ENVISIONING A BUILDING INFORMATION MODEL (BIM) INTEGRATED BUILDING PERFORMANCE VISUALIZATION (iPViz) INTERFACE

by

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Abstract

The dispersed nature, complexity, and amount of information available in modern buildings with advanced management and control systems, makes it challenging for building operators to holistically understand building performance. One of the reasons is the lack of integration among multiple information sources and tools making it harder to align performance data with user’s experiential model of the physical systems.

The goal of this research is to envision an integrated building performance visualization interface that provides contextually relevant, on-demand information to building operators. The research was executed in three sequential phases including an extensive literature review, a detailed case study, and development of a mockup prototype. I conducted an extensive literature review to capture the state-of-the-art in related academic domains and to establish a point-of-departure for the proposed research. The case study focused on a high performance building to understand operation and maintenance practices with an emphasis on building management systems (BMS). The case study involved two phases. In the first phase, I collected qualitative data by conducting interviews, contextual inquiries, and shadowing of building operators. In the second phase, I conducted a survey to collect quantitative data that further expanded upon the initial findings from first phase.

The results revealed several overlapping and interrelated challenges that were further analyzed and grouped into two sets of issues: visualization related and system’s interactivity related. I also identified two core problems in the overall use of the BMS: a lack of spatial and informational context, and disconnected monitoring of energy and system performance data.
Based on the findings, I developed a BIM Integrated Performance Visualization (iPViz) interface mockup as a proof-of-concept to support the work of building operators. I demonstrated the proposed interface features by using storyboard illustrations based on task-specific scenarios. I designed the scenarios and storyboards to demonstrate the proposed interface’s ability to provide spatially contextual information in response to a building operator’s interactions.

The research provides some future directions for the development of BIM-based performance visualization systems. Additional research is required to implement and evaluate the proposed solutions and to analyze their effectiveness in facilitating building management functions.
Preface

The dissertation is an original intellectual work carried out by the author, Syed Raza Ali Jaffery. The data collection work described in Chapter 03 was conducted as part of a collaborative research team, which is covered by the University of British Columbia (UBC) Behavioral Research Ethics Board Certification No.: H12-01745.

Some of the illustrations of the Building Management System used in Chapter 03 and 04 were developed originally by Honeywell Inc., for their Enterprise Building Integrator Interface. Architects Perkins and Will originally designed the Autodesk® Revit® model of CIRS which was used with permission in various illustrations in Chapter 03 and 04.
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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>A-EIMS</td>
<td>Advanced Energy Information Management System</td>
</tr>
<tr>
<td>ACC</td>
<td>Auxiliary Alarm and Control Center</td>
</tr>
<tr>
<td>AEC</td>
<td>Architectural, Engineering and Construction</td>
</tr>
<tr>
<td>AECO</td>
<td>Architectural, Engineering, Construction and Operation</td>
</tr>
<tr>
<td>AEX</td>
<td>Automating Equipment Information Exchange</td>
</tr>
<tr>
<td>aFDD</td>
<td>Automated Fault Detection and Diagnostic System</td>
</tr>
<tr>
<td>AHR</td>
<td>Air Handling Unit w/Heat Recovery</td>
</tr>
<tr>
<td>AHU</td>
<td>Air Handling Unit</td>
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<tr>
<td>AM</td>
<td>Advanced Management</td>
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<td>ANSI</td>
<td>American National Standards Institute</td>
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<td>ASHRAE</td>
<td>American Society of Heating, Refrigerating &amp; Air-Conditioning Engineers</td>
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<td>Building Automation System</td>
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<td>BOps</td>
<td>Building Operations</td>
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<td>CAB</td>
<td>Core Academic Buildings</td>
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<td>CAD</td>
<td>Computer-Aided Design</td>
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<tr>
<td>CAFM</td>
<td>Computer-Aided Facility Management</td>
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<tr>
<td>CBMS</td>
<td>Central Building Management System</td>
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<tr>
<td>CIRS</td>
<td>Centre for Interactive Research on Sustainability</td>
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<td>CMMS</td>
<td>Computerized Maintenance Management Systems</td>
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<td>COBie</td>
<td>Construction Operations Building Information Exchange</td>
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<td>COC</td>
<td>CIRS Operations Center</td>
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<td>dBS</td>
<td>Dedicated BMS Specialist</td>
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<td>DDC</td>
<td>Direct Digital Control</td>
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<td>DMS</td>
<td>Document Management System</td>
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<td>DRS</td>
<td>Demand Response System</td>
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<td>Dedicated Special Systems</td>
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<td>EA</td>
<td>Exhaust Air</td>
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<td>EBI</td>
<td>Enterprise Building Integrator</td>
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<td>Enterprise Energy Management</td>
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<td>Energy Management Information System</td>
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<td>EOS</td>
<td>Earth and Ocean Sciences Building</td>
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<td>EPI</td>
<td>Energy Planning and Innovation</td>
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</table>
EUI  Energy Use Intensity
EWS  Energy and Water Services
FCU  Fan Coil Unit
FDD  Fault Detection and Diagnostics
FFH  Forced Flor Heaters
FM   Facility Management
FMIS Facility Management Information System
HCI  Human-Computer Interaction
HCI  Human-Computer Interface
HIP  Human Information Processing
HPWA Air to Water Heat Pumps
HRV  Heat Recovery Unit
HVAC Heating, Ventilation and Air-Conditioning
HVACie Heating, Ventilation and Air-Conditioning Information Exchange
IAQ  Indoor Air Quality
IBMCS Integrated Building Management and Control Systems
iBMS Integrated Building Management System
IDP  Integrated Design Process
IEQ  Indoor Environmental Quality
IFC  Industry Foundation Classes
IMCS Integrated Management and Control System
InfoRev Information Review
InfoViz Information Visualization
IPMVP International Performance Measurement and Verification Protocol
iPViz Integrated Building Performance Visualization
IWMS Integrated Work Management System
LAN  Local Area Network
LEED Leadership in Energy and Environmental Design
MACC Master Alarm and Control Center
MDV  Model View Definition
MUA  Make-up Air Handling Unit
NDS  Network Data Server
ODBC Open Database Connectivity
OEM  Original Equipment Manufacturer
O&M  Operation and Maintenance
OA   Outside Air
OWS  Operator's Work Station
PLC  Programmable Logic Controllers
RFID Radio-frequency Identification
RH   Relative Humidity
SAS  Solar Aquatic System
SOP  Standard Operating Procedures
UBC  University of British Columbia
VOC  Volatile Organic Compound
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Above all, I am most grateful to my wife for her patience, encouragement, guidance and her support throughout my studies. I would also like to thank my parents for their prayers and love.
Dedication

Dedicated to Naghmi and Faiha Raza.

You guys were the light at the end of the tunnel that kept me going all this time. Without you two I can’t imagine my life let alone completion of this thesis.
Chapter 1: Introduction

Modern buildings are being designed and constructed with increasingly complex technological systems (Lewis et al., 2010), such as automated Heating, Ventilation and Air-conditioning (HVAC) systems (Yang & Ergan, 2014), motion and daylight sensing artificial lighting (Lu et al., 2010) and intelligent water storage and disposal systems (Vary, 2010). Given the functional sophistication of these systems, continuous monitoring and control of performance parameters become imperative to ensure efficient and consistent facility operations (Piette et al., 2001; O’Sullivan et al., 2004; Haves et al., 2008; Costa et al., 2013). Recent advancements in the field of Direct Digital Control (DDC) systems have allowed facility managers to use computer-aided automation and management systems to monitor, analyze and optimize building energy and system performance. Systems like Building Automation System (BAS) and Building/Energy Management and Control Systems (BMCS/EMCS) use a vast network of sensory and control devices to continuously monitor performance parameters of different building systems and present the collected information through computer-based graphical interfaces. In addition, a significant amount of information is also available through analog means including occupant comfort complaints, maintenance orders, trouble calls and inspection reports (Yang, 2014). Typically, this type of information is not integrated into the management tools and operators often end up manually updating the system or use other software, which is error-prone and inefficient.

The distributed nature, inherent complexity, and amount of information available from different building systems (HVAC, fire alarm, lighting, security, water management, etc.) requires building operators and managers to use multiple information sources and tools to collect and analyze
performance related data. This diversity and consequent reliance on multiple tools to understand building behavior have increased the gap between information data and a user’s experiential mental model of the physical world (Hailemariam et al., 2010). Most available Building Management Systems (BMS)\(^1\) present higher level performance information without providing any contextual relation of the system to the building space or its dependent components (Lehrer & Vasudev, 2011). For example, most management tools may provide performance information at system or space level granularity (i.e., fan coil status, air speed or relative humidity and temperature of a space), however, they are unable to specify dependencies between systems and spatial elements (i.e., which air handling unit is serving which space, how is the ventilation system connected to the heating systems, etc.).

