (IoT) Data Standards**

### **Research Report**

Submitted to Center for the Development and Application  
of Internet of Things Technologies (CDAIT)

September 2018

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## Project Summary

This research systematically investigates how to achieve data interoperability between building systems and the Internet of Things (IoT). Even though the built environment is a critical component of the IoT paradigm, it is frequently overlooked. One major reason is that building systems lack inter-system connectivity or exposure to the larger networks of IoT devices. With the networks of sophisticated sensors and devices, building systems have the potential to serve as the infrastructure that provides essential data for IoT, and as the actuators that execute intelligent controls. Building Information Modeling (BIM) offers a clear potential as the “digital twin” of the built environment – one that can provide significantly enhanced spatial context for distributed IoT systems. A strategy for connecting emerging IoT data standards with the relatively mature building information standards can a) potentially advance a more consolidated approach to aspects of IoT device geo-positioning and metadata tagging, b) provide a critical layer of spatial semantics to IoT systems and c) enrich intelligent building efforts while harmonizing these data sources with emerging IoT protocols.

This research aims to develop a strategy and preliminary framework for building level IoT semantic models and open data strategies. Components of this approach will include:

- 1) **Collection, analysis, and taxonomy of existing standards.** This work collects, analyzes and compares existing data schemas and open standards for BIM, sensor networks, and smart building/building controls systems, as well as more general IoT networks and potentially adjacent (smart city) standards.
- 2) **Identify use cases.** Industry partners and organizations with interest in Building-IoT are identified. This research solicits and organizes these constituents' requirements, use cases, data needs and existing strategies for integrated intelligent building and facilities.
- 3) **Framework and Pilot Proposals.** We propose a scalable data acquisition framework for the smart built environment – Smart Buildings, Smart Communities, and Smart Cities – that enables the utilization of the data housed in separate building systems for innovative IoT use cases. An architecture of IoT-enabled Smart Cities based on this data acquisition framework is also demonstrated. A pilot project is proposed to demonstrate the method for establishing the federated data framework and prove its feasibility.

In this report, Section 2 introduces the background related to Cyber-Physical Systems (CPS), IoT-enabled Smart City, and BIM. Section 3 discusses building and city data standards. Section 4 summarizes IoT data standards and protocols. In Section 5, we propose a data acquisition framework for the smart built environment – Smart Buildings, Smart Communities, and Smart Cities – that enables the utilization of the data housed in separate building systems for innovative IoT use cases, by understanding IoT stakeholders' common data needs from buildings and identifying the overlaps between the data protocols used by different building systems. Section 6 introduces the method we proposed to integrate the IoT protocol BACnet and the BIM data standard IFC. Section 7 presents the potential use cases enabled by the proposed IoT-enabled data framework for the smart built environment. Section 8 introduces an ongoing study – using the data in building systems to predict a facility's life cycle cost through machine learning, which is based on the findings and data integration methods proposed in this research.

## 1. Introduction

According to the United Nations, the world's urban population is projected to grow by 2.5 billion from 2014 to 2050, and will account for 66 percent of the total global population by then [1]. The growing population in cities increases the demand for the fundamental needs of people living there, such as housing, utilities, medical care, welfare, education and employment [2]. To deal with challenges faced during the growth of cities, the concept of Smart City has been envisioned, which denotes “the effective integration of physical, digital and human systems in the built environment to deliver a sustainable, prosperous and inclusive future for its citizens” [3]. As the cells of smart cities, Smart Buildings are buildings which integrate intelligence, enterprise, control, and materials and construction as an entire building system to meet the drivers for building progression: energy efficiency, longevity, comfort, and satisfaction [4]. In both the contexts of smart cities and smart buildings, the “smart” refers to the development, integration, and utilization of intelligent systems based on Information and Communication Technologies (ICT) and, more specifically, the Cyber-physical Systems (CPS) [5].

The built environment is a critical – but frequently overlooked – component of the Internet of Things (IoT) paradigm. Buildings – along with cities and vehicular / transit systems – comprise the platform into which ubiquitous computing and IoT systems are embedded. Buildings represent highly structured spatial environments – organizational systems of connecting spaces and components – that can provide a strong semantic overlay on the organization and interaction between IoT devices and their environments. Buildings provide intrinsic organizational information about the communities, businesses and operations of the people, equipment and systems they house. Buildings systems already incorporate proprietary networks of sophisticated sensors and devices in the form of energy systems, security systems, and emerging smart home devices, albeit with limited inter-system connectivity or exposure to the larger networks of IoT devices. These smart building sensor networks represent potential platforms for the deployment of more generalized IoT networks, and are sources of occupancy and space that can provide significantly enhanced value to new IoT systems.

Building Information Modeling (BIM) is a maturing paradigm for the development of higher level semantic information assets for facilities [6]. For the past two decades, the building industries have been evolving from two-dimensional symbolic drawing documents to BIM: three-dimensional, metadata rich, object models representing building spaces, components and their relations. With the advancement of cloud data stores and now IoT, BIM models offer a clear potential as the “digital twin” of the built environment – one that can provide significantly enhanced spatial context for distributed IoT systems.



## 2. Background

### 2.1 The NIST Cyber-Physical Systems Framework

IoT is a novel concept with various potential applications that cannot be fully described yet. Besides IoT, there are many other words and phrases that describe similar or related intelligent systems, including machine-to-machine (M2M), industrial internet, smart city, digital city, etc. All of them can be represented by an umbrella term and concept "Cyber-physical Systems" (CPS). CPSs are highly interconnected and integrated smart systems that include engineered interacting networks of physical and computational components [7]. Typically, a CPS consists of the physical part – a device, a machine, or a building – and the digital or cyber part – the software system, communication network, and the data. The cyber part of CPS represents digitally the state of the physical part and impacts it by automated control or informing people of control actions. For example, if a modern car is looked at from a CPS perspective, the physical part consists of the car’s physical being, while the cyber part may involve the data from the sensors, the navigation system, and the radio system, which provide the driver required information while driving.

The National Institute of Standards and Technology (NIST) Engineering Laboratory is leading a program to advance Cyber-Physical Systems [5]. In this program, the NIST’s CPS Public Working Group has developed a CPS Framework that presents a set of high-level concepts, their relationships, and a vocabulary for clear communication among stakeholders (e.g. designers, engineers, users) [7]. The goal of the CPS Framework is “to provide a common language for describing interoperable CPS architectures in various domains so that these CPS can interoperate within and across domains and form systems of systems” (SoS) [7]. Figure 1 shows the CPS framework developed by the NIST’s CPS Public Working Group.

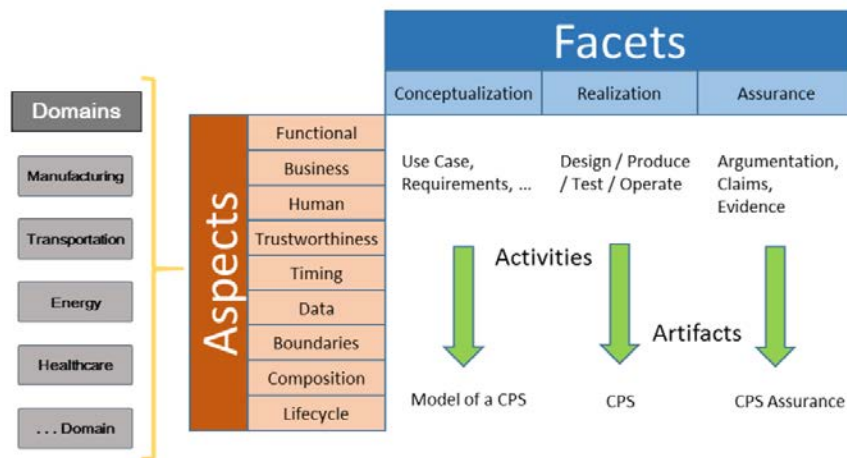


Figure 1. CPS Framework – Domains, Facets, Aspects [7]

The NIST CPS framework can be used as guidance in designing, building, and verifying CPS and as a tool for analyzing complex CPS [7]. It consists of three major components: domains, aspects, and facets. The domains are the industries that the CPS can be specialized and applied to, such as manufacturing, transportation, and energy. The aspects are high-level groupings of cross-cutting concerns of CPS, involving

functional, business, human, data, etc. Concerns are interests in a system relevant to one or more stakeholders. The facets are views on CPS encompassing identified responsibilities in the system engineering process. They contain well-defined activities and artifacts (outputs) for addressing concerns [7]. The three facets, conceptualization, realization, and assurance, deal with three major questions, respectively, which are 1) what things should be and what things are supposed to do, 2) how things should be made and operate, and 3) how to prove things work the way they should [7].

This research uses the NIST CPS framework to further investigate how to enable buildings to be “Smart” so that they can serve as the infrastructure that provides essential data for IoT. It is an effort in the realization facet, which addresses the CPS concerns of data aspects.

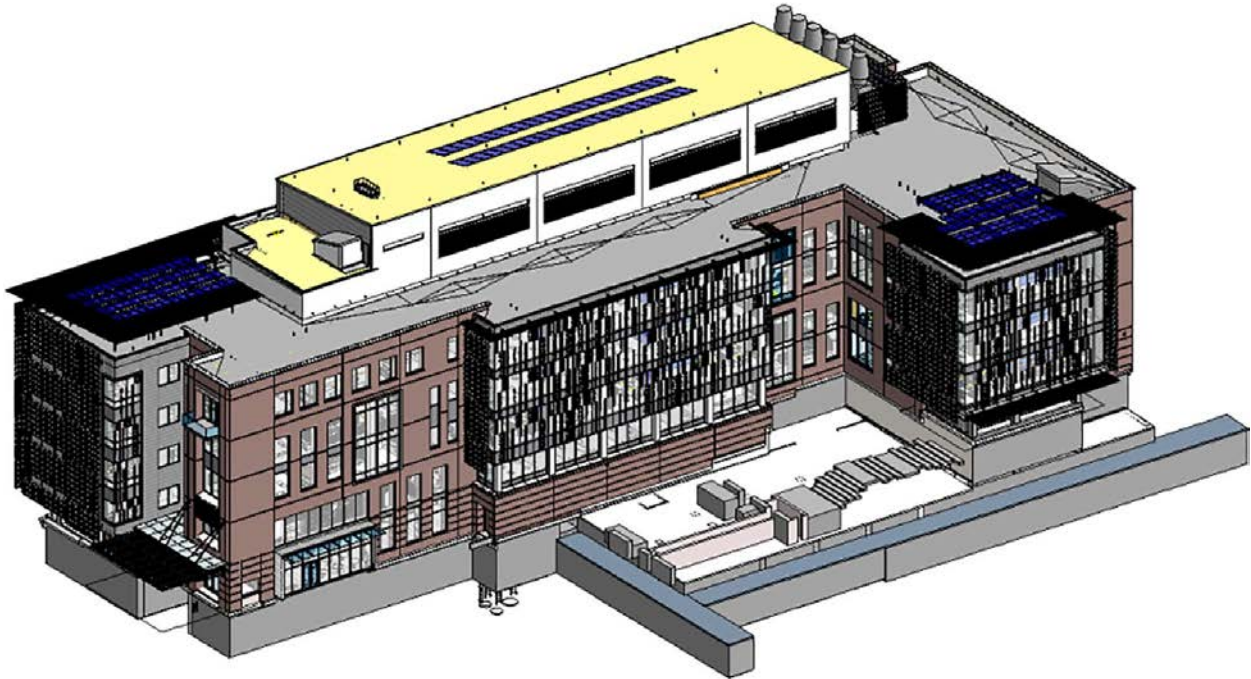
## **2.2 The IoT-Enabled Smart City Framework**

Effective smart city solutions are facing two major barriers. First, many current smart city ICT solutions are based on custom systems that are not interoperable, extensible, or cost-effective [8]. Second, many smart city standardization efforts, such as the ones carried out by ISO/IEC JTC1 [3], IEC [9], and IEEE[10], are currently underway but have not yet converged, creating uncertainty among stakeholders [8]. To reduce these barriers, NIST and its partners are convening an international public working group to develop a consensus framework of a common language/taxonomy and smart city architectural principles that can align existing smart city efforts that will support interoperable and portable smart applications. [8]. The framework is named “IoT-Enabled Smart City Framework” (IES-City Framework). It adopts the concepts defined in the NIST CPS framework (e.g. domains, aspects, concerns, and facets) and maps them to exemplary smart city deployments. For example, the sensor network deployed in a smart building is considered as the CPS system that addresses the *Communication* concern of the *Functional* aspect.

Currently, the IES-City Framework is still under developing but the list of requirements for the Smart City applications are identified [11]. This research fits in the framework and is an effort to address the Data aspect concerns in smart buildings, including the data semantics, the operations on data, and the relationship between data.

## **2.3 Building Information Modeling**

Building Information Modeling (BIM) is one major progress in the Architecture, Engineering, Construction, and Operations (AECO) industry [6]. BIM technology involves the creation and utilization of digital building models. It has various applications in building design, construction, and facilities management, including 3D visualization, design checking, various building performance analysis, constructability checking, improved facility operation and maintenance, etc. BIM, as the digital representation of buildings, can provide significantly enhanced spatial context for distributed CPS systems [12]. It also has the potential to integrate the data collected through the sensing devices deployed in the building and link to larger IoT networks. Figure 2 shows an example of a BIM model.



Properties

Lab Exhaust Fans 2  
Tri-Stack Exhaust Fan Unit

Mechanical Equipment (1) Edit Type

Constraints

Level	ROOF LOW POINT
Host	Level : ROOF LOW POI...
Offset	14' 6"

COBieDescription	High Induction Lab Ex...
COBieInstallationDate	
COBieSerialNumber	10843-03-1, 10843-03-2...
COBieTagNumber	F-R01A, F-R01B, F-R01C
COBieWarrantyStartD...	
COBieStatusCode	
COBieShop	
COBieLockout	
COBieWarrantyExpire...	
COBieLocationID	
COBieSystemName	
COBieModel	TS4L600-C12
COBieManufacturer	Strobic Air
COBieRegionCode	
COBieFacilityID	
COBieBuilding	
COBieAssetGroup	
COBieOmniClassNum...	23-33 31 19
COBieOmniClassTitel	Fans
COBieAssetType	HVAC
COBieDocument	
COBieContact	Bob Campbell (770 495...
COBieWarrantyGuara...	
COBieManual	<a href="http://www.strobica...">http://www.strobica...</a>

Electrical - Loads

Panel

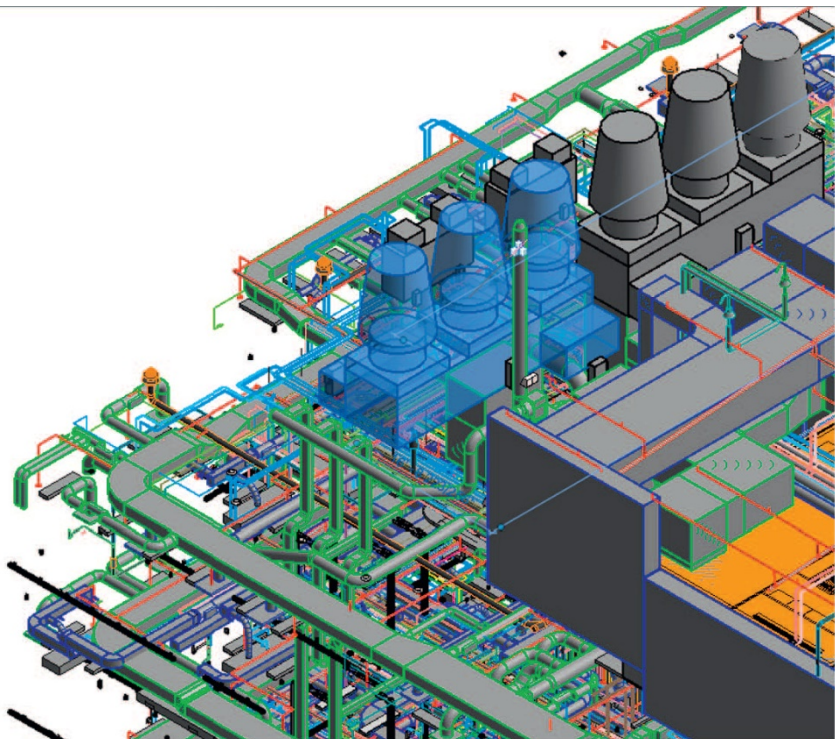


Figure 2. A BIM model example [13]

### 3. Building and City Data Standards

The organizations working on Smart Building standards are listed in Appendix A. The prevailing building automation standards and protocols are summarized in Appendix B. The prevailing smart city standards and the organizations are summarized in Appendix C. In this section, the three dominating open building data standards are introduced.

#### 3.1 Industry Foundation Classes (IFC)

As many other ICT technologies, BIM also has interoperability issues. Different BIM software solutions may have different data formats that do not interoperate. The Industry Foundation Classes (IFC) specification is developed to address this issue. IFC is a neutral data format to describe, exchange and share building information and it is the leading interoperability standard in the AECO industry [14]. Most of the BIM software applications support IFC. Currently, 653 entities (geometry, properties, and relationships of building components) can be defined in IFC and the capabilities of IFC as a data standard keep expanding [15]. Moreover, the IFC standard can be implemented by using Extensible Markup Language (XML) technologies [16] – ifcXML, as Figure 3 shows. This research adopts IFC as the data standard to represent buildings and explores the overlaps between IFC and other IoT related data standards and protocols. The latest version of IFC is IFC4 Add2.