Rezgui et al. (2010) argues that buildings are complex systems with interdependent sub-systems and components that interact within and across these systems. Understanding the pattern of these interactions and their behavior can only be achieved by looking at the building holistically rather than analyzing constituent components individually (Dibley et al., 2012). Information disparity and the lack of any direct visual/spatial connection between virtual and real world objects have caused building operators to spend additional time and resources in relating the acquired information from the BMS with the physical objects (Akcamete et al., 2009). Hailmariam et al. (2010) highlights that the challenge is to, “[…] define methods of organizing, studying and

\(^1\) From this point forward, the term BMS – Building Management System – would be used in lieu of the terms BMCS/EMCS, expressing the both management and controllability of building and energy systems, unless otherwise explicitly stated as required by the context of the statement.
communicating data in a manner that promotes a more holistic understanding of building performance in relation to the spatial and contextual configuration of the building.” (p. 117)

Haber and McNabb (1990) observes that:

“Computer visualization methods have emerged as the most effective tool for rapidly communicating large amounts of information to scientists and engineers in a format that enhances comprehension and deepens insight” (Haber & McNabb, 1990, p. 74).

A number of visualization tools are available that may provide sufficient representation of complex data structures, yet they may not convey the contextual intent of information that is inherently spatial like buildings. Such information can be represented through visualizations that “exist within, or overlay, the base geometry [of the built environment]” (Hailmariam et al., 2010, p. 1) and take advantage of how humans understand and perceive physical world and its attributes.

Building Information Models (BIM) have garnered growing interest in the past few decades within the Architectural, Engineering, Construction and Operations (AECO) industry due the numerous benefits and resource saving opportunities it presents across building lifecycle phases (Volk et al., 2014; Nepal et al., 2008; Bryde et al., 2013). BIM can be defined as a technological platform and a process to develop model-based three dimensional (3D) geometric representations of building objects with embedded physical, functional and relational characteristic information of the object and its surroundings (Succar, 2009; Irizarry et al., 2014; Nepal et al., 2008). Each element and its information within a BIM is parametrically linked to its surrounding elements so that any change in the object or its information is reflected in the entire model. All this linked information resides in a digital, transferable and reusable central database. Development and formalization of
information exchange protocols such as IFC\(^2\), COBie\(^2\), HVACie\(^2\), etc., have further streamlined the process of integrating and communicating information between different stakeholders; reducing the interoperability and disassociation of information problems that usually inhibit construction processes (Irizzary et al., 2014; Cavka et al., 2015). Becerik-Gerber et al. (2012) points out that due to these characteristics BIM has the potential to be successfully adopted and integrated into facility management and building operation practices including practical applications of O&M tasks like locating building components, checking maintainability, creating and updating digital assets, space management, planning, emergency management, controlling and monitoring energy, access & visualization of real-time data (Irizarry et al., 2014).

Recently many BMCS/EMCS tools have been proposed with integrated 3D geometric models. However, most of them have used 3D geometry as a virtual representation of the building without any inherent intelligence or contextual information within the visualization. This in one way can be attributed to the fact that there has been little or no research done in the past to explore how BIM enabled novel interaction methods and visual representations can facilitate understanding of building behavior or how potential integration of BIM with BMS systems can provide direct spatial context in monitoring and control of building elements (Srivastav et al., 2009; Yang & Ergan, 2016). Fortunately, recent research studies have initiated a shift in focus toward utilizing BIM for providing intelligent, on-demand and holistic performance information. Examples of some noteworthy research in this regard are: ambient intelligence environments (Irizarry et al., 2014),

integrated visual platform for HVAC troubleshooting (Yang & Ergan, 2016), using BIM for automated fault detection (Golabchi et al., 2013), BIM as a building energy model (O’Donnell et al., 2013), unified representation of performance information (Hailemariam et al., 2010).

Most building maintenance works are carried out in response to occupant complaints, equipment breakdowns, routine maintenance schedules or upgrades of legacy hardware. Building operators usually use building and energy management systems to detect, analyze and diagnose operational problems in response to these issues. It is, therefore, important that the performance information represented by the BMS should be such that it facilitates an operator’s understanding of the situation and enhances his or her ability to analyze the data in the context of environmental and physical relations that existed at the time of the problem. Current systems are designed to provide pure analytical data, which may be useful for analysis based decisions but greatly fail in providing the environmental or spatial context of that data.

Observation of different building O&M and BMS experts during this study also highlighted the fact that most of the information available to building operators is not in one place, missing or outdated. Most of the documents handed over during the commissioning process typically do not represent the as-built condition of the building, equipment or systems at all, but are rather based on either design or construction information. It was also observed that even high-performance buildings designed or constructed using data enriched virtual design and construction tools like BIM, did not fully utilize the embedded information in those models. Further, building operators had to use different tools to either access, extract or consolidate required information to make informed decisions.
This research aims to address these issues by envisioning an integrated building performance visualization system that provides contextually relevant, on-demand information to building operators by aggregating and mapping data in a unified database from different information sources including BIM. Since building operation and maintenance practices highly depend on the building and organizational requirements, the research was carried out taking a pragmatic approach to realizing this vision. The underlying processes involved in O&M practices were explored especially concerning the use of BMS by carrying out a case study at a high-performance academic building in a large centrally operated academic institution - University of British Columbia.

The research study started by first observing building O&M and management practices at the campus level to get a broad understanding of the overarching processes and work practices at University of British Columbia (UBC). Based on those initial observations, I further explored the use of BMS tools for performance management at the case study building. The Centre for Interactive Research on Sustainability (CIRS) was selected for the case study for two main reasons: 1) It is one of the first few buildings at UBC to be designed using a BIM and an Integrated Designed Process (IDP) from the start, and 2) It is equipped with the state-of-art, sensor enriched Building Automation and Management System (BAS/BMS), with over 3000 data collection and control points across the building. Data related to operational practices was collected at CIRS Operation Center by shadowing and interviewing the resident BMS manager over several sessions. The data gathered through this case study was analyzed along with the findings from the literature review, to identify and categorize different visualization and interaction issues in using BMS for routine building O&M work. The results from this study were valuable in understanding how management
tools influence an operator’s understanding of the facility’s behavior and were used as a baseline for designing and prototyping solution mockups for the envisioned system interface.

A medium-fidelity mockup of the envisioned performance visualization interface is developed as a proof-of-concept and to showcase different visualization and interaction solutions that are proposed based on the case study findings. High-resolution renderings from the existing building information model of the CIRS building are used as the base geometric visualization in the mockup to signify the value that BIM integration would bring to the platform. Various visualization and interaction techniques, identified from the literature review, are used to mockup different information visualization and interactive features of the system in response to user queries. The overarching theme, however, of the entire interface mockup is to highlight unified information availability and that too in the context of the spatial characteristics of the graphical model, the query in concern and the operator’s interaction patterns with the system. All the information available to the operator is envision to be on-demand and at a level of fidelity appropriate to the context of the interaction.

1.1 Research Objectives:

The main objective of the research proposal is to put to develop a proof-of-concept idea of an integrated BIM-based BMS performance visualization interface with the specific aim to enhance understanding and controllability of building performance parameters by providing building operators context-aware, on-demand information in a spatially relevant geometric setting. The research work is an exploratory exercise combining both academic and investigative research (case study) methods to achieve substantially grounded proposed solutions. There are three main
activites: 1) literature review, 2) study of prevalent O&M practices, and 3) exploration of BIM as an integrated platform for building performance visualization.

1.1.1 An Encompassing Review of the Relevant Literature:

A literature review is one of the primary and most important steps in any research process as it provides the foundation, justification, and inspiration for a substantial and useful research venture (Boote & Beile, 2005). This thesis is an exploratory exercise encompassing multiple disciplines, which converge to define the intent of the research and provide a foundation for the proposal. The importance of such an undertaking is justified by the fact that there has been little research done in exploring novel interactions and visual interfaces for building automation and management systems (Srivastav et al., 2009; Castelo, 2012). While I did not attempt to produce an exhaustive review of literature of every concerned discipline, I did, however, try to provide enough literature based evidence to ground the proposed solutions and to provide an encompassing overview of the relevant domains that may guide and inspire any future research work in this field.

1.1.2 Study of Current Building O&M Practices:

Building O&M practices vary to a large extent depending on various factors including the size, use and location of the facility, its stakeholder’s requirements and regional climatic conditions and organizational goals. The disparity in O&M practices is further amplified by the sophistication of the building systems and integrated technologies currently being adopted in the modern building. Because of the dynamic nature of the O&M practices, researchers have increasingly felt the need to bridge academic research with the practical realities of the field through grounded case-based studies (McCutcheon & Meredith, 1993). A case study research is best suited when a large variety
of directly observable factors and relationships are involved (Fidel, 1984) and where the primary purpose of the research is to understand how or why an event occurred rather than prove its occurrence (Yin, 2003).

A case study was carried out to capture various operational practices that are prevalent in an academic institution by investigating a modern high-performance building with a state-of-the-art BAS and BMS. The case study would help to develop a richer understanding of the various nuances that exist in current performance monitoring and O&M practices, and the capabilities of current BMS graphical interface in representing these to the operators. Interaction task-based scenarios would be developed from the data collected from the case study and would be used to demonstrate the mockup interface design as a proof-of-concept of the proposed solutions.