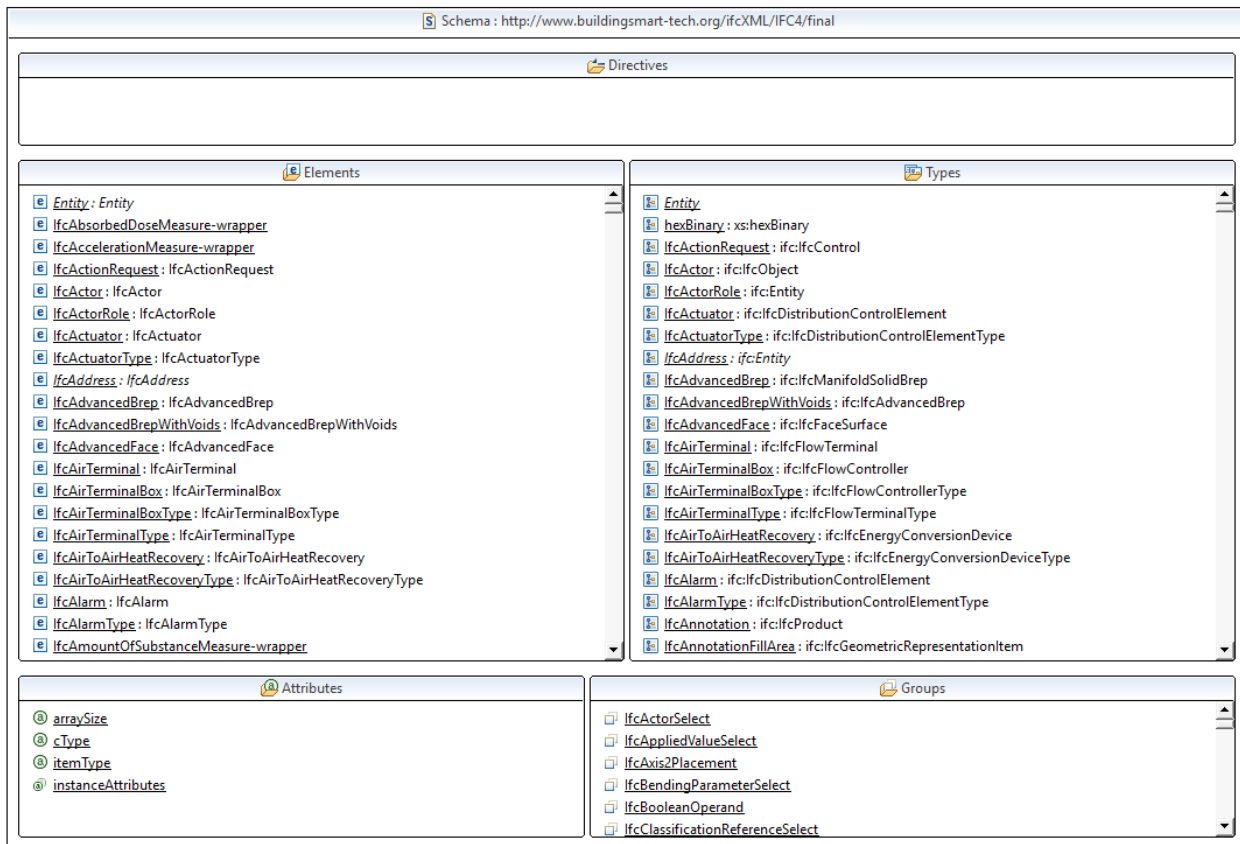


Figure 3. Overview of the ifcXML schema for IFC4 Add2 [17]

As a data standard developed to respond to all the different needs of stakeholders in the AECO industry, IFC has provided a platform for building-related information exchange. However, a fully developed IFC file is highly redundant for a specific data exchange task because it contains almost all the information pertaining to a building. Therefore, a clear specification of the information requirements and workflow is critical for successful information exchanges using IFC. A Model View Definition (MVD) defines a subset of the IFC schema that is needed to satisfy one or many data exchange requirements [18]. MVD identify what should be expected for an exchange to be effective [6]. For example, the information required by facilities managers is a subset of the full information of a building. An MVD can be created to identify what information is expected by the facility managers, thereby the export (from the general contractor, or the builder) and import (to the facility manager) are aligned. In general, MVD is the “filter” to filter out the useless information in IFC for a certain data exchange task.

### **3.2 Green Building XML (gbXML)**

“The Green Building XML schema, or ‘gbXML’, was developed to facilitate the transfer of building information stored in CAD-based building information models, enabling interoperability between disparate building design and engineering analysis software tools”[19]. The gbXML schema was developed by Green Building Studio with the support of the California Energy Commission Public Interest Energy Research (PIER) Program, and the California Utilities (Pacific Gas and Electric Company, Southern California EDISON and Sempra Energy Utility) [20]. The gbXML schema is the most common data format for the exchange of building information between BIM and energy simulation tools such as EnergyPlus and Ecotect [21].

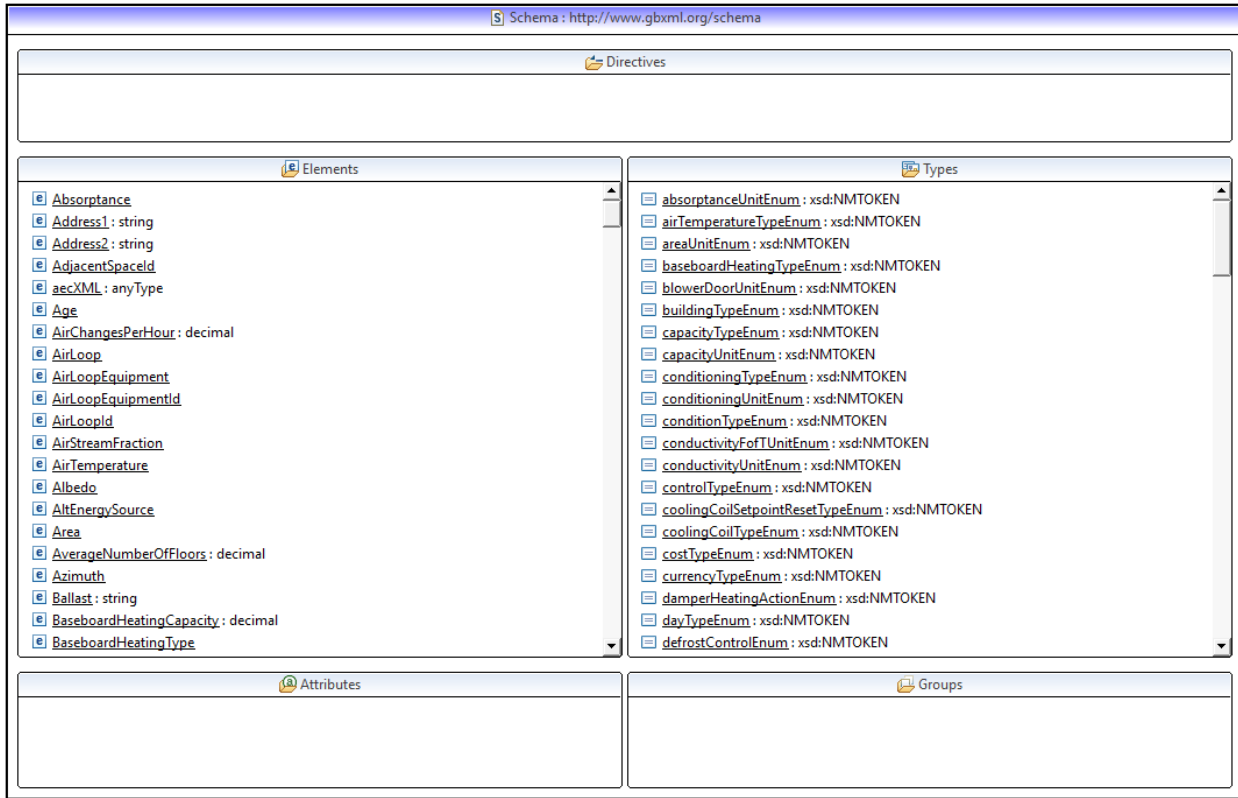


Figure 4. Overview of the gbXML schema

### 3.3 CityGML

“CityGML is an open standardized data model and exchange format to store digital 3D models of cities and landscapes” [22]. It is a multi-purpose and multi-scale representation for the geometrical, topological, and semantic aspects of 3D city models [23]. Because CityGML is based on Geography Markup Language (GML) – which is also XML-based – “it can be used with the whole family of GML-compatible web services for data access, processing, and cataloging, such as Web Feature Services, Web Processing Services, and Catalog Services” [22]. The overview of the up-to-date CityGML 2.0 schema is shown in Figure 5 and the separate modules of CityGML and their schema dependencies is shown in Figure 6.

Schema: <http://www.opengis.net/citygml/2.0>

Directives

- \*- <http://schemas.opengis.net/gml/3.1.1/base/gml.xsd> (<http://www.opengis.net/gml>)
- \*- <http://docs.oasis-open.org/election/external/xAL.xsd> (urn:oasis:names:tc:ciq:xsdschema:xAL:2.0)

Elements	Types
<ul style="list-style-type: none"> <li><a href="#">CityObject</a> : AbstractCityObjectType</li> <li><a href="#">GenericApplicationPropertyOfAddress</a> : anyType</li> <li><a href="#">GenericApplicationPropertyOfCityModel</a> : anyType</li> <li><a href="#">GenericApplicationPropertyOfCityObject</a> : anyType</li> <li><a href="#">GenericApplicationPropertyOfSite</a> : anyType</li> <li><a href="#">Site</a> : AbstractSiteType</li> <li><a href="#">Address</a> : AddressType</li> <li><a href="#">CityModel</a> : CityModelType</li> <li><a href="#">cityObjectMember</a> : FeaturePropertyType</li> <li><a href="#">ImplicitGeometry</a> : ImplicitGeometryType</li> </ul>	<ul style="list-style-type: none"> <li><a href="#">AbstractCityObjectType</a> : gml:AbstractFeatureType</li> <li><a href="#">AbstractSiteType</a> : AbstractCityObjectType</li> <li><a href="#">AddressPropertyType</a></li> <li><a href="#">AddressType</a> : gml:AbstractFeatureType</li> <li><a href="#">CityModelType</a> : gml:AbstractFeatureCollectionType</li> <li><a href="#">ExternalObjectReferenceType</a></li> <li><a href="#">ExternalReferenceType</a></li> <li><a href="#">GeneralizationRelationType</a></li> <li><a href="#">ImplicitGeometryType</a> : gml:AbstractGMLType</li> <li><a href="#">ImplicitRepresentationPropertyType</a></li> <li><a href="#">xalAddressPropertyType</a></li> <li><a href="#">doubleBetween0and1</a> : xs:double</li> <li><a href="#">doubleBetween0and1List</a> : doubleBetween0and1</li> <li><a href="#">integerBetween0and4</a> : xs:integer</li> <li><a href="#">RelativeToTerrainType</a> : xs:string</li> <li><a href="#">RelativeToWaterType</a> : xs:string</li> <li><a href="#">TransformationMatrix2x2Type</a> : xs:double</li> <li><a href="#">TransformationMatrix3x4Type</a> : xs:double</li> <li><a href="#">TransformationMatrix4x4Type</a> : xs:double</li> </ul>
Attributes	Groups

Figure 5. Overview of the CityGML 2.0 schema.

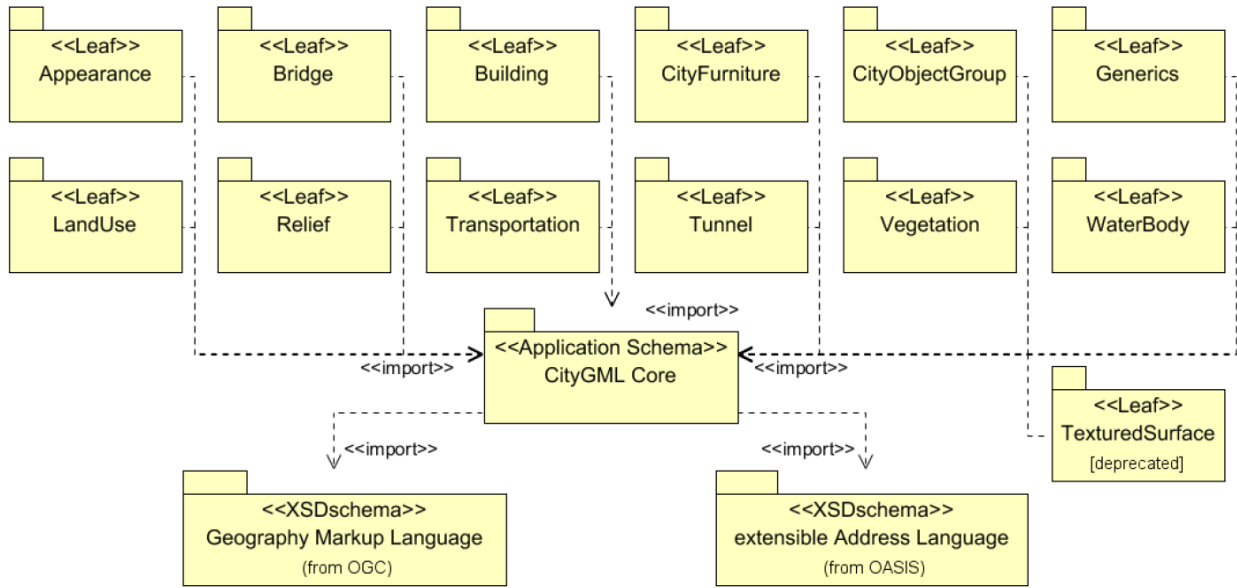


Figure 6. The separate modules of CityGML and their schema dependencies [24]



## 4. IoT Data Protocols

The organizations and alliances working on IoT standards and protocols are listed in Appendix D and E, respectively. The prevailing IoT Standards and Protocols [25] are summarized in Appendix F. This section briefly introduces three primary IoT-building/building automation protocols – BACnet, Modbus, and LonWorks.

### 4.1 BACnet

BACnet (A Data Communication Protocol for Building Automation and Control Networks) is designed to be applicable to all building automation needs, hence it specifies most of the common functions: analog and binary input, output, and values; control loops; schedules, etc., that apply to almost any kind of monitoring or control application [26]. BACnet applications involve HVAC control, fire detection and alarm, lighting control, security, etc. [26]. The rules of BACnet apply to all aspects of data communication, including electrical signaling, addressing, network access (Master/Slave, Peer-to-Peer), error checking, flow control, message sequencing, segmentation, checkpointing, presentation format, and message format [26]. BACnet has a layered protocol architecture based on a collapsed version of the Open Systems Interconnection (OSI) Basic Reference Model [27,28], as shown in Figure 7 [29].

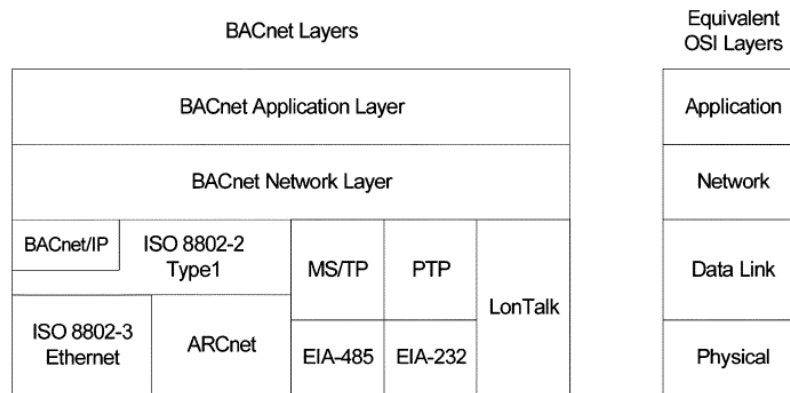


Figure 7. BACnet collapsed architecture [29]

BACnet defines a collection of abstract data structures called "objects", the properties of which represent the various aspects of the hardware, software, and operation of the device [28]. The objects provide a means of identifying and accessing information without requiring knowledge of the details of a device's internal design [28]. The communication software in the device can interpret requests for information about these abstract objects and translate those requests to obtain the information from the real data structures inside the device [28]. Figure 8 shows the list of BACnet objects. A list of standard BACnet objects is given in Appendix II [30].

# BACnet Objects

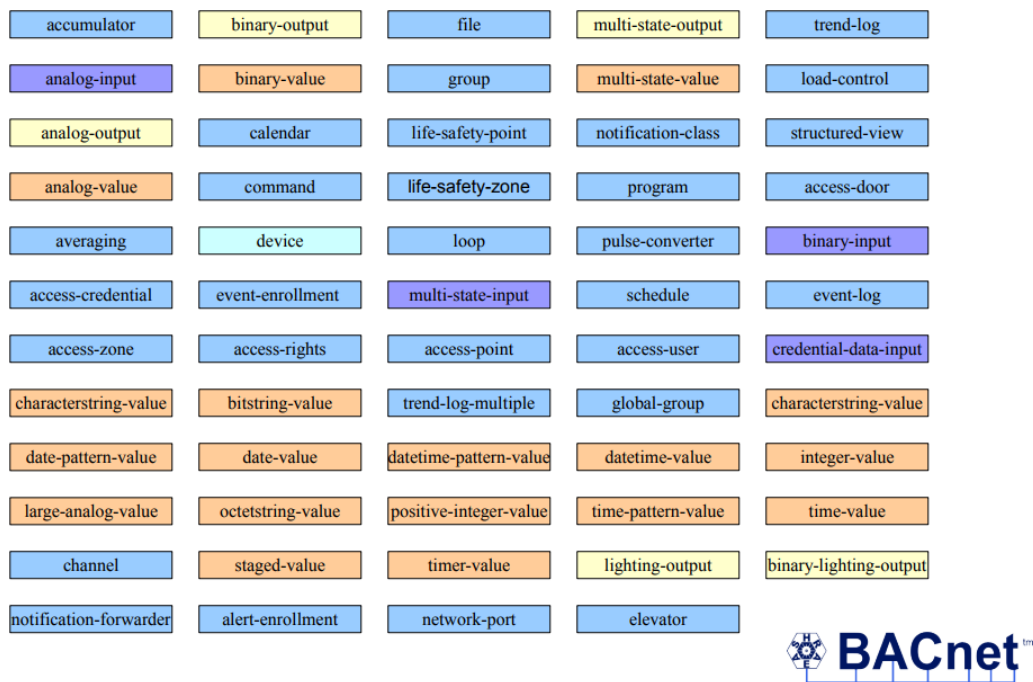


Figure 8. BACnet Objects [31]

The BACnet Objects are evaluated and controlled by their properties. The BACnet standard identifies 123 different Properties of Objects [30]. A different subset of these Properties is specified for each type of Object [30]. There are two types of BACnet objects – standard objects (Appendix II) and non-standard objects. A standard object is one whose properties and what they do, are defined in the BACnet standard [32]. Among all the BACnet objects, the Device object is the only one required by all BACnet devices. Other objects are included as appropriate to the device's functions, that may include non-standard objects [32].

A BACnet device is a container with different BACnet objects that represent the actual functions and I/O present in the actual device. Figure 9 shows an example of a BACnet device.



Figure 9. An example of a BACnet device [32]

BACnet Services are the means by which one BACnet device acquires information from another device, commands another device to perform some actions, or announces to one or more devices that some event has taken place [30].

This research adopts BACnet as the building automation and control protocol to demonstrate the data acquisition framework proposed in Section 5. Overlaps between the building data standards (IFC and gbXML) and BACnet are identified and discussed in Section 5.5.

#### 4.2 Modbus

“Modbus is an application layer messaging protocol provides client/server communication between devices connected on different types of buses or networks” [33]. Although never formally standardized, Modbus is regarded as an industry proven and open protocol [34]. It is a request/reply protocol and offers services specified by function codes, which are elements of Modbus request/reply PDUs (Protocol Data Unit) [33]. Modbus application layer messaging protocol, positioned at level 7 of the OSI model, provides client/server communication between devices connected on buses or networks [35]. On the Modbus serial line, the client role is provided by the Master of the serial bus and the Slaves nodes act as servers [35].