1.1.3 Exploration of BIM as an Integrated Platform for Performance Visualization:

The AECO industry has always been infamous for its slow adoption of technological trends (Williams, 2013), with facility management being the last to utilize advancements in the information technology industry (Froese, 2009; Froese et al., 2007). Although BIM has established itself as a capable platform for modeling and communicating information, explicitly visualizing building components and facilitating collaboration among different AECO disciplines, it has yet to achieve its full potential in O&M practices (Bowman et al., 2006; Eadie et al., 2013). This is drastically apparent in the field of building management and control, where most of the information is still segregated across various platforms requiring building operators to use multiple tools to carry out routine tasks (Motawa & Almarshad, 2013). In this thesis, BIM was utilized in two ways: 1) as a high-fidelity visual platform, and 2) as a parametric, context-aware information
repository. Since BIM is inherently an object-based modeling platform, visual aspect can easily be aligned with BAS objects using IFC object library. On the other hand, an information-enriched as-built BIM model is required so that information can also be aligned and integrated with the BMS monitoring and control functions. Implementation and evaluation of the proposed interface are not part of the scope of this research, for the purpose of this thesis I have assumed that such resolution of information is available within the model. Such assumption is sufficient enough to illustrate the intent of the solution and to showcase its potential visualization aspects.

1.2 Methodology:

Exploratory research methodology provides a great platform for exploration and evaluation of different ideas and insights concerning a phenomena or research venture (Marshall & Rossman, 2006; Kothari, 2004). Literature review, surveys/interviews, and case studies are the three major constituents of an exploratory research methodology (Kothari, 2004). I used these methods to demonstrate the state-of-the-art in established academic research as well as from current practitioners in the concerned field. The results were utilized to develop problem-specific scenarios and interface usability aspects that would potentially address different observed problems in using BMS interface for O&M work. Figure 1.1, summarizes the research methodology used to achieve the aforementioned goals. A brief description of these methods is discussed further in this section.
1.2.1 Literature Review:

An encompassing, if not exhaustive literature review was carried out, adhering as much as possible to the framework proposed by Onwuegbuzie et al., (2012) in collecting, analyzing and reporting the body of knowledge relevant to the research objectives.

In order to capture the prevalent state-of-art, identify overlapping relationships and to establish a point-of-departure for the proposed research; literature of various disciplines including Building Operation and Maintenance (O&M), Building Performance, Automation and Management, Monitoring and Control Tools, Visualization, Human-Computer Interaction (HCI) principles, Interaction and Interface design, Cognitive Theories, Information Exchange Protocols and Building Information Modeling.
(BIM), was collected and preliminarily reviewed. Analysis of the collected literature highlighted four major academic domains that significantly overlap and contribute toward this research discourse: Building O&M, Building Performance and Visualization, HCI, and BIM. A more focused literature review was carried out to investigate prevalent methods, techniques, principles and theories that can be used as a grounded point-of-departure for the research proposal. Most of the literature for this purpose was collected from various publically available academic and applied database sources in the form of books, journal articles, and conference proceedings, dissertations, online content, reports, and surveys, etc.

1.2.2 Data Collection and Analysis:

As already discussed data was collected from two different but complementary sources, i.e., academic literature and case study (observation and interviews of practitioners). The data collected from the academic literature is not a temporally bounded process, and inferences were made and included in the thesis in an ongoing process. The author held a graduate office space at the case study building – CIRS for the duration of his master’s program (2011- 2014). Data on O&M practices was collected during the residing period through observation of practitioners including UBC building operation personnel and BMS manager at CIRS. Informal interviews were conducted to acquire practitioners’ insight on various issues concerning routine O&M activities, particularly in regards to the use of building management systems (Honeywell-Enterprise Building Integrator) for building performance monitoring and control.

Collected data was analyzed using “constant comparison analysis” technique (Onwuegbuzie et al., 2012, p. 10) by segregating larger content into smaller meaningful chunks of information. Each chunk of information was compared to other information portions having similar content or
meaning or purpose, thus making complementary themes or clusters of information providing insight on a particular aspect. By using this technique, I was able to identify various aspects related to the use of BMS interface in O&M practices, BIM integration opportunities, pertinent techniques, and tools facilitating information integration and HCI requirements for the interface design.

1.2.3 Interface Mockup Design:

Two core problem areas were identified from the results of the data analysis 1) Visualization problems and 2) Interaction related issues in the current use of BMS tools for O&M works. A medium-fidelity mockup of the envisioned front-end Integrated Performance Visualization (iPViz) interface was designed to address these core problems by showcasing the integration of high-fidelity 3D geometric graphics with contextually sensitive semantic information using storyboards of static images. The storyboard illustrations were designed to demonstrate both visual fidelity and interaction dynamics of the envisioned interface by highlighting variations in information visualization and 3D graphics in response to different interactions from a hypothetical user as static snapshots of that interaction session. The computer interaction dynamics were further demonstrated by the proposed iPViz interface through real-world inspired hypothetical task-based scenarios; interface illustrations described various features used by the user within the scenario.

1.3 Research Scope and Assumptions:

The main scope of the research work in this thesis includes:

1. The research work primarily focuses on visualization aspects of the front-end interface of building management systems; especially from the perspective of the system’s ability to
present actionable information that may facilitate an operator’s understanding of a building performance scenario.

2. This research is carried out from a case-specific point of view, and a case-specific ideal vision of an integrated visual interface for monitoring and controlling performance information is provided as a mockup. Building automation, system integration, sensor reliability, and accuracy, as well as information mapping and implementation of proposed visualization, are not within the scope of this research.

3. The research focuses on energy and system/equipment performance information visualization. However, comfort performance information, occupant evaluations or indoor environmental information is not part of the scope and is not discussed in the thesis.

4. Further, since different interactive and visualization features of the proposed interface are mocked up and demonstrated as static images in a storyboard as proof-of-concept, evaluation of these features is also not part of the scope.

The following assumptions were made to make the above research scope feasible:

1. That the data sources required for demonstration of the proposed systems including a data enriched as-built BIM, a comprehensive user-level sensor enriched BAS and bi-directional integration of these information sources.

2. All required information is updated to as-built status, is readily available and accurate including information embedded in the as-built BIM, sensors and meters output, drawings, manuals, and specifications, etc.

For other system-specific assumptions and limitations refer to 4.3.2.
1.4 Thesis Overview:

The thesis consists of five chapters. The first chapter is introduction to the thesis and gives an overview account of the carried out research work. It also includes a brief description of the problem areas, main research objectives, as well as the methodologies, undertook to carry out the research study.

The next chapter comprises of the Literature Review conducted as part of the research objectives. It includes an account of the four major identified literature domains and provides an exploratory review of established theories, techniques, and findings in these fields that overlap or inform the research discourse of this thesis.

The third chapter contains the main body of the research carried out during the case study of CIRS building at UBC. The chapter details the case study background, the organizational hierarchy at UBC as well as prevalent O&M practices. The chapter gives an insight into the motivation and need, behind the research work by describing current building O&M practices both at campus and building level. A detailed description of the methodologies, processes, and techniques used to collect data during the case study is also included in the chapter.

The fourth chapter is the synthesis of my research study and includes both analysis of the collected data, identification of the main problematic areas as well as illustrations of the proposed performance visualization interface mockup. The chapter entails a detailed description of the conceptual vision behind the proposed interface solution along with related graphical illustrations of different information visualization and interaction features. Task-based scenarios used to
demonstrate different interactive features of the proposed interface using storyboard techniques are also described in this chapter.

The final chapter provides a summary of the entire research work, a discussion of the findings of the case study and my recommendation on future works.
Chapter 2: Literature Review and Synthesis

“A thorough, sophisticated literature review is the foundation and inspiration for substantial, useful research.” (Boote & Beile, 2005, p. 3)

Review of prevalent literature represents the most important step in any research venture (Onwuegbuzie et al., 2012). A comprehensive literature review provides the foundation for a useful and grounded research (Boote & Beile, 2005). To make substantial contributions researchers need to acquaint themselves with the state-of-art in their field of study (Galliers, 1992), identify appropriate methodologies and establish relationships between the theoretical and practical approaches. Machi and McEvoy (2009) in this regards notes that “a literature review is a written document that presents a logically argued case founded on a comprehensive understanding of the current state of knowledge about a topic of study.” (p. 4)

A significant amount of research material is available proposing various frameworks to carry out a thorough literature review (to name a few: Combs et al., 2010; Fink, 2009; Leech et al., 2010; etc.). Onwuegbuzie et al., (2012) in this regards, specifies two major steps that should comprise any literature review: 1) a formal analysis, and 2) interpretation of the selected literature. He further argues that a rigorous literature review process\(^3\) should reflect three attributes: 1) it should be warranted, i.e., adequate evidence should be available to justify the results, 2) it should be transparent, i.e., logical progression of activities throughout the research process should be explicitly visible and, 3) it should be comprehensive, i.e., providing a complete picture of the

\(^3\) Both analysis and interpretation of selected literature should aspire rigor in their approach (Onwuegbuzie et al., 2012)
Unfortunately, there is very little literature available regarding integration of BIM with building performance monitoring and control tools (BAS, BMS, EMCS) to facilitate building O&M tasks (Bozány, 2003). The research in this thesis, therefore, is an exploratory endeavor that encompasses multiple overlapping domains in an attempt to consolidate and extrapolate different interrelated concepts into a singular vision of an interactive interface for building operators and managers. To understand the underlying processes, principles, and relationships within these overlapping domains and use them to inform the research goals I had to break the higher level topics into concerned constituents; as Schwandt (2007) suggests that “through assembly of the parts, one comes to understand the integrity of the whole.” (p. 6). I studied previously established theories, concepts, and methodologies in the literature to identify, analyze and synthesize useful approaches which can be used as a point-of-departure for the proposed research. In this aspect, I tried to incorporate the principles proposed by Onwuegbuzie et al., (2012), as much as possible - not to an exhaustive extent, but within the scope of this thesis work.

The main objective of my research work is to explore an idea/vision of an integrated interface that combines the high-fidelity geometric and spatially contextual information of a BIM with the performance monitoring and control capabilities of a BMS that may enhance building operator’s understanding of building performance and facilitate O&M works in an intuitive manner. Now if the objective statement is to be dissected, we would find that it is comprised of several discreet but overlapping domains contributing toward defining the underlying concept.
1. Integrated Interface: Interface design is in itself a sub-class of information and interaction design, which are based on root principles of visualization and Human-Computer Interaction (HCI) disciplines.

2. High-fidelity geometrics and contextual information of BIM: BIM takes its roots from information modeling and integration, computer-aided design (CAD) strategies and visualization theories and delivers a collaborative 3D digital model that contextually represents the real world built objects and their associated metadata (Cerovsek, 2011).

3. Building performance: Buildings are highly interactive environments with dynamic performance mechanics; which require constant monitoring and control to provide effective and optimized comfort conditions to its occupants. Modern buildings utilize sophisticated BAS and BMCS to automate the monitoring and control process and to provide building operators with understandable and actionable information visualization (Hoffmann, 2012).

4. Building Operations and Maintenance works: Although, Building O&M is in itself an encompassing field, it is usually considered under a much broader Facility Management (FM) discipline (Atkins & Brooks, 2009).

I grouped the above-highlighted research domains in a quasi-hierarchal manner, defining the breadth of the principal research domains first and then delving into the relevant sub-domains in more depth. For example, although a more pertinent topic to this research is building O&M, however, since it falls under the research domain of FM, the breadth of FM research work was described first and then focused more in-depth on the prevalent research work in O&M field. The four major research groups that would be discussed in the coming sections are:
• Building Operations and Maintenance
• Building Performance and Visualization
• Human-Computer Interaction
• Building Information Modeling

2.1 Facility Management (FM):

Built environments and facilities are among the largest assets of any organization (Rondeau et al., 1995) and entails significant business value in their successful execution and operation. Built facilities account as the second largest expense of an organization after human resource (Alexander, 2002; Moragn, 2002). However, in comparison to the efforts dedicated to design and construction phases, little attention is given to operational and management requirements of these built facilities (Clayton et al., 1999). FM has traditionally been associated with routine maintenance and space management activities – which are non-core services domain when compared to construction or design disciplines. This is one of the main reasons that even the most performance-driven and advanced buildings are lagging behind in achieving their design objectives (Newsham et al., 2009). To add value to the building operations and to holistically achieve an organization’s business goals, facility operations and management processes should be considered as strategic objectives rather than a day-to-day service (Barrett, 1995).

Facilities management is a growing discipline in AECO industry that had its roots mostly in the building custodial roles (Best et al., 2003) but is rapidly evolving into a process focused discipline (Amaratunga, 2001) encompassing a spectrum of asset and facility management functions (Atkin & Brooks, 2000). Broadly, FM can be understood to constitute of two major functional groups
(Chotipanich, 2004; Jensen, 2011), see Table 2.1: 1) Strategic/tactical functions - which mostly involve coordination and execution of core business goals and services, and 2) Operational functions – which caters to the physical domain – operations and maintenance of the built environment. These two functional groups are effectively integrated through management processes to successfully manage and achieve organizational goals. For the purpose of this research, I would be mostly focusing on the domain of O&M functions in facility management.

Availability and adequacy of information during the operational phase of the building lifecycle is one of the main elements for proper management and operation of any built facility (Atkin & Brooks, 2009; Lavy & Jawadekar, 2014; Wang et al., 2013). Many a time considerable amount of information, e.g., as-built drawings and models, operating procedures, specifications, etc., gets lost or go unrecorded during the commissioning process of a facility (Lavy & Jawadekar, 2014). Such discrepancies can mostly be attributed to manual or paper-based information recording processes. Retrieval and management of all this information is a time consuming and expensive process and may take years to consolidate into actionable information (Williams, 2014). Liu et al. (1994) and Clayton et al. (1999) attempted to formally identify information datasets required for effective operation and management of facilities. The challenge in this regards is not only collection of relevant information, but to keep the information updated and provide context toward other dependencies to reflect the as-is operational condition of the facility (Akcamete, 2011).
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Various technological solutions have been availed to digitize and consolidate different forms of building information, e.g., personnel lists, work orders, as-built drawings, standard operating procedures (SOP), with the help of computer-aided O&M management software tools (Abel & Lennerts, 2005) like CAFM⁴, CMMS⁴ and IWMS⁴. Use of these tools has greatly increased the aggregation, accuracy, modifiability, reproducibility and communication of information among different facility management stakeholders (Teicholz, 2013; El-Ammari, 2006). However, even with the integration of computer-aided tools in the facility management processes a considerable amount of data has to be manually inserted and updated by the facility managers causing almost 70% reduction in utilization of these tools over the operational phase of the building (Keller, 2013).

Many researchers have tried to facilitate this processes by automating information exchange across different building phases (Ammari & Hammad, 2014) or by incorporating artificial intelligence into FM tools (Morcous & Lounis, 2005; Lee et al., 2008; Moradi et al., 2011). Others have studied the potential of using Building Information Models (Becerik-gerber et al., 2012; Volk et al., 2014; Teicholz, 2013) to present information to facility managers from a building lifecycle approach (Parsanezhad, 2015). One of the key advantages of using BIM is its ability to capture and present information across building lifecycle phases and the potential to incorporate information models from other non-spatial systems (RFID⁵ tags, sensors, CMMS, CAFM, etc.) providing a richer context to spatial geometric elements (Ammari & Hammad, 2014; Taneja et al., 2012; Cahill et

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⁵ RFID: Radio-frequency Identification - “It is an automatic identification technology which uses radio frequencies to exchange” (Meadati et al., 2010)
al., 2012; Liu & Akinci, 2009). However, due to the prevalence of different propriety systems and variable information formats, interoperability between BIM and various FM tools is still an unresolved issue among AECO stakeholders (Akcamete et al., 2011). Different information exchange models have been developed to facilitate exchange of information from design and construction phases to building operation phase including Industry Foundation Classes (IFC), Construction Operations Building Information Exchange (COBie), BIM Collaborative Format (BCF), HVAC information exchange (HVACie) and Automating Equipment Information Exchange (AEX), but complete interoperability among tools is a still long way from achieving.

2.2 Building Operations and Maintenance (O&M):

Buildings are designed to last for decades, with their operational phase extending to at least 80% of the entire lifespan and costing as much as 65%-85% of total lifecycle cost - almost three times the design and construction costs (Liu et al., 1994; Clayton, 1999; Fuller, 2009). Still, building O&M is often the most neglected and undervalued activity in construction, with Seeley (1987) relating its unglamorous-ness as the “Cinderella” of the industry. Research carried out by National Research Council (NRC) suggest that “a building’s performance will decline because of its age, the use it receives, or functional adaptation to new uses” (Gallaher et al., 2004, p. 1-21; NRC, 1998), Figure 2.1. Effective management of building operations and proactive maintenance regimen thus becomes crucial to guarantee a cost effective function of built facilities (Forns-Samso, 2010; Muhey, 2012).
O&M is an ongoing recurring process, undertaken to sustain or bring the built facility to its desired operational intent while ensuring functional efficiency (Sullivan et al., 2010; CEN, 2001; Effinger et al., 1999). Seely (1987) suggested that the core functions of O&M include maintenance of services and objects, occupant safety, cleaning and repairing works and preventive measures. Meador (1995) argued that to reduce the loss of efficiency in trade-offs associated with various maintenance scenarios, O&M functions should be approached from a systems perspective\(^6\), and he grouped different functional areas into five categories: operations, maintenance, engineering, training and administration, Figure 2.2. To highlight the underlying scope of O&M works; Effinger et al., (1999) and Sullivan et al., (2010) attempted a definition by distinguishing between different

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\(^6\) A systems perspective calls for an integration of all functional processes to provide optimum operating opportunities (Meador, 1995)
O&M functions, relating operations with strategic/decision-making processes and maintenance with more actionable functions.

“Operations and Maintenance are the decisions and actions regarding the control and upkeep of property and equipment. These are inclusive, but not limited to, the following: 1) actions focused on scheduling, procedures, and work/systems control and optimization; and 2) performance of routine, preventive, predictive, scheduled and unscheduled actions aimed at preventing equipment failure or decline with the goal of increasing efficiency, reliability, and safety.” (Sullivan et al., 2010, p. 2.1)

![Figure 2.2 - Interaction and integration of O&M functions within an organization (Meador, 1995)](image)

It is quite interesting to note that the above definitions focus on formalizing maintenance processes, even describing operational functions in the context of maintenance tasks. One of the reasons can be because there is “very little information on building operations [available in literature]
compared to the volumes written on building maintenance” (PECI, 1999, p. 2); leaving a huge gap in formalized knowledge of operational strategies for building facilities. Another reason can be due to higher costs factors associated with recurring maintenance tasks; given that most of the O&M management practices are based on reactive maintenance strategies rather than preventive ones. A study carried out by U.S. Department of Energy concluded that "more than 55% of maintenance resources and activities of an average facility are still reactive" with only 30% resources allocated as preventive measures (Sullivan et al., 2010, p. 50). This is one of the main reasons that O&M costs alone are as much as three times higher than design and construction expenditure combined (Yalcinkaya & Singh, 2014).