Layer	ISO/OSI Model	
7	Application	MODBUS Application Protocol
6	Presentation	Empty
5	Session	Empty
4	Transport	Empty
3	Network	Empty
2	Data Link	MODBUS Serial Line Protocol
1	Physical	EIA/TIA-485 (or EIA/TIA-232)

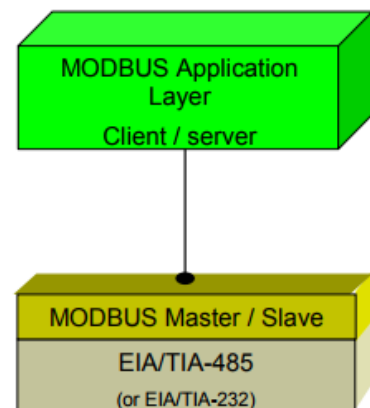


Figure 10. Modbus Protocols and ISO/OSI Model [35]

### 4.3 LonWorks

LonWorks (local operating network) is a networking platform for control applications. The platform is created by Echelon Corporation and built on the ISO/IEC 14908-1 Control Network Protocol (CNP), which provides a reliable, cost-effective, and robust communications standard for control applications [36]. “The goal of the LonWorks platform is to provide a well-integrated, optimally designed, and economical platform for creating smart devices and networks” [36]. It supports a variety of different communication media and different wiring topologies, and various building functions such as lighting and HVAC use LonWorks-based systems [34]. Figure 11 shows the LonWorks Control Network.

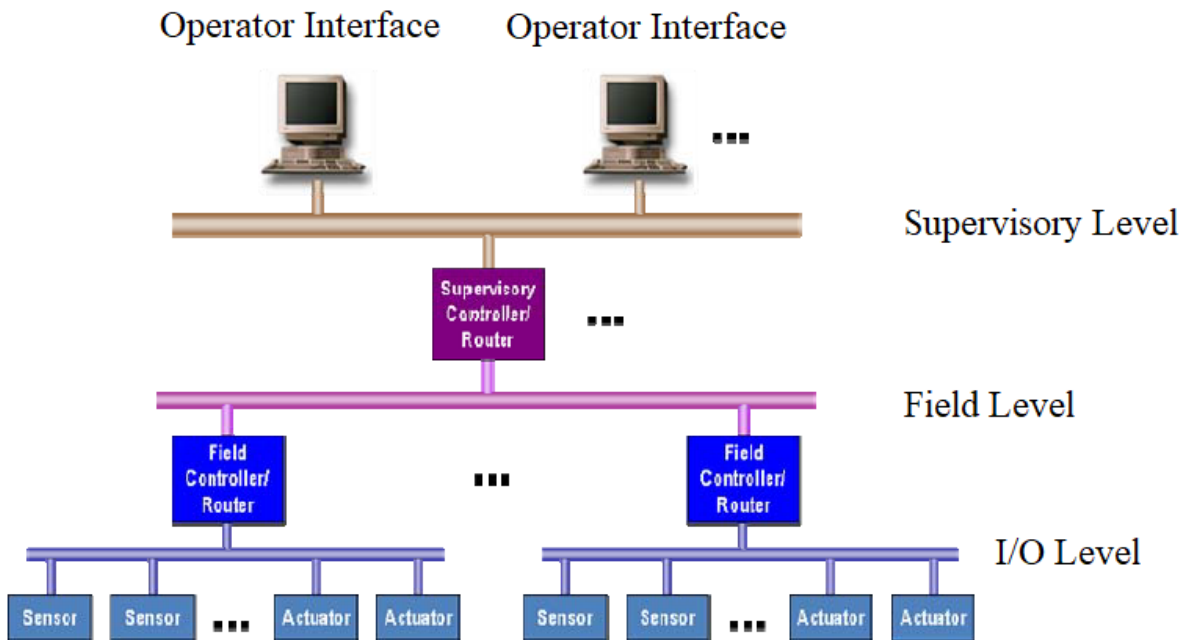


Figure 11. LonWorks Control Network

The LonWorks platform is consist of the following components [36]:

- Smart Transceivers
- Development Tools
- Routers
- Network Interfaces
- Internet Servers
- Network Management
- Network Tools

## 5. A Scalable Cyber-Physical System Data Acquisition Framework for the Smart Built Environment

In this section, we propose a data acquisition framework for the smart built environment – Smart Buildings, Smart Communities, and Smart Cities – that enables the utilization of the data housed in separate building systems for innovative IoT use cases, by understanding IoT stakeholders’ common data needs from buildings and identifying the overlaps between the data protocols used by different building systems. The relevant works are presented in a “top-down” sequence. An architecture of IoT-enabled Smart Cities, which is based on the proposed data acquisition framework, and example use cases are presented in Section 5.1. The proposed conceptual framework to establish the basic data package is described in Section 5.2. The methods of creating the data schemas for connecting separate building databases are illustrated in Section 5.3. An experiment designed for demonstrating the proposed data acquisition framework is presented in Section 5.4.

### 5.1 The IoT-enabled Smart City – a network of smart facilities

A conceptual IoT-enabled Smart City architecture in the perspective of a smart building network is proposed and shown in Figure 12. It is our vision of future smart cities. The work done in this research is to establish the data infrastructure for this vision.

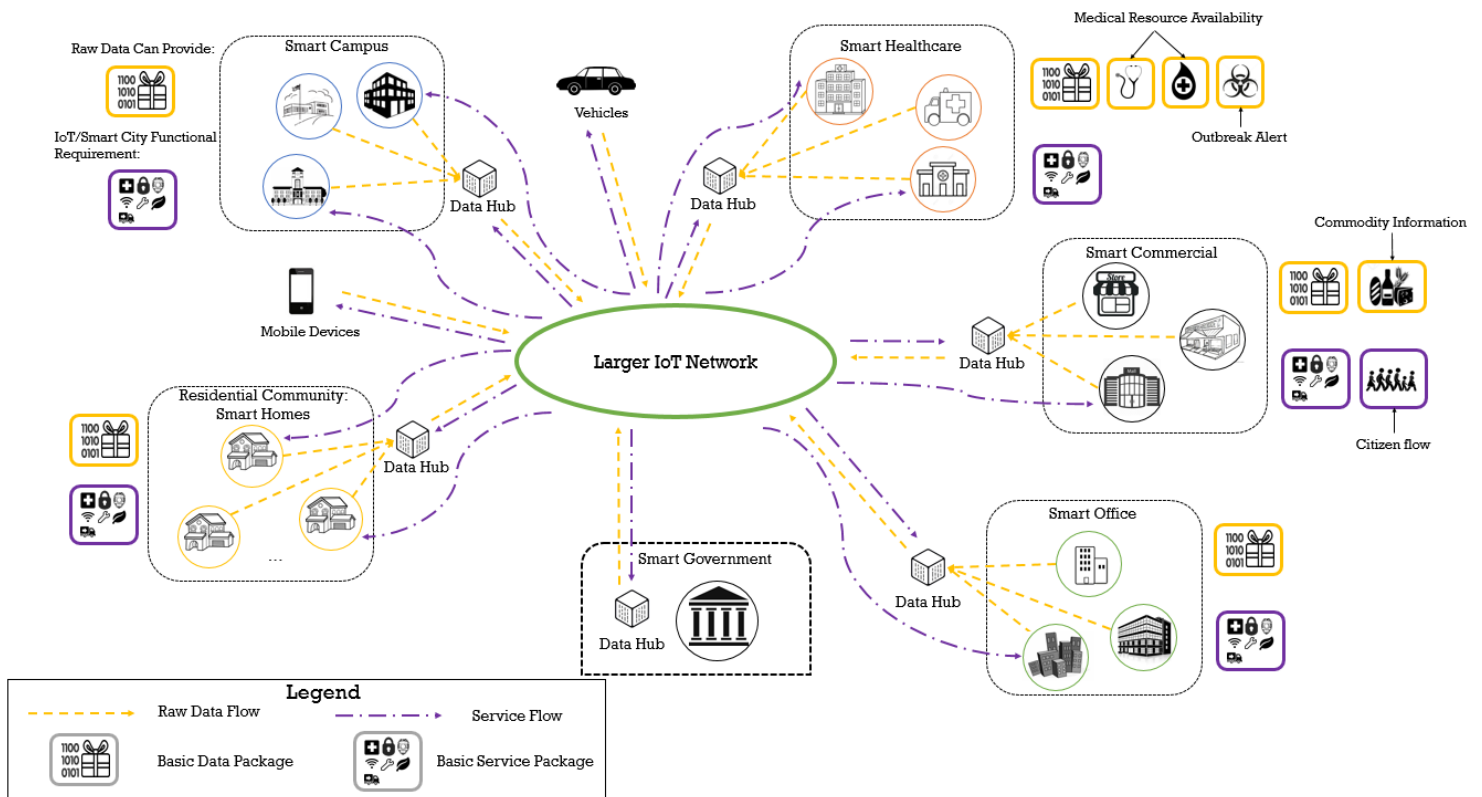


Figure 12. An architecture of the IoT-enabled Smart City – a network of smart facilities

In the IoT-enabled Smart City we proposed, as Figure 12 shows, multiple smart buildings form a community and many communities – residential community, campus, healthcare, commercial, office, government, etc. – form a smart city. In the future, each facility will be “smart” enough to provide a certain amount of data to the IoT-enabled Smart City network in real-time. The data flow generated in each building is collected by the data hub of each community, and then connected to the city-level IoT network. The data contents can vary based on the facility type but some of them are universal. We name the data will be provided by all smart buildings “the basic data package”. The basic data package provides the fundamental data for the Smart Building network and is the basis of innovative IoT-enabled Smart City applications.

Besides the basic data package, different data will be provided by certain types of facilities and we name them “extra data”. For example, healthcare facilities can provide information pertaining to medical resource availabilities, such as the doctors’ schedules and the blood bank inventory. They can also send outbreak alert to the smart city network if an infectious disease case is identified. Another example of extra data is that the supermarket in the smart commercial community can provide real-time commodity information to the smart city network so that citizens can locate the commodities they need. This is particularly crucial when natural disasters, such as the hurricane, tsunami, and sandstorm, are threatening the city and citizens are hoarding necessities.

The smart buildings in the proposed architecture not only provide data to the network but also require services from it. The service requirements may vary based on the facility types but there are some common services required by all. We name them “the basic service package”, which is shown in Table 2. Some examples of the basic service package involve security, emergency assistance, data connection, operation and maintenance, etc. Besides the basic service package, different services may be requested by certain types of facilities and we name them “extra service”. For example, a shopping mall may request the real-time citizen flow information from the smart city network to predict the customer flow (Figure 12).

This Smart City architecture and the contents of the basic data package and basic service package are still under developing. A preliminary list of the basic data package’s contents is shown in Table 1.

Table 1. A preliminary list of the basic data package’s contents

#	Basic Data	Description
1	Space occupancy rate	The ratio of rented or used space compared to the total amount of available space
2	People counting	Number of people in a space during a certain time
3	Electricity usage	Real-time electricity consumption
4	Water usage	Real-time water consumption
5	Lighting relevant information	e.g. illuminance, natural lighting information
6	Audio relevant information	e.g. noise level
7	Access relevant information	e.g. personnel attendance record, visitor access record
8	Logistics	e.g. inventory information, accessibility of the facility, RFID tagged goods in/out records

9	Environmental information	e.g. Real-time temperature, humidity, harmful substances content
10	Emergency information	e.g. smoke detection, fire alarm equipment information
11	Operation & maintenance	e.g. work order, maintenance record
12	Information and Communication Technology relevant information	e.g. Internet usage, WIFI coverage

Table 2. A preliminary list of the basic service package's contents

#	Basic Services	Description
1	Security	Protection personnel and property from damage or harm, e.g. police patrol.
2	Emergency Assistance	e.g. first-aid
3	Data Connection	e.g. Internet connection
4	Resource	e.g. electricity, water, gas
5	Operation & Maintenance	Services pertaining to maintain the facility
6	Sustainability relevant service	e.g. garbage disposal and recycle resource
7	Logistics	e.g. the accessibility of a facility

This Smart City framework and the contents of the basic data package and basic service package are still under developing. Different smart facilities' extra data and extra service are not fully understood yet. To further develop and justify this list requires an extensive survey, which has not been conducted yet. Because the functional requirements of the smart city will evolve with the development of technology, the required data and services lists may never be exhaustive.

## 5.2 The conceptual framework to establish the basic data package

Currently, multiple building systems, such as the Building Automation System (BAS), the Building Energy Management Systems (BEMS), the Computerized Maintenance Management System (CMMS) and the security systems, are collecting a large amount of data through sophisticated sensors and emerging smart devices. However, the inter-system data interoperability is limited, and the data formats vary based on different vendors. Our hypothesis is that the evolving building systems already contain many valuable data for IoT-enabled Smart City innovations but not being used because they are not connected, available to analysts and developers in a consumable way. By extracting relevant data from multiple building systems, storing them in web-accessible databases, and connecting these databases through customized Extensible Markup Language (XML) schemas, which are derived from the data mapping between different data standards, we can establish the integrated building data foundation that enables innovations in future Smart Cities – the basic data package in the proposed IoT-enabled Smart City architecture.

Figure 13 illustrates the high-level framework to establish the basic data package. Separate building systems with different data protocols generate various types of raw data, such as the surveillance system generate videos, the Heating, Ventilation, and Air Conditioning (HVAC) system generates temperature

information, the security and access control system generate access record, etc. The raw data can be processed by certain techniques – data mining, pattern recognition, Artificial Intelligence, etc. – to produce the “basic data”, such as space occupancy rate, people counting, and electricity usage, which consist the basic data package (as Table 1 shows).

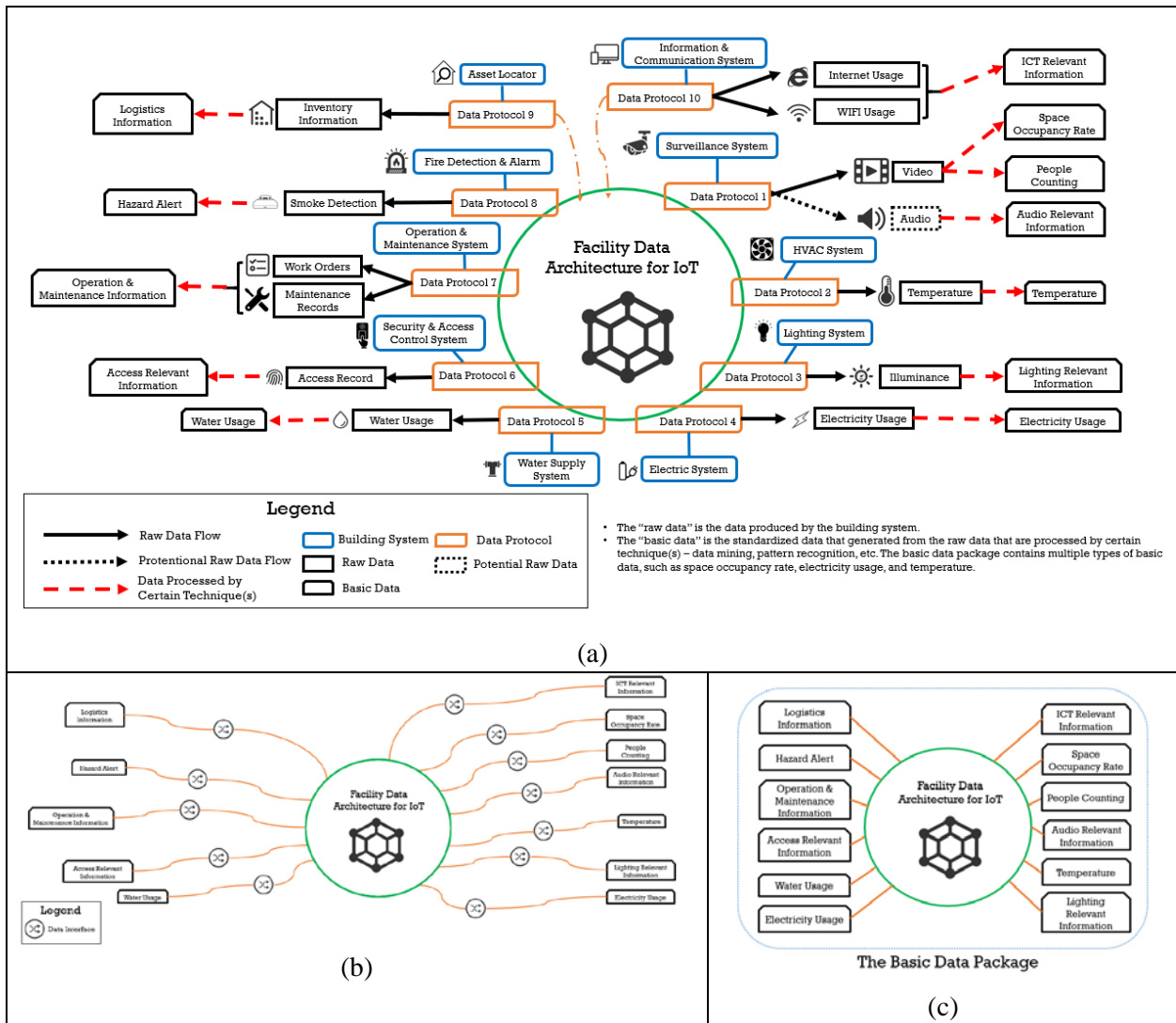


Figure 13. The basic data package generation

Although a huge amount of building data is being generated every hour, the systems that generate these data are established based on various data standards and protocols. Currently, each type of the building data is only used for a single purpose. For example, the electricity consumption is for energy monitoring, temperature data is for HVAC system control, etc. The lack of a comprehensive usage of these building data is hindering the innovative applications of the IoT-enabled Smart Building/Smart City. A data framework that can provide integrated and comprehensive building data by connecting multiple databases, which are based on various standards and protocols, is the basis of the innovative IoT-enabled Smart City use cases.



BIM models offer a clear potential as the “digital twin” of the built environment – one that can provide significantly enhanced spatial context for distributed building automation and control systems, which can be regarded as IoT systems and CPS. A strategy for connecting the building automation and control (IoT) data protocols with the BIM data schemas can provide a critical layer of spatial semantics to these IoT systems, such as device geo-positioning and metadata tagging, and enrich Smart Building/Smart City efforts while harmonizing these data sources with various data protocols.