One of the major factors that often gets neglected in terms of identifying potential causes for lack of proactive and strategic initiatives in building O&M activities is the human factor. Building operators usually have limited routine interaction with physical building systems and mostly rely on the performance data from different information sources. Operators may also have to consider other variables such as occupant behavior and comfort, ambient climate conditions, illumination requirements, ventilation, occupancy, and cost functions, to understand the collected performance data (O’Sullivan et al., 2004; Augenbroe & Park, 2005). Depending upon the size of the facility, sophistication of its equipment, integrated technology, and operational functions, a huge amount of complex data can be generated in relations to building behavior and operational performance. In most cases, operational efficiency is compromised due to misinterpretation and lack of understanding of the building performance data. To understand building performance patterns and make proactive maintenance strategies human operators may require significant assistance in interpreting and analyzing complex data (Piette et al., 2001).
Another challenge in understanding and standardizing O&M practices is that a building is not a homogenous object but is an assemblage of integrated systems, with varying material and component lifecycles (Brand, 1995). Duffy (1990) and Brand (1995) suggests that a building is "conceived of several layers of longevity of built components" (Ch.2) with interdependencies in terms of their function, performance and even life span, Figure 2.3. For example, updating an older HVAC system or plumbing system may also require changing related components like electric output, ducts or pipes to make that upgrade effective. In most cases, this information about interdependencies among different building elements and systems is either not readily available or is inaccessible to building operators; impeding their ability to holistically understand the situation and make informed decisions.

Timely availability and accessibility to quality information is one of the key factors in understanding and improving the operational efficiency and maintenance processes of any built environment (Aðalsteinsson, 2014; Yalcinkaya & Singh, 2014). However, as discussed above, most of the building information available to building operators is scattered across different platforms and is usually available in multiple formats ranging from paper documents (Liu et al., 1994; Clayton et al., 1998; Song et al., 2002) - to 3D geometrical models (Teicholz, 2013).
considerable amount of time and resources are often allocated to organize, relate and verify the
information in order to make it workable for facility management and operations (Corry et al.,
2011). Gallaher et al. (2004) reported an estimated cost of $15.8 billion spent to make-up for the
lack of interoperability between various information applications out of which $10.6 billion is
attributed to consolidation and verification of information during O&M phase (Gallaher et al.,

2.3 Building Automation and Management Systems (BAS, BMS):

The demand for integrated security, optimized operational processes, energy and environmentally
efficient building systems and requirements for greater occupant comfort, has drastically increased
the use of sophisticated building automation and management systems in commercial buildings
(Castelo, 2012). Building automation, which is often associated with building intelligence\(^7\)
(Wigginton & Harris, 2002) - allows interaction and integration among various otherwise siloed
building systems, enabling devices to communicate seamlessly and share information with each
other (Wong et al., 2005), Figure 2.4. BAS provides real-time information of operational
conditions, enabling building operators to understand and respond to any performance anomalies
and situations in a built facility (Burns, 2005).

Many researchers have attempted to categorize various building services and functions in order to
determine the level of automation and control required to fulfill operational tasks. McKinley

\(^7\) As per So and Chan (1999), “A sophisticated building automation system (BAS) is actually the heart of every intelligent building
(IB)”, whereas Cardin (1983) defined IB as “one which has fully automated building services control system”
(1988) divided building services into: 1) Systems - HVAC, lighting, water, etc., 2) Services - security, operations, etc., and 3) Management - maintenance, training, technology, etc. Klien (1988) looked at O&M services from an occupant’s perspective, i.e., automation, communication, tenant services, etc. Atkin (1993) on the other hand, categorized building functions according to their technological input: building automation, communication and information processing (Arkin & Pacuik, 1997). Interestingly, the above researchers identified almost similar building functions, though from different viewpoints. Integration and interaction of all these functions - from a technical context – can be categorized into different hierarchical layers or levels (Kastner et al., 2005; Soucek & Loy, 2007; Domingues et al., 2015; Vincent et al., 2015), i.e., low or field level, mid or automation level and high or management level; with each level carrying discrete yet interdependent set of operational functions, Figure 2.5. The interactions between these levels can either be structured vertically or horizontally or a combination thereof, depending on the scale and complexity of the built facility and its systems.

1. **Low/Field Level:**

Information from various sensors, actuators and measurement devices regarding the interaction of building components with the environment or physical conditions is originated and collected at this level (Kastner, et al., 2005; Ihasalo, 2012; So et al., 1999). The basic function of these sensing and metering devices is to collect information on various building performance parameters and transmit it to the Direct Digital Controls (DDC) station for further processing. In addition to collection of information, physical or environmental attributes of the built environment can also be manipulated and controlled by utilizing switches, actuators or gates/valves directly.
2. **Mid/Automation Level:**

Most of the automation including execution of automatic control sequences and communication (interpretation and dissemination of information) between management and field levels is assigned to this level (Soucek & Loy, 2007; Kastner et al., 2005). DDC stations, computing servers, and building controllers are used to execute logical connections and control loop algorithms on the data collected from the field level devices. Servers are used to collect and aggregate bi-direction information including data from field level and commands from the management level. Environmental information from other sources may also be collected and used to process control sequence triggers at this level, e.g., outside temperature values may be used to adjust heating or cooling in the building (Merz et al., 2009). Automation networks and information exchange
protocols like LonWorks, KNX, BACnet or Zigbee (Merz et al., 2009; Brambley et al., 2005; ANSI/ASHRAE Std., 135, 2004; Zigbee Alliance, 2008) are commonly used to connect building controllers to DDC and data servers, and to communicate between sub-systems.

3. **High/Management Level:**

Management and control of the entire building systems and corresponding services are carried out at the management level. Information from the lower two levels is accessible to building operators at this level through software interface with the ability to modify different parameters of the automation systems. Real-time information from field level devices, as well as recorded data from the servers, allow building operators to understand performance parameters and make informed decisions regarding any operational changes or maintenance requirements in the building (Kastner et al., 2005; Ihasalo, 2012). Automation parameters like operational schedules for different equipment, set point values, control logics and loop parameters are usually modified at this level (Soucek & Loy, 2007). Alarms can also be configured to indicate and manage any exceptions or anomalies in the specified operating parameters (Domingues et al., 2015).

Various Dedicated Special Systems (DSS) like fire alarm system, vertical transportation system, emergency lights, etc., which cannot be integrated into tight automated loops, can be connected, monitored and controlled at management level through software integration (Kastner et al., 2005; Fernbach et al., 2011). Energy data from meters and sub-meters in the building can also be collected and presented at this level, allowing building operators to monitor and control energy parameters of the built systems along with their operational efficiency (Zong & Wang, 2011). Collection and management of energy information have mostly been carried out separately from
building system automation (Friedman et al., 2011). However, increasing costs and resources required for commissioning and maintaining separate systems for managing equipment and energy have heightened the need for integrated and unified management systems (Gonzalez, 2007; Hui, 2007; Mustafa & Bansal, 2002). Innovative solutions like unified information visualization and soft Programmable Logic Controllers (PLC) for management systems (Kastner et al., 2007; Kensby & Olsson, 2012; Domingues et al., 2015) may allow operators to monitor, analyze and even automate complex operational and fault diagnostic tasks. However, such solutions are in very initial development phases and may require considerable time to mature and provide tangible results.

2.4 Building Performance and Visualization:

Building automation, monitoring, and control are fundamentally driven by the need to optimize performance in terms of “comfort, functionality, energy efficiency, resource efficiency, economic return, and lifecycle value” (U.S. Department of Energy, 2000, p. 1). However, recent studies show that considerable number of high-performance buildings fall short in meeting their designed performance goals (Scofield, 2009; O'Donnell, 2009; Newsham et al., 2009; Zheng, 2013). In their study of 100 LEED\(^8\) certified buildings Newsham et al., (2009) reported that almost 28%-35% of them “use more energy than their conventional counterparts” (p. 904) with a potential of further deviation based on variation in environmental and building characteristics. Reasons for such deviations in building performance may include optimistic design assumptions, malfunctioning or

\(^8\) Leadership in Energy and Environmental Design (http://www.usgbc.org/leed)
oversizing equipment, incorrectly configured control systems (Haves et al., 2001) and lack of post-commission performance monitoring and feedback (Piette et al., 2001; Newsham et al., 2009). Fragmentation in building performance monitoring and assessment practices (O’Sullivan et al., 2004) and focus on individual aspects rather than whole building performance are also some of the reasons behind escalating O&M costs, energy consumptions and occupant dissatisfaction in modern buildings (Douglas, 1996; Then et al., 2005).

Performance is a relative term, which is highly empirical and subjective in its determination. According to Lebas (1995) very “few people agree on what performance really means: it can mean anything from efficiency, to robustness or resistance or return on investment, or plenty of other definitions never fully specified” (p. 1). Traditionally, the term building performance has been used in context of environmental attributes of a built environment like energy, acoustics, thermal comfort, air quality, lighting and ventilation, etc., (IPMVP Committee, 2001). From building O&M perspective, however, performance has always been interpreted as functional competency of building systems and equipment, like HVAC systems, fire alarm systems, water pumps, etc. Although these “micro-level” environmental and physical attributes play a vital role in understanding a building’s operational efficiency, they provide mere glimpses of a much bigger picture. A more holistic approach is required to understand the dynamics and interdependencies of these environmental and physical attributes affecting the overall performance of a building (Cotts & Lee, 1992).