Extensive work is needed to enable the data connections between different building systems and to establish the proposed dataset. One of the prerequisites is a thorough investigation of the data standards and protocols of the IoT devices – sensors, cameras, actuators, etc. – and the BIM data schemas. The most commonly-used data protocols of building automation and control are summarized in Table 3.

Table 3. Data protocols of building automation and control

Data standards	Data standards	Data standards
1-Wire	Dynet	VSCP
BACnet	EnOcean	xAP
C-Bus	KNX	X10
CC-Link	LonTalk	Z-Wave
DALI	Modbus	ZigBee
DSI	oBIX	INSTEON

Industry Foundation Classes (IFC) specification is the leading neutral BIM data schema to describe, exchange and share building information [14]. Most of the BIM software applications support IFC. Currently, 653 entities (geometry, properties, and relationships of building components) can be defined in IFC and the capabilities of IFC as a data standard keep expanding [15]. gbXML [19] is another commonly used building data schema. CityGML is a city-level open data standard and exchange format to store digital 3D models of cities and landscapes [22].

### 5.3 The method for establishing the linkage among different databases

The connections between the IoT data protocols with the BIM data schema can be established by identifying the overlaps between them and creating a federated data framework that enables the data collection, query, and exchange. Figure 14 shows an example in which the overlaps of the data protocol in each level – device level, building level (BIM), and city level – are identified. Then, as Figure 15 shows, the overlaps can be used to establish the linkage among the databases of devices, buildings, and the city, thereby we can establish a federated dataset that provides real-time building data for IoT-enabled Smart City applications. In the visionary IoT-enabled Smart City, innovative CPS with appropriate permission will be able to query the real-time data generated by each IoT device. The proposed framework to establish the federated dataset is a critical effort to realize this vision.

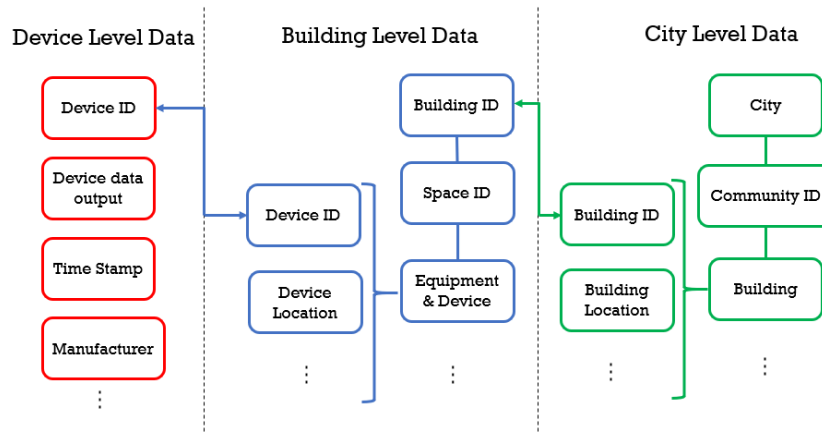


Figure 14. Identifying the overlaps between data protocols

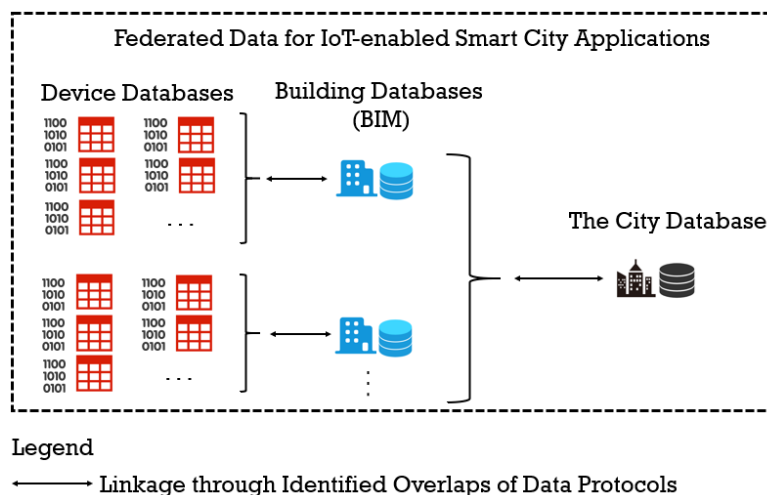


Figure 15. Federated data for IoT-enabled Smart City applications

The challenge of establishing the linkage among the databases lies in how to align the “common” data – such as device ID and building ID – in each database. For example, the device ID is “abcd123” in the device database but it may be “123-abcd” in the building database. To address this issue, we create XML schemas that enable automatically editing and concatenating the values of the key data fields, thus to align the common data.

#### 5.4 An example experiment: connecting BACnet, IFC, and CityGML based databases

An example experiment is designed to demonstrate the proposed method for establishing the federated data framework and prove its feasibility. In this experiment, BACnet, IFC, and CityGML are adopted as the data protocol of device level, building level, and city level, respectively.

BACnet (A Data Communication Protocol for Building Automation and Control Networks) is the dominant protocol in the Building Automation Industry [37]. The BAS used in the experiment – Johnson Controls’ Metasys system – is based on BACnet and its devices are BACnet compatible [38].

Figure 16 shows the experiment framework. The data generated by the BAS's sensor network deployed in multiple campus buildings are collected and stored in a MySQL database. We did not use the database of Metasys directly due to lack of privilege and the need of making changes in the database without disturbing the BAS' normal operations. An open-source tool named BCVTB (Building Controls Virtual Test Bed) [39] is used to read the data generated by BACnet devices and write them to the database. This approach can extract any type of building data from BACnet supported device networks. In this experiment, we use the electricity consumption data as the device level data to connect with the IFC-based building database.

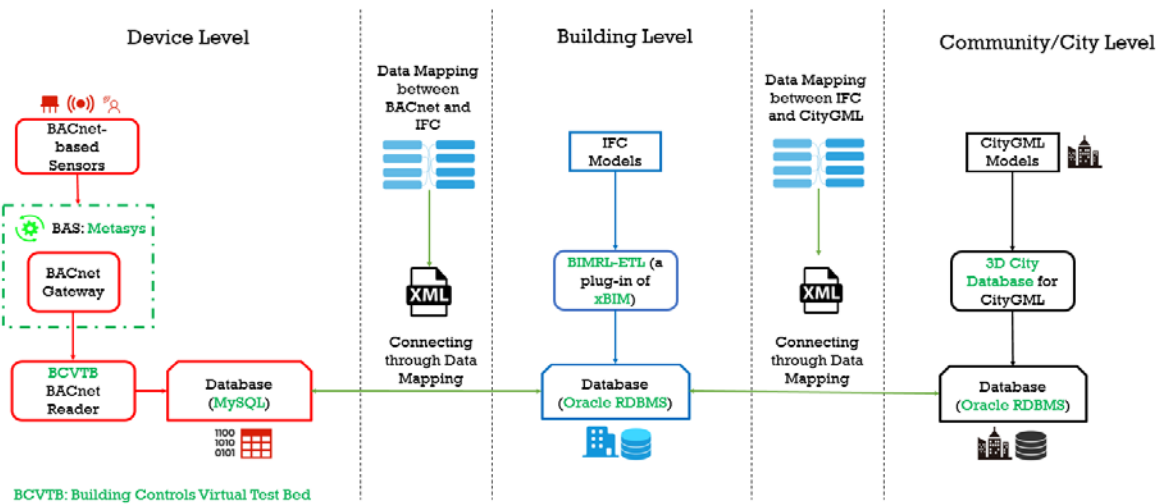


Figure 16. The experiment framework: connecting BACnet, IFC, and CityGML based databases

In the building level, to provide an efficient query-ability into BIM data, which is traditionally difficult and slow, two IFC models are transformed into a simplified RDBMS (Relational Database Management System) data format and stored in an Oracle Database Server (Oracle RDBMS). The tool we used in this step is called BIMRL-ETL (BIM Rule Language - Extract, Transform and Load) [40], which is a plug-in of xBIM [41]. The xBIM project aims to provide developers the codebase for innovative BIM applications.

In the community/city level, a CityGML city model is also transformed and stored in an Oracle Database Server. A tool named 3D City Database (3DCityDB) [42] is used to automate this process. The 3DCityDB is an open-source package consisting of a database schema and a set of software tools to import, manage, analyze, visualize, and export CityGML city models. “The database schema results from a mapping of the object-oriented data model of CityGML 2.0 to the relational structure of a spatially-enhanced relational database management system” (SRDBMS) [43].

To federate the data in each level's database by using the common data fields, we have identified the overlaps (not exhaustively) between BACnet XML [44] and ifcXML (IFC in the XML form) [17], and that between ifcXML and CityGML XML [45]. The common data fields used for database federation are shown in Table 4 and 5.

Table 4. The common data fields between BACnet XML and IFC XML

BACnet XML (DR-034A-28)	IFC XML (IFC4 ADD2)
▼Object	▼ifcBuilding
propertyIdentifier	id
name	Name
type	ObjectType
description	Description
contextTag	Tag

Table 5. The common data fields between IFC XML and CityGML

IFC XML (IFC4 ADD2)	CityGML 2.0 XML
▼ifcBuilding	▼Building
id	gmlid
Name	gmlname
Description	gmldescription
ElevationOfRefHeight	measuredHeight
ifcBuildingAddress	address

Based on the identified overlaps of these data schemas, we created XML files in MapForce [46] to automatically editing and concatenating the values of the identified data fields, thus to align the common data in each database.

This experiment demonstrates the proposed framework of establishing the basic data package – 1) studying different IoT data schemas, 2) identifying common data fields between these schemas and BIM data schemas, 3) creating the tools (may be as simple as an XML schema) to establish the linkage between databases, and thus 4) establishing the federated dataset for IoT-enabled Smart City applications. The proposed framework is scalable, which means if one type of building data can be extracted and stored in an SQL database, and this database can be linked to the building level database and then the community/city level database using the proposed methods, other types of data can also be processed by similar methods according to the framework, although the specific tools may be different in each case. Therefore, this experiment will prove the feasibility of the proposed framework – a scalable CPS data acquisition framework for the smart built environment.

## 6. Integrating BACnet and IFC

Smart buildings are empowered by Building Automation Systems (BASs) that enable data collection, process, and analysis to assist facility functions and service [47]. BAS is a data acquisition and control system that incorporates various building functionalities. It is also known as Energy Management Systems (EMS), Building Management Systems (BMS), Building Energy Management Systems (BEMS), Facility Management systems (FMS) and Building Automation and Control System (BACS) [34]. A BAS's common functionalities involve temperature and air quality monitoring, lighting system control, HVAC system control, electricity control, access control security control, fire control and sending signals when faults occur [48]. A BAS uses sensors to collect data pertaining to the building conditions and uses actuators to conduct physical control. Different subsystems of BAS and their devices manufactured by various vendors need to communicate with each other, hence data communication protocols play a key role in information exchange in the BAS. Predominant protocols of BAS communication networks involve BACnet, LonWorks, EIB/KNX, and Modbus.

The BACnet protocol was developed by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), to address communication needs of BAS for different applications like heating, lighting control, and fire detection systems [49]. BACnet aims to solve interoperability issues among different devices vendors by modeling exchanged information with object-oriented representations [34]. BACnet's object-oriented representations of device information provide possibilities for integrating the BAS design with BIM [50]. BIM has been adopted to assist data exchange and information flow among architects, engineers, clients and contractors throughout the building project lifecycle [6]. Starting from the design phase, the BAS – represented by a collection of BACnet objects – can be modeled using BIM tools without specifying device vendors. In this way, the design of BAS can be conveniently modified in a BIM model. During the construction phase, the BIM model, which contains information about the devices and their interconnections, can facilitate the device selection process. Then, the BIM model that contains the updated BAS model can be handover to owners and facility managers for operation and maintenance (O&M).

Data standards and schemas for devices, buildings, and cities are diverse. In the IoT device level, there are many data communication protocols such as BACnet, LonWorks, EIB/KNX, OPC, and Modbus that play key roles for information exchange between different sensors and subsystems in BAS. In the building level, the IFC standard acts as a medium for data exchange across domains, stages, and parties for BIM applications [51]. While IFC is the most commonly known data exchange schema for BIM, CityGML dominates the city level data interoperability. Some effort has been made in data schemas mapping. buildingSmart has partially mapped BACnet and OPC objects with IFC Entities in IFC 2x4 RC1 [52]. In terms of interoperability between CityGML and IFC, research works such as [53-58] have mapped some CityGML objects with IFC entities. However, i) only part of the communication protocol's objects has been mapped to IFC entities; ii) neither the object's attributes nor services have been mapped; iii) communication protocols are updating with time, hence continuous data mapping is necessary; iv) no device level data has been mapped to the city level; v) data mapping between all these schemas and protocols are heavy, various application requires distinguished data, standard data models views for different applications need to be

generated to achieve efficient data exchange.; vi) Current CityGML and IFC integration is not sufficient to represent the entire built environment lifecycle, and hence hindering some IoT applications [59].

To full fill the research gaps, we have mapped IFC and BACnet data standard using IDM/MVD methodology [18,60]. The Information Delivery Manuals (IDM) method was utilized first to identify BAS information sharing process and exchange requirements (ER) at the user level. This part uses ANSI/ASHREA Standard 135-2016 [49] to identify the requirements for BIM and BAS information exchange. The second part involves developing a Model View Definition (MVD) using the tool named IfcDoc [61]. The MVD created focused on the latest release of the IFC schema – IFC4 Addendum 2 (IFC4 Add2) [62]. The steps for mapping the data standards are described as follows [50]:

- a) Process modeling is the initial step to describe the flow of the actors’ activities and their information requirements. Business Process Modelling Notation (BPMN) is used to identify the key activities, their logical sequence, and administrative information pertaining to exchange requirements. Figure 17 shows the activities and information related to the BIM-enabled BAS information exchange process.

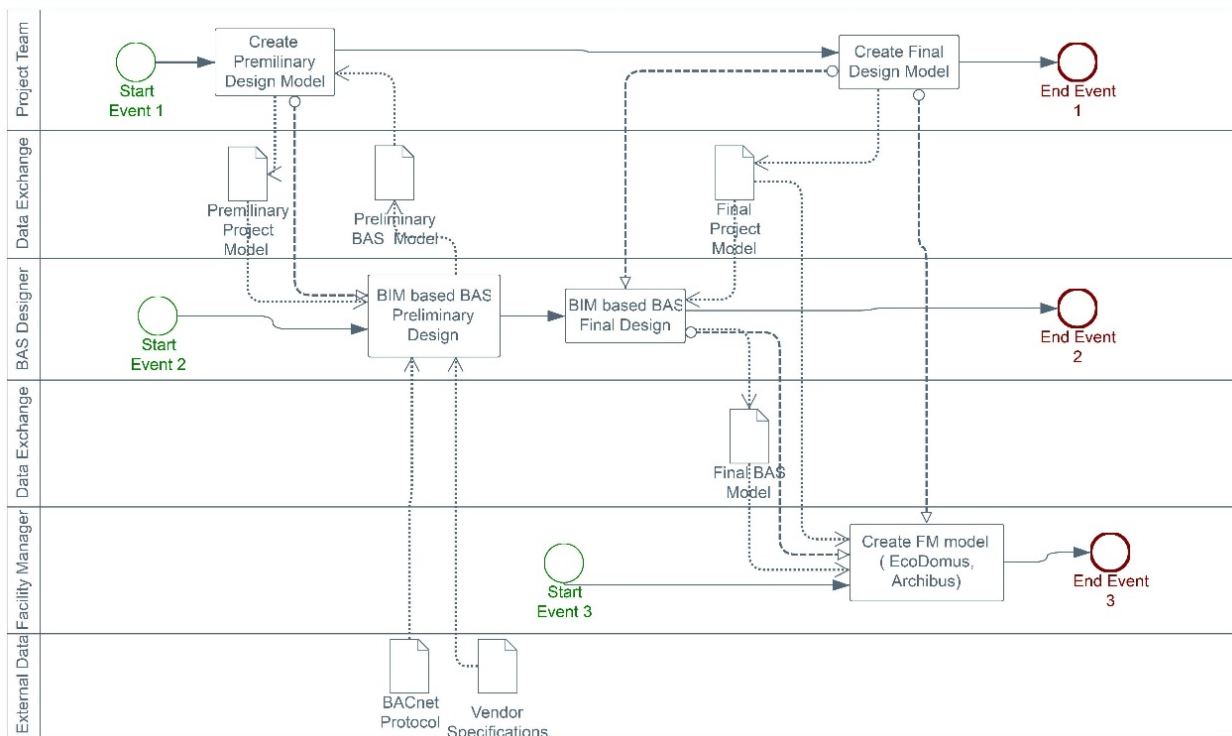


Figure 17. BPMN for BIM and BAS information exchange

- b) The next step is identifying information units in ERs. The information units, as shown in Table 6, are the objects and attributes listed in BACnet protocols. This project has detected mandatory BACnet objects and attributes to demonstrate the proposed mapping method.

Table 6. Example information unites

BACnet Binary Output Object Type		IfcController			
Object Geometric Representation		IfcProductRepresentation::IfcProductDefinitionShape		√	
Object Placement		IfcProductObjectPlacement::IfcObjectPlacement		√	
Object Contained in Space	the object contained in space	IfcElementContainedInStructure::IfcRelContainedInSpatialStructure			√
Object Connected From		IfcElementConnectedFrom::IfcRelConnectsElements			√
Decomposes	which device is the object decomposed by	IfcObjectDefinitionDecomposes::IfcRelAggregates			√
Object Identifier		IfcRootGlobalId::IfcGloballyUniqueId		√	
Object Name		IfcRootName::IfcLabel		√	
Object Type	Predefined Type =MULTIPOSITION	IfcControllerPredefinedType::IfcControllerTypeEnum		√	
Present Value		Pset_ControllerTypeMultiPositionValue::IfcInteger		√	
Description		IfcRootDescription::IfcText			√
Status Flags	PEnum_BACnetStatusFlags = ENUMERATION OF (IN_ALARM, FAULT, OVERRIDEN, OUT_OF_SERVICE);	IfcPropertyEnumerationEnumerationValues::IfcLabel		√	
Event State	PEnum_BACnetEventState = ENUMERATION OF (NORMAL, OFFNORMAL, FAULT);	IfcPropertyEnumerationEnumerationValues::IfcLabel		√	
Out of Service		IfcProperty::IfcPropertySingleValue.NominalValue::IfcBoolean		√	
Polarity	PEnum_BACnetPolarity = ENUMERATION OF (NORMAL, REVERSE);	IfcEnumerationEnumerationValues::IfcLabel		√	
Priority Array	array of BACnetPriorityValue::=CHOICE of (NULL, REAL, ENUMERATED, UNSIGNED, INTEGER, DOUBLE, TIME, CHARACTER STRING, OCTETS STRING, BIT STRING, DATE, BACNETOBJECTIDENTIFIER, ABSTRACT-SYNTAX&TYPE, BACNETDATETIME)	IfcProperty::IfcSimpleProperty		√	
Relinquish Default	This property is the default value to be used for the Present Value property when all command priority values in the Priority Array property have a NULL value.	IfcProperty::IfcPropertySingleValue.NominalValue::IfcReal		√	
Property List		IfcPropertySet		√	
Current Command Priority	Indicates the currently active priority. The value of this property shall be equal to the index of the entry in the Priority Array from which the Present Value's value has been taken. If Present Value has taken on the value of Relinquish Default, this property shall have the value Null.	IfcProperty::IfcSimpleProperty::IfcInteger		√	
Tags		IfcElement.Tag::IfcIdentifier			√

c) After the information units were listed, the description and data type of each information unit were compared with related IFC entities. Then, BACnet objects and attributes were mapped to IFC entities with the same data type, as shown in Table 6 and Table 7.

Table 7. Example of BACnet object and attributes mapping to IFC entities

Device Object Type		IfcController		
Object Geometric Representation		IfcProduct.Representation:IfcProductDefinitionShape	√	
Object Placement		IfcProduct.ObjectPlacement:IfcObjectPlacement	√	
Object Contained in Space	the object contained in space	IfcElement.ContainedInStructure:IfcRelContainedInSpatialStructure		√
Object Connected From		IfcElement.ConnectedFrom:IfcRelConnectsElements		√
IsDecomposedBy		IfcObjectDefinition.IsdecomposedBy:IfcRelAggregates		√
Object Quantity	Identify the number of Device in project	IfcObject.IsDefinedBy:IfcElementQuantity		√
Object Identifier		IfcRoot.GlobalId:IfcGloballyUniqueId	√	
Object Name		IfcRoot.Name:IfcLabel	√	
Object Type	Predefined Type =PROGRAMABLE	IfcController.PredefinedType:IfcControllerTypeEnum	√	
System Status	This property, of type BACnetDeviceStatus, reflects the current physical and logical status of the BACnet device. The values that may be taken on by this property are: PEnum_BACnetDeviceStatus = ENUMERATION OF( OPERATIONAL, OPERATIONAL_READ_ONLY, DOWNLOAD_REQUIRED, DOWNLOAD_IN_PROGRESS, NON_OPERATIONAL, BACKUP_IN_PROGRESS)	IfcEnumeration.EnumerationValues:IfcLabel	√	
Vendor Name	This property, of type CharacterString, identifies the manufacturer of the BACnet device.	Pset_ManufacturerTypeInformation.Manufacturer:IfcLabel	√	
Vendor Identifier	This read-only property, of type Unsigned16, is a unique vendor identification code, assigned by ASHRAE, which is used to distinguish proprietary extensions to the protocol.	IfcProperty:IfcPropertySingleValue.NominalValue:IfcString	√	
Model Name	This read-only property, of type CharacterString, is assigned by the vendor to represent the model of the BACnet device	Pset_ManufacturerTypeInformation.ModelLabel:IfcLabel	√	
Firmware Revision	This property, of type CharacterString, is assigned by the vendor to represent the level of firmware installed in the BACnet device.	Pset_ControllerTypeProgrammable.FirmwareVersion:IfcPropertySingleValue:IfcLabel	√	
Application Software Version	This property, of type CharacterString, identifies the version of application software installed in the machine. The content of this string is a local matter, but it could be a date-and-time stamp, a programmer's name, a host file version number, etc	Pset_ControllerTypeProgrammable.SoftwareVersion:IfcPropertySingleValue:IfcLabel	√	
Protocol Version	This property, of type Unsigned, represents the version of the BACnet protocol supported by this BACnet device. Every major revision of BACnet shall increase this version number by one. The initial release of BACnet shall be version 1.	IfcProperty:IfcPropertySingleValue.NominalValue:IfcString	√	

d) The final step was to create an MVD using IfcDoc tool to create a documentation for the information exchange process, as shown in Figure 18.



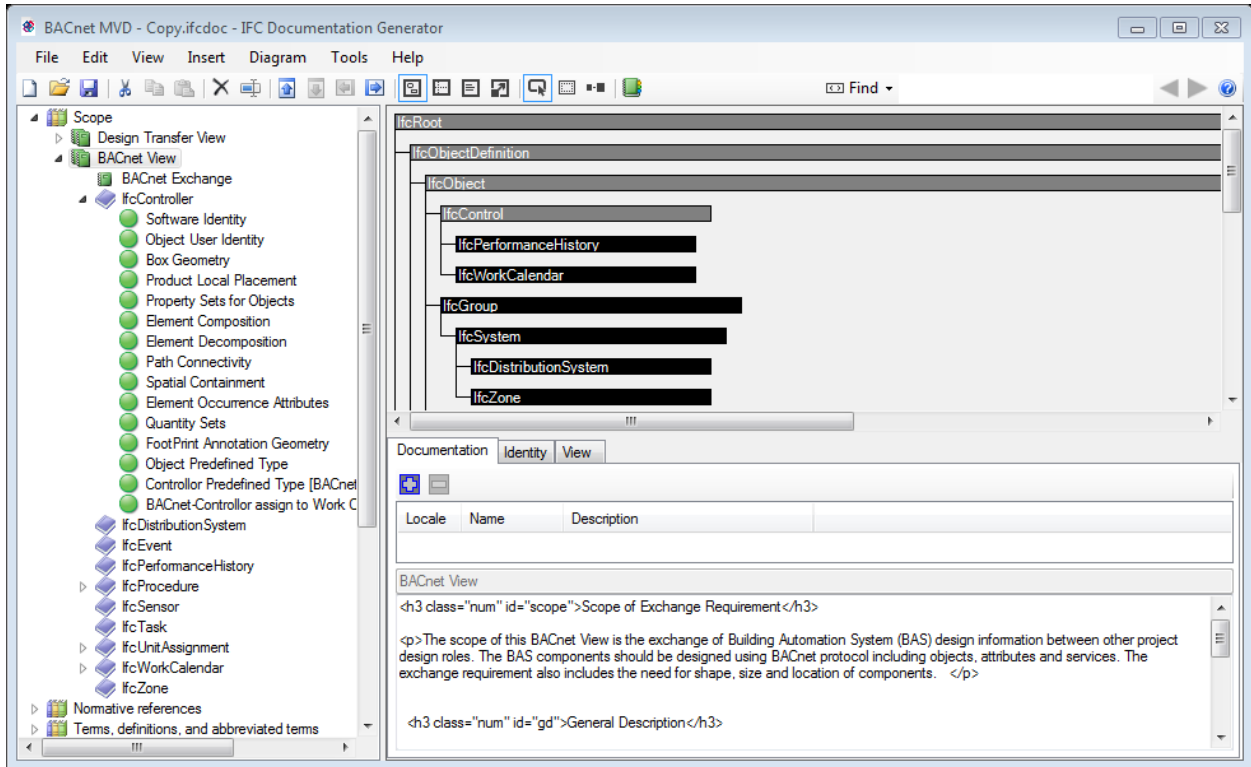


Figure 18. MVD created in IfcDoc

Through this process, BAS information consistent with the BACnet protocol can be represented in an IFC model for information exchange throughout each project stage with BIM tools, such as Revit. Enabling BAS information to be represented in an open BIM standard unlocks the potential of future BIM-IoT information exchange in smart buildings [50].

## **7. Identified Application Scenarios**

To get further insights into the potential demands of IoT-enabled Smart City/Community, semi-structured interviews with facility managers and a focused workshop were carried out at Georgia Tech. Potential use cases enabled by the proposed basic facility data package were identified. Each of these systems uses a subset of the basic data package to enable new functions. The use cases are described in this section.

### **7.1 A Life-cycle Cost Analysis (LCCA) system for facilities management decision makings**

The university's facility management (FM) departments usually face decision making challenges because the estimated life-cycle cost of a building component or system is not available to facility managers. For example, if the energy performance of a building's the HVAC system is worse than expected, it is difficult to determine which of the following options is the most economical one: hiring a vendor to identify the cause and repair it if possible, updating the HVAC system by replacing the old energy-intensive equipment such as the heaters, or just running the system as usual and bearing the extra energy cost. The life-cycle cost analysis (LCCA) can be complicated because if renovation or installation work is required, the facility managers should consider not only the purchasing expense and the actual energy consumption but also the cost of labor, building closure, business interruption, and the influences on the future maintenance.

The data analyst and communications manager pointed out that, Georgia Tech's building systems, such as the Computerized Maintenance Management System (CMMS) and Building Automation System (BAS), already contain the information that can be used to derive the life-cycle cost of facility components. However, the facility managers do not have an efficient way to acquire this type of information because these building systems are not connected to each other. The facility managers need a method to extract the relevant information from these systems and perform LCCA to support their decision making.

Facility managers are making important decisions in that affect the operation of organizations but, usually, they do not have the life-cycle cost information of facility components to support decision making because the building systems are lack of connectivity, even though these systems already contain the information that can be used to derive the life-cycle cost. It is critical to develop a method to enable facility managers to perform LCCA efficiently during their decision-making process by connecting the separated building systems, thereby to optimize FM budget allocations. Moreover, the success of developing such as method is a proof of concept that there are already many valuable building-related data that is not being taken advantage of because it's not connected, available to users in a consumable way; by identifying the required information from different building systems and understanding the facility managers' needs we can create a system by connecting these building systems together and provide more value to the building owners, managers, and occupants.

### **7.2 A sensor alert interpretation system**

Georgia Tech facility managers are continuously receiving alert messages from different building systems. Most of these alerts are generated because the sensors detect "abnormalities" that were defined in their initial settings. For example, Georgia Tech facility departments are using energy models to predict and

control the energy consumption of certain campus buildings. To monitor the real energy consumption and inform the facility managers automatically, certain rules are set in the building automation system (BAS), such as “send an alert if the electricity usage of a computer lab is higher than 100 kWh per day”. However, the initial settings are seldom updated after the commissioning of systems, even if changing is being made in each building over time. A computer lab that had 30 computers in it two years ago may have 50 computers now, but no one is making changes in the BAS to change the warning bar to 150 kWh. Moreover, the alert messages are not in a form that allows facility managers to understand what the problem is, which systems it involves, where it is, and what the potential consequences are. Eventually, Georgia Tech facility managers are receiving many alert messages every day and it is practically impossible to check them one by one and find out what is happening. Therefore, these alerts are being ignored, which could lead to risks for facilities management.

Georgia Tech’s building systems already contain the information that can be used to interpret these alert messages. The information pertaining to the sensor’s location and setting, relevant building components and systems, the occupancy schedules, the actual space utilization, etc., can be found in systems such as the BAS, the Computerized Maintenance Management System (CMMS), BIM models, the events reservation website, etc. The challenge is that facility managers do not have an efficient way to acquire this type of information because these building systems are not connected to each other. The facility managers need a system that can analyze these alert messages to identify the important ones and to provide them 1) the problem description, 2) the severity degree of the problem, 3) possible influences with 3D visualization in BIM, 4) possible solutions, and 5) potential resources needed to solve the problem.

The alert messages from building systems should be taken seriously because they may be pertinent to critical building components’ operation and maintenance, facility emergency, or even life safety. However, because the alert rules are not set properly, and the facility managers lack the means to quickly understand their reasons and potential influences, the alert messages can be so overwhelming that the facility managers have no choice but to ignore them. This may lead to overlooking the important alert messages that report serious risks, such as electric leakage, potential water damage, fire alarm failures, etc. Therefore, it is critical to, first, understand the natures of these alert messages, and then develop a method to interpret them into a comprehensible form so that facility managers can understand them quickly.

### **7.3 A real-time occupancy information visualization and recording system**

A university’s facility management department is using an innovative web service that can show the real-time occupancy information of each space in every campus building. Through color schemed 3D building models, the web shows whether there are people in a certain space or not, and the web server has been recording the historical data of the occupancy information. This web service can be used for the following purposes:

- a) The facility management department analyzes the statistical data to support the decision making in space management: identifying underused and overused spaces, forecasting space requirements, and managing the new or renovation construction projects accordingly.
- b) The facility management department can use it to control energy consumption. For example,

corrective measures can be taken when a room is unoccupied, such as turning off the computers and air conditioner remotely.

- c) During an emergency (fire, shooting, etc.), the police department can use the web to understand which buildings/rooms close to the incident site still have people in them, and dispatch police force and first aid accordingly.
- d) The police department can also use the web as a supplementary security system. If the access control system shows there should not be anyone in the building/room but the web shows there is, the police can identify a potential problem.

To realize the use case, a system architecture is proposed, as Figure 17 shows. The system aims to achieve two information flow – the occupancy information flow and the building information flow – and integrate them with an IFC model database. After the integration, the building model with real-time occupancy information is visualized by a rendering engine, such as WebGL or Online BIMViewer, and then presented by a web application.

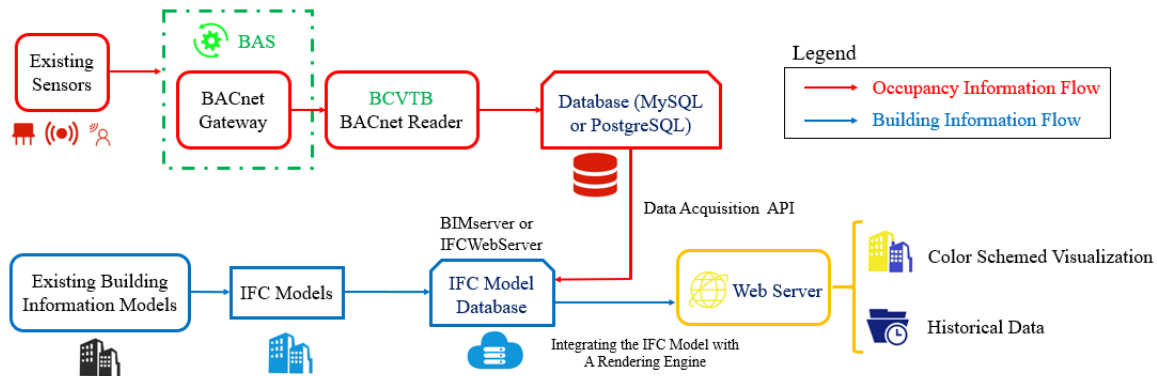


Figure 17. The proposed real-time occupancy status visualization system architecture

Regarding the occupancy information flow, the existing sensors – lighting sensors, security sensors, etc. – provide the occupancy information to the BAS. Then, we can use a tool called Building Control Virtual Test Bed (BCVTB), a simulation software environment developed by the Lawrence Berkeley National Laboratory, to extract the sensor data from the BACnet gateway of the BAS [39]. The BACnet stack module of BCVTB allows exchanging data with the BACnet compliant BAS (bacnet.sourceforge.net). The process of using BCVTB to extract sensor data is described by [63-66]. The data extracted by BCVTB can be imported into a specific database, such as MySQL and PostgreSQL. Figure 18 shows one example of reading properties from BACnet devices and then sending the values to a database [64].

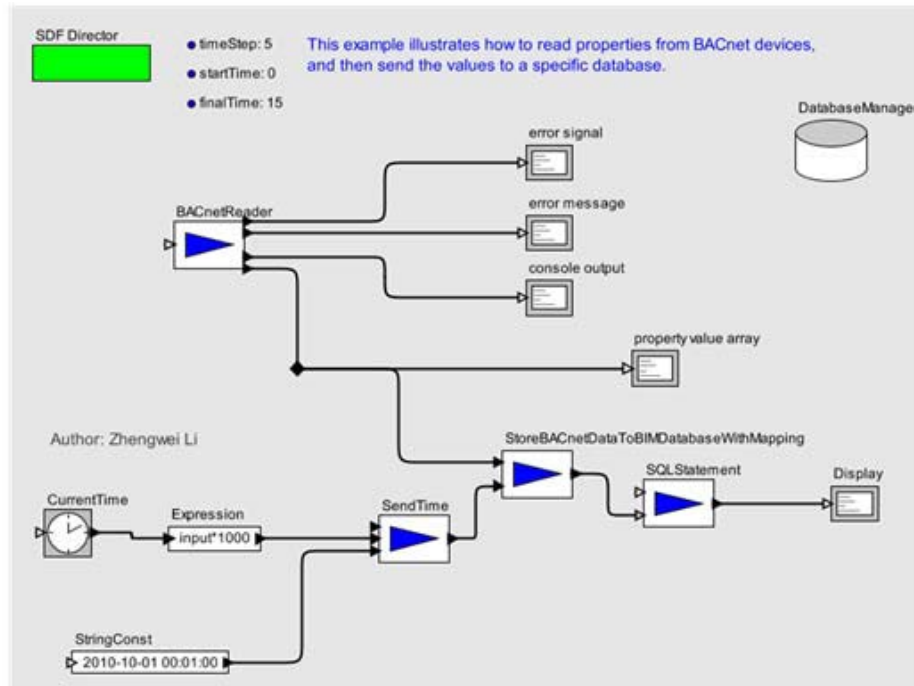


Figure 18. An example of reading properties from BACnet devices and then sending the values to a database [64]

The building information flow from the existing building information models to IFC models and then to an IFC Model Database (BIMserver or IFCWebServer) can be achieved easily by commercial software and has been done by many studies [67-69].

The challenging part is the integration. If there is any IFC model database can import dynamic data from an external database and provide the “real-time” IFC model to a rendering engine that can visualize the model through a web application, then the proposed system can be realized without an extensive effort. However, this is a big “if”. To my knowledge, a powerful IFC model database like this has yet been developed. Otherwise, the effort of a recently published study would be in vain [70]. In this study, the authors developed their own language, named Building Information Modeling Sensor Language(BIMSL), to addresses the engineering complexity associated with integrating sensor data with BIM [70]. The system architecture is shown in Figure 19 [70].