Amaratunga (2001) citing Williams (1994) highlighted physical, functional and financial efficiencies as key aspects of building performance. Similarly, Lavy et al., (2010) also suggested four major indicators that can be used to holistically quantify whole building performance, i.e.,
financial, physical, functional and empirical (surveys). Costa et al., (2013) argued that a building may have hundreds of performance objectives at any given instance which ought to be categorized as performance metrics under similar performance aspects, i.e., building function, thermal loads, energy consumption, system performance and legislation. Douglas (1996) argues that all these building performance aspects are interdependent with symbiotic relationships and are equally important in “understanding how well a building is satisfying specific user or functional requirements” (Douglas, 1996, p. 2). For the purpose of this research, I would use the classification proposed by Amaratunga (2001), focusing mainly on physical and functional aspects of a building’s performance; financial attributes although highly important are not within the scope of this research.

1. Building Physical Performance:

Physical performance encompasses both environmental and physical attributes of the built environment including physical shape, ambient and internal environment, conditional attributes, systems, components and resource consumption (Ho et al., 2000; Lavy et al., 2010). Considering both qualitative and quantitative information of environmental and physical aspects provide building operators a holistic and contextual overview of the building’s condition. In addition, monitoring and analysis of performance data may also provide insight into resource consumption and environmental impacts of the built environment; with potential of understanding discrete interdependencies and relationships between various operational aspects (Ahmed et al., 2009).

Many researchers have attempted to formalize the process of performance measurement through identifying and categorizing various performance metrics (Cable & Davis, 2004; Barret & Barldry,
Some researchers have focused entirely on physical performance of building elements and proposed maintenance performance metrics as a framework to determine component and equipment level performance and to identify strategic improvement opportunities (Campbell & Reyes-Picknell, 2015; Tsang, 1998; Parida & Chattopadhyay, 2007; Muchiri et al., 2011; Parida et al., 2015). While others have proposed metrics to represent building performance objectives or goals (Becker, 1999; Hitchcock, 2002; Deru & Torcellini, 2004; Deru & Torcellini, 2005). ASHRAE (2010) in this regards developed a “standardized, consistent set of protocols […] to facilitate the appropriate and accurate comparison of measured energy, water and indoor environmental quality (IEQ), thermal comfort, indoor air quality (IAQ), lightning, and acoustics performance of commercial buildings” (Ihasalo, 2012, p. 66).

2. Building Functional Performance:

A lot of times, building O&M strategies focus entirely on monitoring and controlling the physical performance aspects and fail to determine whether the building is meeting its functional goals or not. Functional performance of a building is an evaluation of aspects related to the “organizational or business mission, space, employees, and other supportive facilities” (Lavy et al., 2010, p. 455). Talib et al. (2012) categorized functional performance in terms of building functionality (how well it serves its intended purpose) and building impact (creating a sensation of place for occupants). Lavy et al. (2010) reports that monitoring functional aspects like overused or underused spaces, productivity and turnover rates may provide valuable information for strategic decisions about the state of space utilization, functional adequacy of space and services, socio-economic impacts, satisfaction as well as potential to consistently achieve long-term goals (Preiser & Vischer, 2005).
Although there has been tremendous progress in terms of highlighting the importance of measuring, monitoring and controlling building performances, the industry is still catching up in terms of adapting performance specific processes and practices during operational phase of the buildings. One of the reasons is the fragmentation in AECO industry itself, in terms of understanding the need to measure, what to measure and how to interpret measured building performance parameters into actionable decisions (Piette et al., 2001).

Another challenge is that multiple systems are used to abstract information of different performance aspects, e.g., BMS for equipment, CMMS for facility/asset, EMS for energy information, etc. Vischer (2005) describes this practice as a disjointed, cost driven, conflict ridden and often ignorant of behavioral patterns. In order to prevent unnecessary errors, misinterpretation and cost incurrences (Bazjanac, 2004), performance information should be represented in a “manner that promotes a more holistic understanding of building performance in relation to the spatial and contextual configuration of the building” (Hailemariam et al., 2010, p. 117). A related problem is that most modern building information systems do not provide monitoring and control capabilities to building operators and are limited in just collecting and displaying relevant information (Piette et al., 2001). Lack of interactivity and real-time monitoring support in management systems may also lead to mistrust of presented information and hamper productive fault detection and diagnostic capabilities of building operators.

2.4.1 Building Performance Monitoring:

Friedman et al. (2003) summarizes the importance of performance monitoring as:
“[Building systems] have become so complex that continuous performance tracking is the key for building operators to know when systems aren’t functioning properly. Unfortunately, a process for data gathering and analysis is not usually established [...] in most commercial facilities, operators are too busy responding to comfort complaints, performing routine maintenance, and troubleshooting problems to perform what are often thought of as “research” tasks. But without tracking, equipment failures that do not result in comfort problems can dramatically increase consumption and will seldom be discovered unless rigorous performance tracking is in place”. (p. 3)

“The primary purpose of a performance monitoring system is to provide facility managers and operators with the means to assess easily the current and historical performance of a building/facility as a whole, and its [...] systems and components” (Haves et al., 2008, p. 2). According to Ulickey et al., (2010) the industry is divided in terms of defining a standardized scope of performance monitoring tools, with different terminologies being adopted to describe different tools, functions and domains (Hui 1996; Domingues et al., 2015). Usually different vendors introduce unique terminologies to highlight distinctive functions or capabilities of their particular tools. Terms like EIS\(^9\) (Motegi & Piette, 2006), FMIS\(^9\) (Varcoe, 1992), DRS\(^9\) (Motegi et al., 2003) and Dashboards (Few, 2006) are often used to describe monitoring tools with limited analytical and management functions. Advanced management and control systems like BMS (Webster, 2005), BEMS\(^10\) (Brendel & Schneider, 1991), EMIS\(^10\) (Kramer et al., 2013), EMCS\(^10\), BMCS\(^10\),

\(^9\) EIS: Energy Information Systems; FMIS: Facility Management Information Systems; DRS: Demand Response Systems
iBMS\textsuperscript{10} (Wong & Li, 2009; Elmualim, 2009), EMCIS\textsuperscript{10} (Yee & Webster, 2004) often prescribe to functions of EIS or FMIS tools with added capabilities of data filtering, autonomous analysis, fault detection and diagnostics, automated alarm alerts, information management and distribution and system-level controls\textsuperscript{11} (Friedman et al., 2010; Brambley et al., 2005; Yee & Webster, 2004; Kramer et al., 2013). Since most of the above described systems have overlapping functions, the above terms are used interchangeably adding to the confusion of using the correct acronym to define the scope of a tool. For example, EMS, EMIS and EIS are often used to describe very similar energy performance monitoring functions (Kramer et al., 2013).

This highlights a more intrinsic problem in the construction industry of distinguishing building performance in terms of two separate metrics – building energy consumption and building system\textsuperscript{12} operations. Tools are developed and marketed by different vendors to provide specific functions in terms of monitoring and controlling either building systems or energy consumption respectively. In line with the commercial developments, academic research has also differentiated between monitoring and control of building systems performance (Mustafa & Bansal, 2002; Bozány, 2003; Gryzkewicz, 2004; Kastner et al., 2005; Soucek et al., 2007; Yang et al., 2012; Domingues et al., 2015) and energy performance (Granderson et al., 2011; Lehrer & Vasudev, 2011; Augenbroe & Park, 2005; O'Sullivan et al., 2004) as separate and at times disconnected concepts. However, in recent years there has been a growing interest in exploring tools and processes that facilitate

\textsuperscript{11} In context of most information management tools, automation is implicitly part of the system, since most of the information used by those tools, is collected through the network of sensors and control devices of a BAS.

\textsuperscript{12} Here buildings systems are “[the] primary elements which together define the shape, utility, and comfort of built space. Systems may include architectural and structural elements, mechanical equipment or electrical components (USACE, 1997).
performance evaluation of all the operating systems including energy, water and resource consumption at whole building level but such efforts are still in infancy and require further research and exploration.

2.4.2 **Performance Monitoring and Control Tools:**

A large number of building performance monitoring tools are commercially available, designed to provide a variety of monitoring and management functions, according to the studies carried out by Marini et al., (2011), Friedman & Piette (2001), Motegi & Piette (2002), and Granderson et al. (2009). However, with the exception of some, most building performance management tools are custom configured as per client’s specific requirements, building characteristics and use profile. Subsequent, lack of common features, terminology and overlapping application areas makes it increasingly difficult to know what exactly the product offers, what is the hardware required at the back-end or how is it more effective compared to other products (Granderson et al., 2009; Karjalainen & Lappalainen, 2011; Haves et al., 2008; Friedman et al., 2011). Many researchers have tried to classify performance management tools, but such efforts were overshadowed by an inclination to distinguish and organize products based on their application in managing either building systems or energy systems (Granderson et al., 2013; Kramer et al., 2013; CEE, 2012; Brambley et al., 2005).