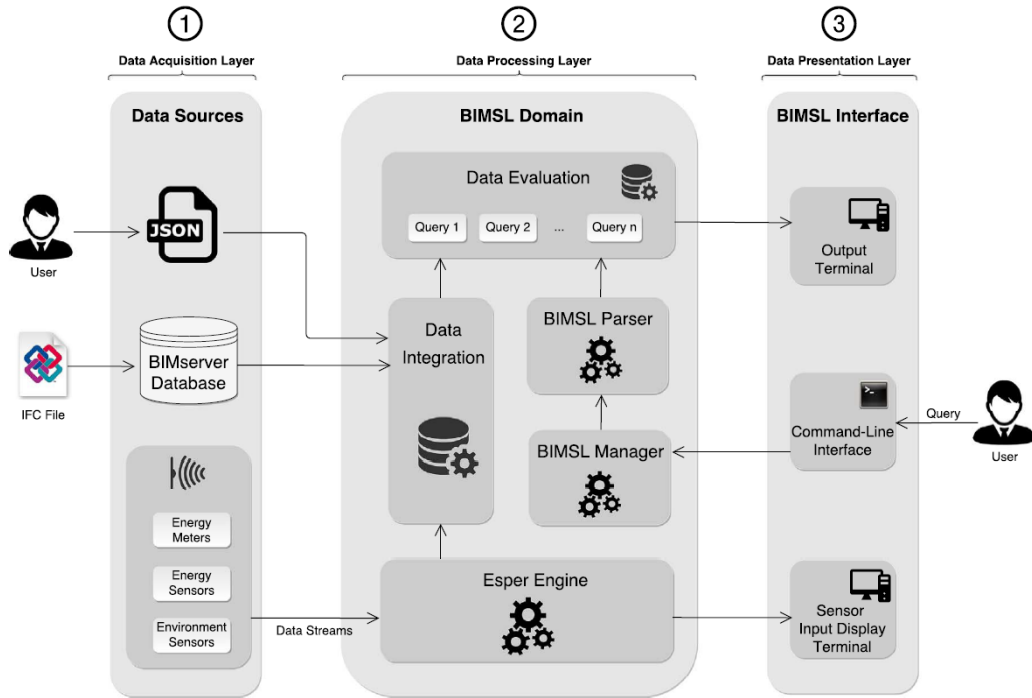


Figure 19. The architecture of BIMSL (Building Information Modeling Sensor Language) [70]

In the proposed use case, the data requirements are simple. Occupancy data can be acquired from the database by API and then imported into the IFC model database. Even if the IFC schema cannot house all the required data from BACnet, we can create several customized tables and columns in the IFC database and link them with primary keys of existing IFC data fields (an example is shown in Figure 20. By doing this, we have the “informed” IFC model to be visualized.

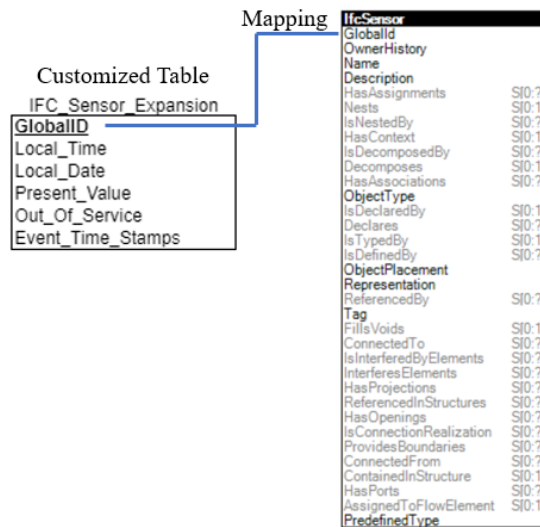


Figure 20. An example of customized data table and columns in the IFC database

#### 7.4 Use cases identified in the Digital Building Laboratory symposium

In the Digital Building Laboratory (DBL) annual symposium in May 2018, we conducted a workshop to understand the DBL members' perceptions of IoT and its potential applications in the built environment. The several innovative use cases proposed are presented in this section.

##### Use case 1: Counter in Screw Guns

This proposed CPS is a smart screw gun with the sensor that can count how many screws have been drilled into wallboards and can recognize who is using it. The project manager would like to know the statistic of how much material (of various types) is installed and by whom. The goal of this product is to know the productivity of an individual laborer. The users involve carpenters, foremen, project managers, and executives.

Sub-devices involve fingerprint gun trigger lock and the counting mechanism/sensor. Probably, the user's smartphone can work as the data collection device.

Data needed: besides the general construction project information, additional data are needed, including the time stamp, the location (floor, room), tool status – how many cycles before failure, proactive and preventative maintenance, degree of completion – material installed/required, problems – questions raised by productivity drops – and force resolution.

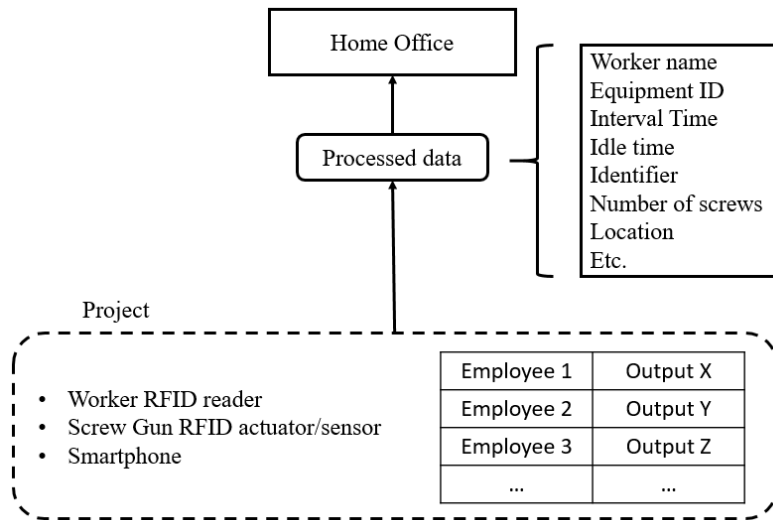


Figure 21. Data flow of the proposed screw gun with counter

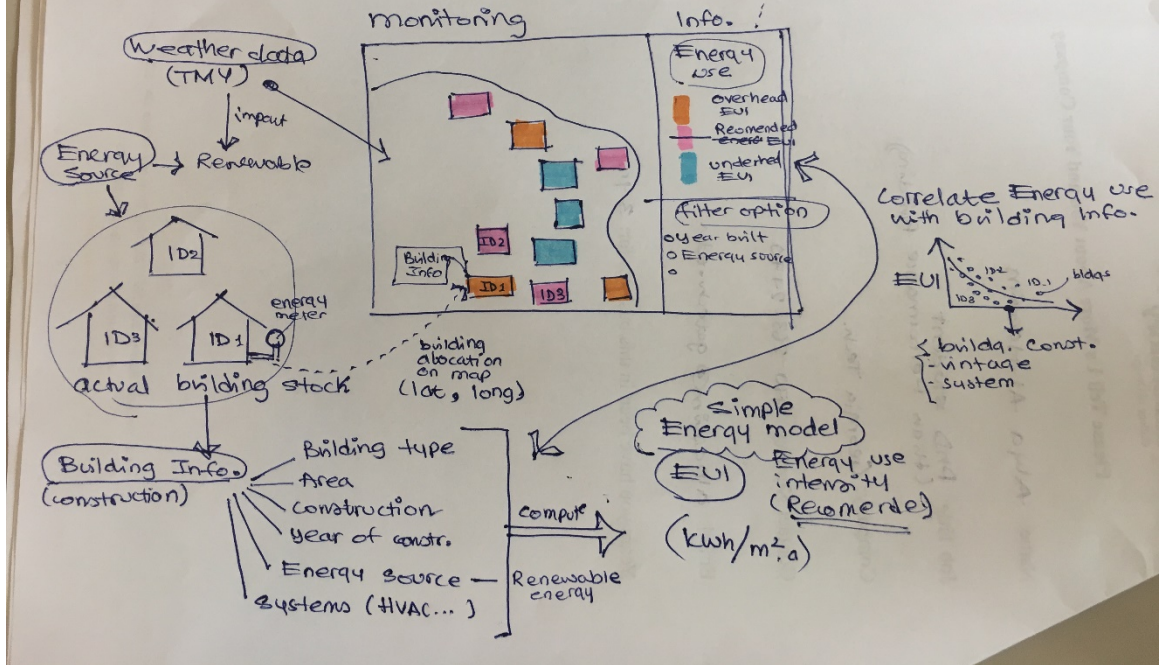
This use case is proposed by John Lord, the Chief Technology Officer at Component Assembly Systems.

**Use case 2: Map-based Energy Use Visualization**

This proposed CPS is a web that connects real-time building energy data for visualization. This system can provide baseline energy consumption for benchmarking with simulation record. The analyst can have a glance at the energy state/statistics on a nationwide scale. Detecting anomaly energy use in a building. The users involve energy companies and the government.



provide public servant/policy makers  
with enhanced evidence of national statistics identifying outliers



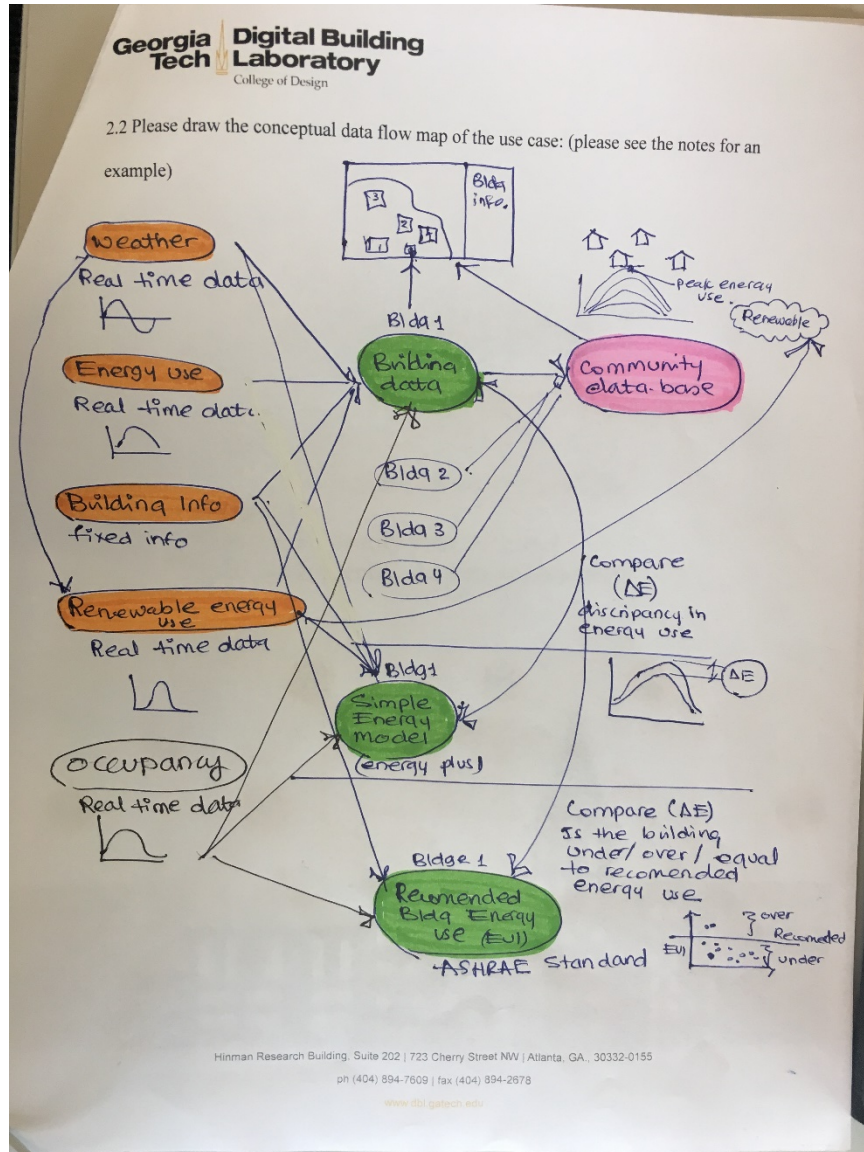


Figure 22. The web-based real-time building energy data visualization system

This use case is proposed by Alya Al-Hassium, a PhD student at Georgia Tech.

### Use case 3: Construction Activity Monitoring

This proposed CPS uses wearables on laborers to track time, productivity, safety, and health. These wearables on vests, helmet, and vehicles can send signals to the server. The data will be processed and analyzed by the proposed system and the managers can receive notifications through the smartphone app. The users are the project management team.

This use case is proposed by Tim Gayiora, Strategic Innovation Leader at DPR.

#### Use case 4: Protecting Inventory at Residential Construction Sites

Currently, inventory is delivered to a job site for construction workers to use but the job site is usually unsecured at night and weekends. There is a need that multiple parties have the proper access to the inventory onsite. The goal is to obtain 100% inventory integrity without shrinkage. The users involve the superintendent, security, police, logistics companies, and subcontractors.

This use case is proposed by Paul Skrovan, the Director of SCM Americas at Flex.

#### Use case 5: Automated Operation and Maintenance Request Generation (Smart Floor)

This proposed CPS uses simple robotic agents to 1) monitor building conditions, 2) perform basic cleaning, and 3) generate maintenance requests automatically. For example, the agent can detect a coffee spill on the floor and clean it. If the agent cannot handle the contamination, it will generate a maintenance request and notify the building operator.

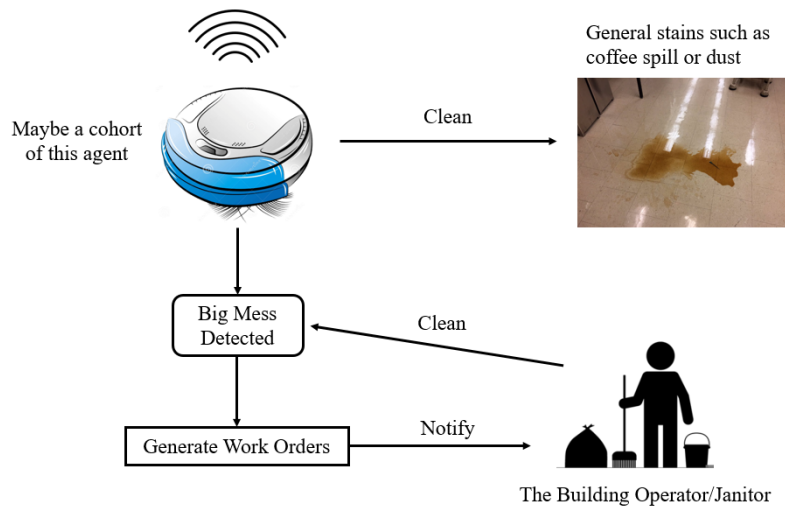


Figure 23. The proposed smart robotic agents

This use case is proposed by Jung-Ho Lew, a Research Engineer at Georgia Tech.

## 8. The Next Step

Based on the findings and methods proposed in this research, we are conducting a research on using the data in building systems to predict a facility's life cycle cost through machine learning, which is one of the identified uses cases that enabled by the IoT applications in the built environment.

A large amount of resources are spent on constructing new facilities and maintaining the existing ones. The total cost of facility ownership can be minimized by focusing on reducing the facilities life-cycle costs rather than the initial design and construction costs. However, Life Cycle Cost Analysis (LCCA) has been difficult to implement in the Architecture, Engineering, Construction and Owner-operated (AECO) industry due to the insufficient understanding of a facility's Life-cycle Cost (LCC). The AECO industry lacks reliable data on LCC of different types of building materials, assemblies, and usage patterns over the broad portfolio of each organization's facilities [71].

In recent years, with the developments of machine learning in predictive analytics and the IoT systems that provide ubiquitous sensing and metering devices in buildings, new opportunities have emerged for AECO professionals to obtain a deeper level of knowledge on buildings and their systems' LCCs. This ongoing research will contribute to the body of knowledge by investigating the feasibility of obtaining an accurate estimation of facilities' LCCs by implementing machine learning on historical data, which are collected through IoT devices deployed in the built environment. It will lead to a clearer understanding of facility LCCs and will enable data-based LCC inputs in future facility cost benchmarking. A generalizable framework will be proposed to forecast the total cost of facility ownership. This kind of knowledge provides a foundation for more informed and effective decision makings in building design, construction, operation, and renovation. Moreover, by analyzing the facility historical data, we also have opportunities to uncover hidden insights of a building system, a facility, or an organization, which are unknown for now. We envision that incorporating this kind of prediction data into the project development will lead to more cost-effective facilities.

## Appendices

### Appendix A. The organizations working on Smart Building standards

Organization Abbreviation	Organization Name	Sub-group/project	Country	Products	Industry /Domain	Establish Date	URL
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers		US	BACnet	AECO	1894	www.ashrae.org
buildingSMART	buildingSMART		US	IFC	AECO	1994	buildingsmart.org
CABA	Continental Automated Buildings Association		North America		AECO	1988	www.caba.org
GSA	General Services Administration	Office of Facilities Management and Services Programs	US	GSA & Smart Buildings	Government Service	1949	www.gsa.gov

Intel	Intel	Smart Buildings with Internet of Things Technologies Intel IT Internet of Things Group (IOTG)	US	IoT Data Standards Provide the Foundation for Smart Buildings		1968	<a href="http://www.intel.com/content/www/us/en/smart-buildings/overview.html">www.intel.com/content/www/us/en/smart-buildings/overview.html</a>
New York Government	New York Government	BuildSmart NY	US	Executive Order 88 Guidelines	AECO	2013	<a href="http://www.nypa.gov/innovation/programs/buildsmart-ny">http://www.nypa.gov/innovation/programs/buildsmart-ny</a>
NIST	National Institute of Standards and Technology	Smart Building Automation and Control Testbed and Standards Project	US		All	2011	<a href="http://www.nist.gov/programs-projects/smart-building-automation-and-control-testbed-and-standards-project">www.nist.gov/programs-projects/smart-building-automation-and-control-testbed-and-standards-project</a>
The Climate Group	The Climate Group	SMART2020	Global (UK headquarters)	SMART2020 report	Environmental Charity	2004	<a href="http://www.theclimategroup.org/">www.theclimategroup.org/</a>
Tridium	Tridium	Niagara Framework	US	Niagara Framework Guide Specification	Engineering automation	1995	<a href="http://tridium.com">tridium.com</a>

## Appendix B. The building automation standards and protocols

Abbreviation	Standard/protocol Name	Organization	Description	URL
1-Wire	1-Wire	Dallas Semiconductor/Maxim	1-Wire is a device communications bus system that provides low-speed data, signaling, and power over a single conductor.	<a href="http://www.maximintegrated.com/en/app-notes/index.mvp/id/1796">www.maximintegrated.com/en/app-notes/index.mvp/id/1796</a>
BACnet	Building Automation and Controls Network	ASHRAE	BACnet is a non-proprietary and open communication protocol for building automation and control networks. BACnet allows communication of building automation and control systems for applications in heating, ventilating and air-conditioning control (HVAC), as well as in lighting control, access control and fire detection systems and their associated equipment.	<a href="http://www.bacnet.org">www.bacnet.org</a>
C-Bus	C-Bus	Clipsal Integrated Systems	C-Bus is a communications protocol based on a seven-layer OSI model for home and building automation that can handle cable lengths up to 1000 meters using Cat-5 cable. It is used in Australia, New Zealand, Asia, the Middle East, Russia, United States, South Africa, the UK and other parts of Europe including Greece and Romania.	<a href="http://en.wikipedia.org/wiki/C-Bus_(protocol)">en.wikipedia.org/wiki/C-Bus_(protocol)</a>

CC-Link Industrial Networks	CC-Link Industrial Networks	Mitsubishi Electric	CC-Link is open industrial network that enables devices from numerous manufacturers to communicate. It is predominantly used in machine, cell or process control applications in manufacturing and production industries, but can also be used in facilities management, process control and building automation.	<a href="http://www.clpa-europe.com">www.clpa-europe.com</a>
DALI	Digital Addressable Lighting Interface	Digital Illumination Interface Alliance	DALI is a trademark for network-based systems that control lighting in building automation. The underlying technology was established by a consortium of lighting equipment manufacturers as a successor for 0-10 V lighting control systems, and as an open standard alternative to Digital Signal Interface (DSI), on which it is based.	<a href="http://en.wikipedia.org/wiki/Digital_Addressable_Lighting_Interface">en.wikipedia.org/wiki/Digital_Addressable_Lighting_Interface</a>
DSI	Digital Serial Interface	Tridonic	DSI is a protocol for the controlling of lighting in buildings (initially electrical ballasts). It was created in 1991 by Austrian company Tridonic and is based on Manchester-coded 8-bit protocol, data rate of 1200 baud, 1 start bit, 8 data bits (dimming value), 4 stop bits, and is the basis of the more sophisticated protocol Digital Addressable Lighting Interface (DALI).	<a href="http://en.wikipedia.org/wiki/Digital_Serial_Interface">en.wikipedia.org/wiki/Digital_Serial_Interface</a>
Dynet	Dynet	Philips Lighting	DyNet is the communications network and communications protocol for Dyalite lighting automation and building automation.	<a href="http://www.lighting.philips.com/main/products/lighting-controls/dynalite">www.lighting.philips.com/main/products/lighting-controls/dynalite</a>



EnOcean	EnOcean	EnOcean GmbH	<p>The EnOcean technology is an energy harvesting wireless technology used primarily in building automation systems, and is also applied to other applications in industry, transportation, logistics and smart homes. Modules based on EnOcean technology combine micro energy converters with ultra low power electronics, and enable wireless communications between batteryless wireless sensors, switches, controllers and gateways.</p>	www.enocean.com/en
IEEE 802.15.4	IEEE 802.15.4 Types of nodes	IEEE (Institute of Electrical and Electronics Engineers)	<p>IEEE 802.15.4 is a technical standard which defines the operation of low-rate wireless personal area networks (LR-WPANs). It specifies the physical layer and media access control for LR-WPANs, and is maintained by the IEEE 802.15 working group, which defined the standard in 2003. It is the basis for the ZigBee, ISA100.11a, WirelessHART, MiWi, SNAP, and Thread specifications, each of which further extends the standard by developing the upper layers which are not defined in IEEE 802.15.4. Alternatively, it can be used with 6LoWPAN, the technology used to deliver the IPv6 version of the Internet Protocol (IP) over WPANs, to define the upper layers.</p>	en.wikipedia.org/wiki/IEEE_802.15.4

SmartHome Labs Pro New 2-way Protocol based on Power-BUS.

Insteon is an Irvine, CA-based developer of home automation (aka domotics) hardware and software. The technology, also called Insteon, allows light switches, lights, thermostats, motion sensors, and other electrical devices to interoperate through power lines, radio frequency (RF) communications, or both. The company produces over 200 products featuring the technology.

KNX is a standardized (EN 50090, ISO/IEC 14543), OSI-based network communications protocol for building automation. KNX is the successor to, and convergence of, three previous standards: the European Home Systems Protocol (EHS), BatiBUS, and the European Installation Bus (EIB or Instabus). The KNX standard is administered by the KNX Association.

Insteon

Insteon

Smartlabs, Inc.

[www.insteon.com](http://www.insteon.com)

KNS

KNS

The KNX Association

[www.knx.org/knx-en/index.php](http://www.knx.org/knx-en/index.php)

LonTalk	LonTalk	Echelon Corporation	<p>LonTalk is a protocol optimized for control. Originally developed by Echelon Corporation for networking devices over media such as twisted pair, powerlines, fiber optics, and RF. It is popular for the automation of various functions in industrial control, home automation, transportation, and buildings systems such as lighting and HVAC; see Intelligent building, the protocol has now been adopted as an open international control networking standard in the ISO/IEC 14908 family of standards. Published through ISO/IEC JTC 1/SC 6, this standard specifies a multi-purpose control network protocol stack optimized for smart grid, smart building, and smart city applications..</p>	<p><a href="https://en.wikipedia.org/wiki/LonTalk">en.wikipedia.org/wiki/LonTalk</a></p>
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LonWorks	local operating network	LonMark International	<p>It is a networking platform specifically created to address the needs of control applications. The platform is built on a protocol created by Echelon Corporation for networking devices over media such as twisted pair, powerlines, fiber optics, and RF. It is used for the automation of various functions within buildings such as lighting and HVAC.</p>	<p><a href="http://www.lonmark.org">www.lonmark.org</a></p>
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The MiWi protocol is based on the MAC and PHY layers of the IEEE 802.15.4 specification. It is designed in order to develop simple networks in the 2.4 GHz band.

MiWi and MiWi P2P are proprietary wireless protocols designed by Microchip Technology that use small, low-power digital radios based on the IEEE 802.15.4 standard for wireless personal area networks (WPANs). It is designed for low data transmission rates and short distance, cost constrained networks, such as industrial monitoring and control, home and building automation, remote control, low-power wireless sensors, lighting control and automated meter reading.

[www.microchip.com/design-centers/wireless-connectivity/embedded-wireless/802-15-4/software/miwi-protocol](http://www.microchip.com/design-centers/wireless-connectivity/embedded-wireless/802-15-4/software/miwi-protocol)

A commonly available means of connecting industrial electronic devices.

oBIX is a standard for RESTful Web Services-based interfaces to building control systems. oBIX is about reading and writing data over a network of devices using XML and URIs, within a framework specifically designed for building automation.

OPC is the interoperability standard for the secure and reliable exchange of data in the industrial automation space and in other industries

[www.modbus.org](http://www.modbus.org)

[www.obix.org](http://www.obix.org)

[opcfoundation.org](http://opcfoundation.org)

VSCP	Very Simple Control Protocol	Paradise of the Frog AB	VSCP is a free automation protocol suitable for all sorts of automation task where building- or home-automation is in the main focus. Its main advantage is that each VSCP-node can work completely autonomous, being part of distributed network of other nodes.	<a href="http://www.vscp.org">www.vscp.org</a>
X10	X10	Pico Electronics of Glenrothes	X10 is a protocol for communication among electronic devices used for home automation (domotics). It primarily uses power line wiring for signaling and control, where the signals involve brief radio frequency bursts representing digital information. A wireless radio based protocol transport is also defined.	<a href="http://kbase.x10.com/wiki/Main_Page">kbase.x10.com/wiki/Main_Page</a>
xAP	xAP	xAP Automation	xAP is an open protocol used for home automation and supports integration of telemetry and control devices primarily within the home. Common communications networks include RS232, RS485, Ethernet & wireless. xAP protocol always uses broadcast for sending the messages. All the receivers listens to the message and introspects the message header to verify whether the message is of its interest. xAP protocol has the following key advantages.	<a href="http://www.xapautomation.org/index.php?title=xAP_Home_Automation_protocol">www.xapautomation.org/index.php?title=xAP_Home_Automation_protocol</a>

Zigbee is an IEEE 802.15.4-based specification for a suite of high-level communication protocols used to create personal area networks with small, low-power digital radios, such as for home automation, medical device data collection, and other low-power low-bandwidth needs, designed for small scale projects which need wireless connection. Hence, zigbee is a low-power, low data rate, and close proximity (i.e., personal area) wireless ad hoc network.

Z-Wave is a wireless communications protocol used primarily for home automation. It is oriented to the residential control and automation market and is intended to provide a simple and reliable method to wirelessly control lighting, HVAC, security systems, home cinema, automated window treatments, swimming pool and spa controls, and garage and home access controls.

Zigbee	Zigbee	Zigbee Alliance		<a href="http://www.zigbee.org">www.zigbee.org</a>
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Z-Wave	Z-Wave	Sigma Designs		<a href="http://www.z-wave.com">www.z-wave.com</a>
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### Appendix C. The smart city standards and the organizations

Organization	Standard Abbreviation	Standard Name	URL
ANSI	ANSSC	The ANSI Network on Smart and Sustainable Cities	<a href="http://www.ansi.org/standards_activities/standards_boards_panels/anssc/overview?menuid=3">www.ansi.org/standards_activities/standards_boards_panels/anssc/overview?menuid=3</a>
	PAS 180	The development of a standard on Smart city terminology	<a href="http://www.bsigroup.com/en-GB/smart-cities/Smart-Cities-Standards-and-Publication/">www.bsigroup.com/en-GB/smart-cities/Smart-Cities-Standards-and-Publication/</a>
	PAS 181	The development of a standard on Smart city terminology	<a href="http://www.bsigroup.com/en-GB/smart-cities/Smart-Cities-Standards-and-Publication/">www.bsigroup.com/en-GB/smart-cities/Smart-Cities-Standards-and-Publication/</a>
British Standards Institute (BSI)	PAS 182	The development of a Data concept model for smart cities	<a href="http://www.bsigroup.com/en-GB/smart-cities/Smart-Cities-Standards-and-Publication/">www.bsigroup.com/en-GB/smart-cities/Smart-Cities-Standards-and-Publication/</a>
	PD 8100	A Smart city overview document	<a href="http://www.bsigroup.com/en-GB/smart-cities/Smart-Cities-Standards-and-Publication/">www.bsigroup.com/en-GB/smart-cities/Smart-Cities-Standards-and-Publication/</a>
	PD 8101	A Smart city planning guidelines document	<a href="http://www.bsigroup.com/en-GB/smart-cities/Smart-Cities-Standards-and-Publication/">www.bsigroup.com/en-GB/smart-cities/Smart-Cities-Standards-and-Publication/</a>
	BS 8904	Guidance for community sustainable development	<a href="http://shop.bsigroup.com/ProductDetail/?pid=000000000030262156">shop.bsigroup.com/ProductDetail/?pid=000000000030262156</a>

CEN			
CENELEC			
ETSI			
Coordination Group on Smart and Sustainable, Cities and Communities	SSCC-CG Final report	Smart and Sustainable Cities and Communities Coordination Group	<a href="http://www.cenelec.eu/standards/Sectors/SmartLiving/smartcities/Pages/SSCC-CG.aspx">www.cenelec.eu/standards/Sectors/SmartLiving/smartcities/Pages/SSCC-CG.aspx</a>
	SCC	Smart Cities and Communities European Innovation Partnership	<a href="http://ec.europa.eu/eip/smartcities/">ec.europa.eu/eip/smartcities/</a>
European Commission	FP7	EU's Seventh Framework Programme for Research	<a href="http://ec.europa.eu/research/fp7/index_en.cfm">ec.europa.eu/research/fp7/index_en.cfm</a>
	European Smart Cities Ranking		<a href="http://www.smart-cities.eu/ranking.html">www.smart-cities.eu/ranking.html</a>
	IEC/TR 62357:2003	Power system control and associated communications - Reference architecture for object models, services and protocols	
IEC Systems Evaluation Group on Smart Cities	IEC 61850	Power Utility Automation	
	IEC 61970	Common Information Model (CIM) / Energy Management	
	IEC 61968	Common Information Model (CIM) / Distribution Management	
	IEC 62351	Information Security for Power System Control Operations	
	IEC PC118	Smart Grid User Interface	
	IEEE 2030.1	Draft Guide for Electric-Sourced Transportation Infrastructure	<a href="http://standards.ieee.org/findstds/standard/2030.1.1-2015.html">standards.ieee.org/findstds/standard/2030.1.1-2015.html</a>



IEEE Standards Association	IEEE 2030.2	Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure	<a href="http://standards.ieee.org/develop/wg/P2030.2_Interop_Energy_Stor..html">standards.ieee.org/develop/wg/P2030.2_Interop_Energy_Stor..html</a>
	IEEE 2030.3	IEEE Standard Test Procedures for Electric Energy Storage Equipment and Systems for Electric Power Systems Applications	<a href="http://standards.ieee.org/findstds/standard/2030.3-2016.html">standards.ieee.org/findstds/standard/2030.3-2016.html</a>
	IEEE 1901		<a href="http://standards.ieee.org/findstds/standard/1901-2010.html">standards.ieee.org/findstds/standard/1901-2010.html</a>
ISO/IEC JTC1 Study Group on Smart Cities	Internet of things Preliminary Report 2014		<a href="http://www.iso.org/isoiec-jtc-1.html">www.iso.org/isoiec-jtc-1.html</a>
	Smart Cities Preliminary Report 2014		<a href="http://www.iso.org/isoiec-jtc-1.html">www.iso.org/isoiec-jtc-1.html</a>
ISO /TC TMB	ISO 20121:2012	Event sustainability management systems -- Requirements with guidance for use	
	ISO 26000:2010	Guidance on social responsibility	
ISO/TC 59	ISO 15686	Buildings and constructed assets – Service life planning	
	ISO 16739	Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries	
ISO/TC 163 and ISO/TC 205	ISO 16346	Energy performance of buildings -- Assessment of overall energy performance	
	ISO 16343	Energy performance of buildings -- Methods for expressing energy performance and for energy certification of buildings	

	ISO 12655	Energy performance of buildings -- Presentation of measured energy use of buildings
	ISO/TR 16344:2012	Energy performance of buildings -- Common terms, definitions and symbols for the overall energy performance rating and certification
	ISO 13153:2012	Framework of the design process for energy-saving single-family residential and small commercial buildings
	ISO 37101	Sustainable development in communities — Management system for sustainable development — Requirements with guidance for use
ISO/TC 268/SC 1 Smart Community Infrastructure	ISO 37120	Sustainable development of communities -- Indicators for city services and quality of life
	ISO/TR 37150	Smart community infrastructures -- Review of existing activities relevant to metrics
	ISO 37151	Smart community infrastructures -- Principles and requirements for performance metrics
	ISO 22316	Security and resilience -- Organizational resilience -- Principles and attributes
	ISO 22301:2012	Societal security -- Business continuity management systems --- Requirements
ISO/TC 223	ISO 22313:2012	Societal security -- Business continuity management systems -- Guidance
	ISO 22398	Societal security -- Guidelines for exercises
	ISO 22320:2011	Societal security -- Emergency management -- Requirements for incident response

	ISO 22324	Societal security -- Emergency management -- Guidelines for colour-coded alerts	
ISO/TC 241	ISO 39001:2012	Road traffic safety (RTS) management systems – Requirements with guidance for use	
ISO /TC 242	ISO 50001:2011	Energy management systems -- Requirements with guidance for use	
ITU-T Focus Group on Smart, Sustainable Cities	SSC-0110	Smart Sustainable Cities 0110	<a href="http://www.itu.int/en/ITU-T/focusgroups/ssc/Pages/default.aspx">www.itu.int/en/ITU-T/focusgroups/ssc/Pages/default.aspx</a>
NIST	IES city	International Technical Working Group on IoT-Enabled Smart City Framework	<a href="http://pages.nist.gov/smartcitiesarchitecture/">pages.nist.gov/smartcitiesarchitecture/</a>

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## Appendix D. The organizations working on IoT Standards and Protocols

Organization Abbreviation	Organization Name	Country	Industry/Domain	Date of Establishment	URL
ANSI	American National Standards Institute	US	All	1918	<a href="http://webstore.ansi.org">webstore.ansi.org</a>
Eclipse Foundation	Eclipse Foundation	US	ICT	2001 (2011)	<a href="http://www.eclipse.org/paho/">http://www.eclipse.org/paho/</a>
ENEA	Italian National Agency for New Technologies	Italy	All	1982	<a href="http://www.enea.it/en/">www.enea.it/en/</a>
EPCglobal	Electronic Product Code Global	US	RFID	2003	<a href="http://workspace.winnforum.org/higherlogic/ws/public">workspace.winnforum.org/higherlogic/ws/public</a>
ETSI	The European Telecommunications Standards Institute	Europe	ICT	1988	<a href="http://www.etsi.org">www.etsi.org</a>
FIWARE	FIWARE	Europe	IoT	2007	<a href="http://www.fiware.org">www.fiware.org</a>
GBCI	Green Business Certification Inc.	US	AECO (Sustainability)	2008	<a href="http://www.gbci.org">www.gbci.org</a>
IEC	International Electrotechnical Commission	Global	Electrical and Electronic	1906	<a href="http://www.iec.ch/">http://www.iec.ch/</a>

IEEE IoT	Institute of Electrical and Electronics Engineers	US	ICT	1963	<a href="http://standards.ieee.org/innovate/iot/">standards.ieee.org/innovate/iot/</a>
IEEE Smart Cities	Institute of Electrical and Electronics Engineers	US	Smart City	2014	<a href="http://smartcities.ieee.org">smartcities.ieee.org</a>
IETF	Internet Engineering Task Force	US	ICT		<a href="http://irtf.org/concluded/hiprg">irtf.org/concluded/hiprg</a>
IETF	Internet Engineering Task Force	US	ICT	2010	<a href="http://datatracker.ietf.org/wg/core/charter/">datatracker.ietf.org/wg/core/charter/</a>
IETF	Internet Engineering Task Force	US	ICT	2005	<a href="http://datatracker.ietf.org/wg/6lowpan/documents/">datatracker.ietf.org/wg/6lowpan/documents/</a>
IETF	Internet Engineering Task Force	US	ICT	2008	<a href="http://datatracker.ietf.org/wg/roll/charter/">datatracker.ietf.org/wg/roll/charter/</a>
IoT-A	Internet-of-Things Architecture	Europe	IoT		<a href="http://open-platforms.eu/standard_protocol/iot-a-architectural-reference-model/">http://open-platforms.eu/standard_protocol/iot-a-architectural-reference-model/</a>

ISA	International Society of Automation	US	Industrial Automation	1945	<a href="http://www.isa.org">www.isa.org</a>
ISO TMB SAG	ISO Technical Management Board Special Advisory Group on Smart Cities	Global	Smart City	2014	<a href="http://www.iso.org/committee/4882545.html">www.iso.org/committee/4882545.html</a>
ISO/IEC JTC 1	The IEC (International Electrotechnical Commission) and ISO (International Organization for Standardization), through the JTC (Joint Technical Committee).		ICT	1987	<a href="http://www.iso.org/isoiec-jtc-1.html">www.iso.org/isoiec-jtc-1.html</a>
MSIP	Ministry of Science, ICT and Future Planning	Korea	All	2013	<a href="http://english.msip.go.kr/english/main/main.do">english.msip.go.kr/english/main/main.do</a>
NIST	National Institute of Standards and Technology	US	All (Smart City)	1901 (2016)	<a href="https://pages.nist.gov/smartcitiesarchitecture/">https://pages.nist.gov/smartcitiesarchitecture/</a>
OGC	Open Geospatial Consortium	Global	GIS, IoT	1994 (2012)	<a href="http://www.opengeospatial.org/">http://www.opengeospatial.org/</a>
OneM2M	OneM2M	Global	M2M IoT	2012	<a href="http://www.onem2m.org">www.onem2m.org</a>