Hatley et al. (2005) and Friedman et al. (2011) classified system and energy level monitoring tools into three high level categories based on their functions: basic tools, benchmarking and analytical tools and advanced fault detection and diagnostic tools. For this study, integrated management system is included into the above classifications since it provides unified system and energy level
performance of a building in the form of a single comprehensive application. The proposed
classification is as:

1. Basic Information Tools
2. Management and Analytical Tools
3. Advance Management
4. Integrated Management and Control Systems (IMCS)

2.4.2.1 Basic Information Tools:

Tools in this category provide very high level performance monitoring functions (total energy and
water usage, annual CO₂ emission, etc.) allowing identification of broad issues causing excessive
energy use or irregular system performance (Friedman et al., 2011). The information is usually
gathered through underlying BAS, meter readings (electric, water, gas, etc.) and utility bills over
certain time periods. All this information is usually presented to the owner through graphical
visualizations using charts, numeric configurations and at times skeuomorphic images, Figure 2.6.
Dashboards¹³ and simplified building report cards are commonly used to visually display the
aggregated information in these tools.

Dashboards are only software front-end visual displays and are relatively inexpensive to setup and
configurable over internet for remote accessing. Despite of their usefulness and popularity,
dashboards are quite limited and do not provide functional capabilities for detecting, analyzing

¹³“A dashboard is a visual display of the most important information needed to achieve one or more objectives; consolidated and
arranged on a single screen so the information can be monitored at a glance”. (Stephen Few, 2007)
and diagnosing potential problems in the building systems at higher resolution (Lehrer & Vasudev, 2011; Friedman et al., 2011).

Figure 2.6 - Examples of Basic Tools: a) and b) UBC Pulse Energy dashboard, c) QA Graphics BAS monitoring dashboard, d) Information card from Noveda Technologies (http://www.noveda.com)
2.4.2.2 Management and Analytical Tools:

Most modern buildings are now equipped with sophisticated building systems and employ complex energy management strategies requiring much more technically robust tools that can analyze, benchmark and represent information at a much higher data resolution than dashboards. Management and Analytical tools go beyond basic information tools and combine software interface, data acquisition hardware, and communication systems in an integrated package that collects, analyzes and displays actionable information at a finer granularity (Granderson et al., 2009; Kramer et al., 2013). Such tools include advanced monitoring functions like remote user access, distributed control units, chronological data trending, ambient user interfaces, autonomous analytical capabilities, etc., (Krukowski et al., 2010; Friedman et al., 2011).

It is quite interesting to note that despite having separate software to measure and monitor energy and system information; data acquisition and storage for both elements is carried out using the same network of sensors, actuators and sub-meters usually controlled through a common automation system. Friedman et al. (2011) notes that most automation systems (BAS) have the capability to monitor and record energy related information, the only major difference lies in data aggregation and visualization. In this section, the term “management systems” would be referred as systems encompassing both energy and system level information processing, benchmarking and analytical capabilities.

The main departure point of management and analytical tools from dashboards is their ability to collect, consolidate and present archived performance information at a much finer granularity, i.e., sub-meter, subsystem or component level data, Figure 2.7. Data types like consumption records,
weather information, demand response information, equipment information, controller status, indoor environmental information, etc., are collected from BAS sensors, sub-meters, weather stations and other sources. With such high information resolution available, various management tools are able to provide building operators with near real-time building performance information at end-user or component level granularity. Building operators are also able to access historical data and identify recurring problems or efficiency of retrofits by comparing data and analyzing performance and energy consumption patterns over defined time periods (Friedman et al., 2011). Building operators can also fine tune systems’ efficiency or optimize operational schedules directly from the management systems to increase equipment efficiency or minimize overall energy consumption patterns.

Figure 2.7 - Component level information available in Management & Analytical tools: a) Delta OrcaView display of Air Handling Unit (AHU) https://www.deltacontrols.com, b) Siemens Apogee interface for the same AHU, http://w3.usa.siemens.com/buildingtechnologies
Despite their tremendous value in understanding performance trends, current tools are still limited in providing some essential functions like forecasting consumptions, control of system performance, fault detection and alarms, etc. They also lack the ability to dig down and extract end-user or component level information (Friedman et al., 2011; Lehrer & Vasudev, 2011). For example, most management tools may provide information at floor level granularity but are unable to specify energy contribution of different zones within that floor. Fortunately, some of the larger vendors have started to provide such features in their advanced tools aimed specifically to facilitate building operators and facility managers in making informed decisions.

2.4.2.3  **Advance Management: Fault Detection and Diagnostic Systems:**

Management and Analytical tools, as described above, are proving to be quite effective in understanding and analyzing system performance and energy use patterns at whole building level. However, most of these tools are designed to gather, analyze and benchmark historical or near real-time performance data and do not have capabilities to produce forecast models or pin point problematic areas or even identify anomalies without operator intervention (Yee & Webster, 2004; Bauman et al., 2013). Researchers have categorized such features under “Advanced management” and are usually added on to existing building system and energy management tools but may also be available as stand-alone tools (Friedman et al., 2011; Kramer et al., 2013; Bauman et al., 2013; Ihasalo, 2012).

Advanced Management (AM) systems are distinguished by their ability to incorporate energy modeling and evaluation functions as well as system-level automated problem detection and diagnostics, alarms and report generation and control capabilities. Most AM systems also provide
both top-to-bottom and bottom-to-top analytical capabilities depending on the sophistication of the underlying sensor and metering BAS network. Based on their application domain, AM systems can be broadly categorized into two major systems.

1. **Advanced Energy Information Systems (A-EIMS):**

   Since most of advance EMIS may include functions of energy management systems, Figure 2.8; this section would only focus on key distinguishing advanced features in this article.

   A-EIMS collects information from the base energy meters or sub-meters (similar to EMIS), analyze and at times normalize it to include numerous variables that affect energy consumption. Variables like ambient air temperature, weather conditions, seasonal and diurnal variations as well as occupancy load and behavior patterns are typically monitored and included in metered information analysis to provide a more holistic energy performance overview. The collected information is analyzed over specified periods of time (typically over a year or more) to develop consumption models that can predict typical energy use based on use patterns, weather conditions or occupancy loads and can be used to run comparative analyses between typical (baseline) vs. actual energy consumption trends. Similarly, some tools allow data from the existing design energy models to be incorporated and carry out design vs. actual consumption evaluations. Automated alerts and reports are generated identifying any performance differences.

   By utilizing sensor and meter networks at end-user level including plug and lighting loads, A-EIMS tools can further provide load disaggregation and end-use benchmarking functions providing performance information at space or component level (Kramer et al., 2013). It is however, important to note that, despite having advanced analytical and automated alert
capabilities, these tools on their own do not generate rich enough data to represent whole building performance and needs be paired with FDD tools in order to make effective decisions.

### 2. Fault Detection and Diagnostic (FDD) systems:

Despite the capabilities of modern management systems collect, analyze and visualize large amounts of data, human operator may still need intervene and interpret the results in order to evaluate and diagnose probable issues. This can be a very resource and time consuming process. Given the magnitude and complexity of information, operators are more prone to make erroneous decisions or miss a fault altogether (Ihasalo, 2012; Schein & Bushby, 2006) leading to loss of service or serious damages. FDD tools utilize sophisticated algorithms to automatically analyze system-level performance data and generate alerts/reports highlighting problematic areas/systems and help diagnose root cause of the problem by identifying the location of the issue (Friedman et al., 2012; Ulickey et al., 2010). These tools continuously monitor the operations of a system to detect and diagnose “abnormal conditions and the faults associated with them, then evaluating the

<table>
<thead>
<tr>
<th>CORE CHARACTERISTICS AVAILABLE THROUGH MOST ENERGY INFORMATION SYSTEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benchmarking</td>
</tr>
<tr>
<td>Data Quality Assurance</td>
</tr>
<tr>
<td>Data Visualization</td>
</tr>
<tr>
<td>Analysis</td>
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<table>
<thead>
<tr>
<th>ADDITIONAL FEATURES AVAILABLE THROUGH SOME EIS SYSTEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benchmarking</td>
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<tr>
<td>Energy Analysis</td>
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<td></td>
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</table>

Figure 2.8 - Potential core features of energy management tools (Friedman et al., 2011)
significance of the detected faults, and deciding how to respond” (Torrens et al., 2011, p. 1259; Katipamula & Brambley, 2005).

Apart from the obvious argument that no system can be fully autonomous, operators also need to be cognizant of the FDD tool’s level of automation in detecting and diagnosing problematic areas which varies significantly among different tools (Friedman et al., 2011). This variation may be due to propriety algorithms used by a specific vendor, sophistication and compatibility of BAS network, methods used for detection, level of automation/intelligence, customization as per client’s requirement or a combination of any of these factors. Another big reason for human intervention is that FDD tools do not necessarily provide energy use data, which is obtained separately from EMIS tools and may be quite useful in understanding a certain problem, its root cause and to properly diagnose the issue.

2.4.2.4 Integrated Building Management and Control Systems (IBMCS):

Due to the decentralized configuration\(^\text{14}\) of even the advanced management tools, building operators end up jumping from one tool to another in order to understand energy impacts on system usage or system-level faults on energy peaks (Bauman et al., 2013; Manru et al., 2010). This puts a considerable cognitive load on users trying to interpret complex information from multiple sources and then corresponding the results to get a holistic idea of a problem’s root cause (Hyvärinen & Kärki, 1996; Wong & Li, 2009). An integrated management system, would have

\(^{14}\) Decentralized configuration is due to separate tools being used to collect, analyze and present energy and system level information, i.e., EMIS for energy information management & BMS for building system information management.
the potential to reduce operator’s work in assessing different aspects of building performance and providing holistic real-time understanding of building behavior (Clark, 1993; Karjalainen & Lappalainen, 2011).