OSIOT	Open Source Internet of Things	US	IoT	2013?	<a href="http://osiot.org">osiot.org</a>
SCC	Smart Cities Council	US	Smart City	2013	<a href="http://smartcitiescouncil.com">smartcitiescouncil.com</a>
SmartM2M	Smart Machine to Machine	Europe	IoT	2013?	<a href="http://portal.etsi.org/tb.aspx?tbid=726&amp;SubTB=726">portal.etsi.org/tb.aspx?tbid=726&amp;SubTB=726</a>
TIA	The Telecommunications Industry Association	Global	ICT	1988	<a href="http://www.tiaonline.org">www.tiaonline.org</a>
UCB	University of California Berkeley	US	IoT	2012?	<a href="http://openwsn.atlassian.net/wiki/pages/viewpage.action?pageId=688187">openwsn.atlassian.net/wiki/pages/viewpage.action?pageId=688187</a>
USGBC	The U.S. Green Building Council	US	AECO	1993	<a href="http://www.usgbc.org">www.usgbc.org</a>

SF-SSCC (CEN/CENELEC/ETSI)	<p>The CEN-CENELEC-ETSI Sector Forum on Smart and Sustainable Cities and Communities</p> <p>The European Committee for Standardization (CEN), the European Committee for Electrotechnical Standardization (CENELEC) and the European Telecommunications Standards Institute (ETSI).</p>	Europe	Smart City	2017	<a href="http://www.cencenelec.eu/standards/Sectors/SmartLiving/smartcities/Pages/SSCC-CG.aspx">www.cencenelec.eu/standards/Sectors/SmartLiving/smartcities/Pages/SSCC-CG.aspx</a>
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## Appendix E. The alliances working on IoT Standards and Protocols

Alliance Abbreviation	Alliance Name	Country	Industry/Domain	Date of Establishment	URL
AIOTI	The Alliance for Internet of Things Innovation	Europe	IoT	2015	<a href="http://aioti-space.org">aioti-space.org</a>
AllSeen Alliance	AllSeen Alliance	Global	IoT		<a href="http://allseenalliance.org">allseenalliance.org</a>
ANSSC	The ANSI Network on Smart and Sustainable Cities	US	Smart City	2014	<a href="http://www.ansi.org/standards_activities/standards_boards_panels/anssc/overview?menuid=3">www.ansi.org/standards_activities/standards_boards_panels/anssc/overview?menuid=3</a>
CASAGRAS	Coordination and support action for global RFID-related activities and standardisation	Europe	RFID	2008	<a href="http://cordis.europa.eu/project/rcn/95714_en.html">cordis.europa.eu/project/rcn/95714_en.html</a>
Industrial Internet Consortium	Industrial Internet Consortium	Global	IoT	2014	<a href="http://www.iiconsortium.org">www.iiconsortium.org</a>
IPSO Alliance		Global	IoT	2008	<a href="http://www.ipso-alliance.org">www.ipso-alliance.org</a>
ITU	International Telegraph Union	United Nations	ICT	1865	<a href="http://www.itu.int/en/ITU-T/gsi/iot/Pages/default.aspx">www.itu.int/en/ITU-T/gsi/iot/Pages/default.aspx</a>
ITU-T	International Telegraph Union Telecommunication Standardization Sector	United Nations	Smart City	2013	<a href="http://www.itu.int/en/ITU-T/focusgroups/ssc/Pages/default.aspx">http://www.itu.int/en/ITU-T/focusgroups/ssc/Pages/default.aspx</a>
OASIS	Organization for the Advancement of Structured Information Standards	Global	ICT	1993	<a href="http://www.oasis-open.org/committees/tc_home.php?wg_abbrev=mqtt">www.oasis-open.org/committees/tc_home.php?wg_abbrev=mqtt</a>

OMA	Open Mobile Alliance	Global	Mobile phone	2002	<a href="http://www.openmobilealliance.org">www.openmobilealliance.org</a>
OMG	Object Management Group	Global	IoT	1989 (2015)	<a href="http://portals.omg.org/dds/">portals.omg.org/dds/</a>
W3C	World Wide Web Consortium	Global	ICT	1994 (2009)	<a href="http://www.w3.org/2005/Incubator/ssn/ssnx/ssn">www.w3.org/2005/Incubator/ssn/ssnx/ssn</a>
W3C	World Wide Web Consortium	Global	IoT	1994 (2013)	<a href="http://www.w3.org/community/wot/">www.w3.org/community/wot/</a>
Wi-SUN Alliance	Wi-SUN Alliance	Global	IoT, Smart City	2012	<a href="http://www.wi-sun.org/index.php/en">www.wi-sun.org/index.php/en</a>
World Smart City Forum	World Smart City Forum	Global	Smart City	2016	<a href="http://www.worldsmartcity.org">www.worldsmartcity.org</a>
City Protocol Society	City Protocol Society	Global	Smart City	2012	<a href="http://cityprotocol.org">cityprotocol.org</a>

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## Appendix F. The IoT Standards and Protocols [25]

Layers	Standard Abbreviation	Standard Name	URL
	IPv6	Internet Protocol version 6	<a href="http://en.wikipedia.org/wiki/IPv6">en.wikipedia.org/wiki/IPv6</a>
	6LoWPAN	IPv6 over Low power Wireless Personal Area Networks	<a href="http://en.wikipedia.org/wiki/6LoWPAN">en.wikipedia.org/wiki/6LoWPAN</a>
	UDP	User Datagram Protocol	<a href="http://tools.ietf.org/html/rfc768">tools.ietf.org/html/rfc768</a>
	QUIC	Quick UDP Internet Connections	<a href="http://en.wikipedia.org/wiki/QUIC">en.wikipedia.org/wiki/QUIC</a>
	Aeron	Aeron	<a href="https://github.com/real-logic/Aeron">github.com/real-logic/Aeron</a>
<b>1. Infrastructure</b>	uIP	micro IP	<a href="http://en.wikipedia.org/wiki/UIP_%28micro_IP%29">en.wikipedia.org/wiki/UIP_%28micro_IP%29</a>
	DTLS	Datagram Transport Layer	<a href="http://tools.ietf.org/html/rfc4347">tools.ietf.org/html/rfc4347</a>
	ROLL / RPL	Routing Over Low power and Lossy networks	<a href="http://datatracker.ietf.org/wg/roll/documents/">datatracker.ietf.org/wg/roll/documents/</a>
	NanoIP	the nano Internet Protocol	<a href="http://www.cwc.oulu.fi/nanoip/">www.cwc.oulu.fi/nanoip/</a>
	CCN	Content-Centric Networking	<a href="http://wiki.fd.io/view/Cicn">wiki.fd.io/view/Cicn</a>
	TSMP	Time Synchronized Mesh Protocol	<a href="http://en.wikipedia.org/wiki/TSMP">en.wikipedia.org/wiki/TSMP</a>

## 2. Communication / Transport layer

<b>Ethernet</b>	<b>Ethernet</b>	<a href="https://en.wikipedia.org/wiki/Ethernet">en.wikipedia.org/wiki/Ethernet</a>
WirelessHart	Highway Addressable Remote Transducer Protocol	<a href="https://en.wikipedia.org/wiki/WirelessHART">en.wikipedia.org/wiki/WirelessHART</a>
DigiMesh	DigiMesh	<a href="http://www.digi.com/products/digimesh">www.digi.com/products/digimesh</a>
ISA100.11a	International Society of Automation 100.11a	<a href="https://en.wikipedia.org/wiki/ISA100.11a">en.wikipedia.org/wiki/ISA100.11a</a>
IEEE 802.15.4	Institute of Electrical and Electronics Engineers 802.15.4	<a href="https://en.wikipedia.org/wiki/IEEE_802.15.4">en.wikipedia.org/wiki/IEEE_802.15.4</a>
NFC	Near Field Communication	<a href="http://nfc-forum.org">nfc-forum.org</a>
ANT		<a href="https://en.wikipedia.org/wiki/ANT_(network)">en.wikipedia.org/wiki/ANT_(network)</a>
Bluetooth	Bluetooth	<a href="http://www.bluetooth.com">www.bluetooth.com</a>
Eddystone	Eddystone	<a href="https://github.com/google/edystone">github.com/google/edystone</a>
ZigBee	ZigBee	<a href="http://www.zigbee.org">www.zigbee.org</a>
EnOcean		<a href="http://www.enocean.com">www.enocean.com</a>
WiFi		<a href="http://www.wi-fi.org">www.wi-fi.org</a>
WiMax	Worldwide Interoperability for Microwave Access	<a href="https://en.wikipedia.org/wiki/WiMAX">en.wikipedia.org/wiki/WiMAX</a>
<b>LPWAN</b>	Low-Power Wide-Area Network	<a href="https://en.wikipedia.org/wiki/LPWAN">en.wikipedia.org/wiki/LPWAN</a>
Weightless		<a href="http://www.weightless.org">www.weightless.org</a>

NB-IoT	Narrow-Band IoT	<a href="https://en.wikipedia.org/wiki/NarrowBand_IOT">en.wikipedia.org/wiki/NarrowBand_IOT</a>
LTE-MTC	LTE-Machine Type Communication	<a href="http://www.gsma.com/iot/long-term-evolution-machine-type-communication-lte-mtc-cat-m1/">www.gsma.com/iot/long-term-evolution-machine-type-communication-lte-mtc-cat-m1/</a>
EC-GSM-IoT	Extended Coverage-GSM-IoT	<a href="http://www.gsma.com/iot/extended-coverage-gsm-internet-of-things-ec-gsm-iot/">www.gsma.com/iot/extended-coverage-gsm-internet-of-things-ec-gsm-iot/</a>
LoRaWAN	LoRaWAN	<a href="http://www.lora-alliance.org">www.lora-alliance.org</a>
RPMA	Random phase multiple access	<a href="https://en.wikipedia.org/wiki/Random_phase_multiple_access">en.wikipedia.org/wiki/Random_phase_multiple_access</a>
<b>GPRS/2G/3G/4G cellular</b>		
mDNS	multicast Domain Name System	<a href="https://en.wikipedia.org/wiki/Multicast_DNS">en.wikipedia.org/wiki/Multicast_DNS</a>
<b>3. Discovery</b>	Physical Web	<a href="https://google.github.io/physical-web/faq">google.github.io/physical-web/faq</a>
	HyperCat	<a href="http://www.hypercat.io/standard.html">www.hypercat.io/standard.html</a>

#### 4. Data Protocols

UPnP	Universal Plug and Play	<a href="http://en.wikipedia.org/wiki/Universal_Plug_and_Play">en.wikipedia.org/wiki/Universal_Plug_and_Play</a>
MQTT	Message Queuing Telemetry Transport	<a href="http://mqtt.org">mqtt.org</a>
MQTT-SN	MQTT For Sensor Networks	<a href="http://mqtt.org/2013/12/mqtt-for-sensor-networks-mqtt-sn">mqtt.org/2013/12/mqtt-for-sensor-networks-mqtt-sn</a>
CoAP	Constrained Application Protocol	<a href="http://datatracker.ietf.org/doc/rfc7252/">datatracker.ietf.org/doc/rfc7252/</a>
SMCP		<a href="https://github.com/darconeous/smcp/tree/smcp-0.6">github.com/darconeous/smcp/tree/smcp-0.6</a>
STOMP	The Simple Text Oriented Messaging Protocol	<a href="http://stomp.github.io/implementations.html">stomp.github.io/implementations.html</a>
XMPP	Extensible Messaging and Presence Protocol	<a href="http://xmpp.org">xmpp.org</a>
XMPP-IoT		<a href="https://github.com/joachimlindborg/XMPP-IoT">github.com/joachimlindborg/XMPP-IoT</a>
Mihini/M3DA		<a href="http://wiki.eclipse.org/Mihini/M3DA_Specification">wiki.eclipse.org/Mihini/M3DA_Specification</a>
AMQP	Advanced Message Queuing Protocol	<a href="http://www.amqp.org">www.amqp.org</a>
DDS	Data-Distribution Service for Real-Time Systems	<a href="http://portals.omg.org/dds/">portals.omg.org/dds/</a>

JMS	Java Message Service	<a href="http://en.wikipedia.org/wiki/Java_Message_Service">en.wikipedia.org/wiki/Java_Message_Service</a>
LLAP	lightweight local automation protocol	
LWM2M	Lightweight M2M	<a href="http://en.wikipedia.org/wiki/OMA_LWM2M">en.wikipedia.org/wiki/OMA_LWM2M</a>
SSI	Simple Sensor Interface	<a href="http://en.wikipedia.org/wiki/Simple_Sensor_Interface_protocol">en.wikipedia.org/wiki/Simple_Sensor_Interface_protocol</a>
Reactive Streams		<a href="http://www.reactive-streams.org">www.reactive-streams.org</a>
ONS 2.0	Object Name Service 2.0	<a href="http://www.gs1.org/epcis/epcis-ons/2-0-1">www.gs1.org/epcis/epcis-ons/2-0-1</a>
REST	Representational state transfer	<a href="http://en.wikipedia.org/wiki/Representational_state_transfer">en.wikipedia.org/wiki/Representational_state_transfer</a>
HTTP/2	Hypertext Transfer Protocol Version 2	<a href="http://httpwg.org/specs/rfc7540.html">httpwg.org/specs/rfc7540.html</a>
SOAP	Simple Object Access Protocol	<a href="http://en.wikipedia.org/wiki/SOAP">en.wikipedia.org/wiki/SOAP</a>
Webhook		<a href="http://en.wikipedia.org/wiki/Webhook">en.wikipedia.org/wiki/Webhook</a>
Jelastic		<a href="http://jelastic.com">jelastic.com</a>
MongoDB		<a href="http://en.wikipedia.org/wiki/MongoDB">en.wikipedia.org/wiki/MongoDB</a>
Websocket		<a href="http://websocket.org">websocket.org</a>
IOTDB		<a href="http://iotdb.org">iotdb.org</a>

## 5. Semantic

	SensorML		<a href="http://en.wikipedia.org/wiki/SensorML">en.wikipedia.org/wiki/SensorML</a>
	Semantic Sensor Net Ontology - W3C		<a href="http://www.w3.org/2005/Incubator/ssn/wiki/Semantic_Sensor_Net_Ontology">www.w3.org/2005/Incubator/ssn/wiki/Semantic_Sensor_Net_Ontology</a>
	Wolfram Language - Connected Devices		<a href="http://wolframlanguage.org">wolframlanguage.org</a>
	RAML	RESTful API Modeling Language	<a href="http://raml.org">raml.org</a>
	SENML	Media Types for Sensor Markup Language	<a href="http://tools.ietf.org/html/draft-jennings-senml-08">tools.ietf.org/html/draft-jennings-senml-08</a>
	LsDL	Lemonbeat smart Device Language	<a href="http://www.lemonbeat.com/lSDL/">www.lemonbeat.com/lSDL/</a>
	Alljoyn		
	IoTivity		
	IEEE P2413		
	Thread		
	IPSO Application Framework		
	OMA		
	LightweightM2M v1.0		
	Weave		
	Telehash - JSON+UDP+DHT=Freedom		
	OTrP	Open Trust Protocol	
	X.509		

**6. Multi-layer Frameworks**

**7. Security**



**Vertical Specific**  
IEEE 1451  
IEEE 1888.3-2013  
IEEE 1905.1-2013  
IEEE 802.16p-2012  
IEEE 1377-2012  
IEEE P1828  
IEEE P1856

**Architectures /  
Graphic**

**Others**

HIP

Host Identity Protocol

[en.wikipedia.org/wiki/Host\\_Identity\\_Protocol](http://en.wikipedia.org/wiki/Host_Identity_Protocol)

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## Note

Complementary information on IoT standards can be found in the July 2018 CDAIT White Paper entitled “Driving New Modes of IoT-Facilitated Citizen/User Engagement”. These standards cover various aspects of IoT, including:

- Horizontal IoT standards (pp. 18-21)
- Security IoT standards and related initiatives (pp. 35-39)
- Privacy in IoT (pp. 82-89)

The White Paper can be found at:

[https://cdait.gatech.edu/sites/default/files/georgia\\_tech\\_cdait\\_thought\\_leadership\\_working\\_group\\_white\\_paper\\_july\\_9\\_2018\\_final.pdf](https://cdait.gatech.edu/sites/default/files/georgia_tech_cdait_thought_leadership_working_group_white_paper_july_9_2018_final.pdf)

## About CDAIT

The Center for the Development and Application of Internet of Things Technologies (CDAIT, pronounced “sedate”) is a global, nonprofit, partner-funded center located in Atlanta, GA that fosters interdisciplinary research and education while driving general awareness about the Internet of Things (IoT).

CDAIT bridges sponsors with Georgia Institute of Technology (Georgia Tech) faculty and researchers, as well as industry members with similar interests.

Central to its value proposition is the belief that only a holistic approach, i.e., mindful of the complexity of the entire IoT value chain and the intricate relationships between the various links, can generate superior results. CDAIT’s broad overarching goal is to expand and promote IoT’s huge potential and transformational capabilities.

Anchored at the Georgia Tech Research Institute (GTRI), a highly regarded applied research and development organization with a global impact and focus on real-world research for government and industry, CDAIT is backed by Georgia Tech’s diverse and distinguished community of faculty and researchers. CDAIT aims to efficiently identify, understand and solve challenges and problems that may arise along the entire Internet of Things value chain through six Working Groups: IoT Education and Training; IoT Startup Ecosystem; IoT Thought Leadership; IoT Security and Privacy; IoT Standards and Management; and IoT Research.

For more information, including the current membership list, visit <https://cdait.gatech.edu>.

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## **CDAIT IoT Research Working Group**

Research at CDAIT is a means towards an end, i.e., through the investigation of a specific IoT use case, members seek to better grasp the IoT space in its many dimensions. As a result, it is expected that the research process will lead to the identification and understanding of IoT challenges as a whole, and encompass technological and non-technological issues (holistic). The projects must meet the following criteria: reflect a common interest among the CDAIT members; and be impactful (fill an IoT gap), actionable (i.e., have a clear goal line [results and timeframe]), and connected to business concerns.

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