Many of the advanced features of performance management tools are under-utilized by building operators; at times simply due to the complexity involved in understanding the information without any contextual relation to the physical world (Duarte et al., 2011; Berhenn et al., 1997). Building operators also require additional information like specifications; warranties and guarantees; equipment O&M manuals and drawings to make informed operational and diagnostic decisions. In order to minimize the learning curve involved in understanding the performance data, the information presented needs to be relevant to that scenario and be available-as-required (Piette et al., 2001). This means that integrated management systems need to provide contextual information as required by the operator to fully understand the problem and make quick informed decisions to rectify any discrepancy. Clark (1993) presented a list of features that can be included in an IBMCS depending on the sophistication and level of integration of equipment and systems, Table 2.2.

Most of the research carried out in exploring IBMCS have been from a perspective of integrating different building services (HVAC, lighting, Fire alarm, etc.) in an intelligent building setting (Elmualim, 2009; Yang, 2013; Dong et al., 2012; Wong & Li, 2009; Wang, 2010). Some researchers have also explored artificial intelligence to fully automate some aspects of building performance monitoring and control functions across the built scape (Manru et al., 2010; Yang, 2013). These concepts are still in development and most of the research has been done from a technological breakthrough standpoint rather than exploring tools that may facilitate building operators in understanding building performance from an operational perspective.
Table 2.2 - List of features in an Integrated Building Management and Control System (IBMCS) (Clark, 1993)

<table>
<thead>
<tr>
<th>Integrated Management and Control System’s main features:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Real-time performance tracking</td>
</tr>
<tr>
<td>2. Automation and Control of HVAC systems</td>
</tr>
<tr>
<td>3. Lighting control systems</td>
</tr>
<tr>
<td>4. Global energy management</td>
</tr>
<tr>
<td>5. Load shedding and control of emergency power</td>
</tr>
<tr>
<td>6. Fire management systems, including detection and smoke control devices</td>
</tr>
<tr>
<td>7. Security management and access control systems</td>
</tr>
<tr>
<td>8. Time and attendance recording systems</td>
</tr>
<tr>
<td>9. Miscellaneous building systems including pumps, sumps, etc.</td>
</tr>
<tr>
<td>10. Elevator and escalator control systems</td>
</tr>
<tr>
<td>11. Telecommunications systems</td>
</tr>
<tr>
<td>12. Data analysis, comparison and forecasting</td>
</tr>
<tr>
<td>13. Fault Detection and diagnostics</td>
</tr>
<tr>
<td>14. Data archiving and remote retrieval</td>
</tr>
</tbody>
</table>

From my understanding, an IBMCS should provide contextual information to users either in response to an alarm from FDD, an energy spike or a trouble call from an occupant regarding a service failure. Building operators should be able to view information regarding the location of the problem, environmental conditions of that instance, energy consumption of that component, its historical maintenance record, specifications, standard operating procedures (SOP) and as-built drawings when interacting with the management system. To achieve such level of contextual information IBMCS may use sophisticated algorithms to classify and store performance information in the database in context to the physical objects. Since the database entries are object-based, all information relative to that object including any historical defects, associated alarms, ambient environmental conditions, sensors and meters can be associated to the database in real-time, Figure 2.9.
2.4.3 Building Performance Visualization:

Given the size and complexity of data most advanced performance management tools usually end up presenting the information as “purely analytical data, [which is inherently] separated form visual context of the built environment” (Hailemariam et al., 2010, p. 117). Complex information that might otherwise be difficult to comprehend by users should ideally be presented in a more visually expressive format, that would enhance a user’s understanding of the context, content and underlying structure of the presented information (Gursel et al., 2009). McCormick et al., (1987) describes the potential of visualization as offering a “method for seeing the unseen” (p. 3).

In the recent decades, visualization has evolved into a significantly broad and diverse discipline, encompassing different input/output tenets, objectives and approaches for different users.
(Lindquist, 2011; Ward et al., 2010; Card et al., 1999). In order to generalize the process of data visualization (Ware, 2004) proposed a framework consisting of four main stages, Figure 2.10:

1. Collection and storage of data
2. Processing and transformation of data into information
3. Graphical display of information
4. Human perceptual and cognitive system

I have already discussed the first two stages of visualization process at length in the above articles. In this section, visualization techniques that support graphical display of information and facilitate human perception and cognition would be further evaluated. Both graphical display and human perception are highly interdependent functions connected through a dynamic loop of feedback and manipulation. A user in interacting with the visualization to enhance his understanding of the displayed information, simultaneously influences both the visual as well perceptual aspects of the displayed information.
2.4.3.1 Visualization Techniques for Building Performance Information:

In general, visualization can be classified into two broad (overlapping) domains:\footnote{Despite the overlapping nature of these domains, information visualization is mostly attributed toward scientific and academic work; visually representing data-driven information to enhance understanding and cognition of otherwise abstract phenomena. Whereas graphics and information display mostly deals with the design of innovative and elegant visualizations to communicate that information, emphasizing on the beauty, elegance and impact of the visual display rather than presentation of the factual information (Lindquist, 2011; Card et al., 1999).} Information Visualization (InfoViz) (Robertson et al., 1989) and Graphics-display (Visual display) (Lindquist, 2011). Some researchers have further distinguished information visualization from scientific visualization (SciViz) (Card et al., 1999; Carr, 1999; Mazza, 2009). The main distinction being that scientific information is primarily based on physical or tangible data like earth, buildings or most 3D phenomena, etc., whereas information visualization is applied to non-physical and abstract data sets like data from sensors, components etc. (Card et al., 1999; Pilgrim, 2003; Yang & Ergan, 2012). Building performance information encompasses both physical information (i.e., systems, components and type of sensors) as well as intangible abstracted information (like temperature sensor readings, energy meter readings, component status, etc.) and may require an integration of both information and scientific visualization as well as graphical display techniques (Hailemariam et al., 2011). Wade et al. (2010) describes such integration as the “application of graphics to display data (scientific and abstract) by mapping data to graphical primitives and rendering the display”.

A study carried out by the National Building Controls Information program (Barwig et al., 2002) found that human interventions including operating errors, lack of awareness and indifference are one of the most significant factors in building control problems. Almost 29% of all building
monitoring and control problems is due to human errors (Yang & Ergan, 2014). Therefore, it is quite important that an interface visualization design of a BMS should be such that it enables building operators to intuitively connect the abstract part of the performance parameters with the physical attributes of the building systems, improving perception and efficiency in understanding the problem (Yang, 2014; Yang & Ergan, 2012). Despite the need, AEC industry has been seriously lacking in leveraging visualization techniques for better monitoring and control of performance information (Castello, 2012; Yang & Ergan, 2012, Golparvar-Fard & Peña-mora, 2007).

Many visualization techniques have been successfully employed in representing performance information of various building aspects like energy consumption and evaluation (Bazjanac, 2004; McGlinn et al., 2010; Maile et al., 2014; Hailemariam et al., 2010; Duarte et al., 2012), facility operations (Yang & Ergan, 2014; Kim et al., 2012; Schulze, 2010), occupancy control (Akbas et al., 2007; Breslav et al., 2014; Attar et al., 2011), HVAC simulation and control (Yang, 2014; Yang & Ergan, 2015; Keller et al., 2007), maintenance works (Akcamete 2011; Su et al. 2011; Sampaio, et al., 2009) and facility management (Castelo, 2012; Su & Huang, 2014; Ehrenfellner, 2012). Selection and appropriate utilization of a visualization technique, however, highly depends on the type of data and the task being undertaken (Pilgrim, 2003). Various researchers have proposed different classifications of data types in order to relate appropriate visualizations. Shneiderman (1998) categorized data according to task attributes into 1D, 2D, 3D, temporal, multidimensional, tree and network types. Hailemariam et al. (2011) suggested that data acquired from building sensors can be also classified in addition to the attributes suggested by Shneiderman (1998) into logical, scalar, vector (directional) and semantic types, where:
1. **Logical data** - includes 1D data points, usually consisting of discrete states – on/off or true/false.

2. **Scalar data** - are continuous 1D or 2D real value data points, usually used to describe performance parameters like temperature or energy use.

3. **Vector data** – are “continuous real values, with direction and magnitude. Data of this type includes air velocity”. (Hailemariam et al., 2011, p. 118)

4. **Semantic data** - includes tags, properties and dependencies which facilitates understanding and identification of other information.

A number of researchers have proposed different data dependent tasks (Shneiderman, 1996; Keller & Keller, 1993; Wilkinson, 2005) but for this research work, I considered the task classification by Salisbury (2001) cited by Pilgrim (2003), as it is more closer to the scope of works, Figure 2.11.

<table>
<thead>
<tr>
<th>Task</th>
<th>Indicators</th>
<th>Question (yes indicates presence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial</td>
<td>Where, distribution, locate, region</td>
<td>Is spatial location important for at least one of the data sets?</td>
</tr>
<tr>
<td>Comparison</td>
<td>difference, gains, losses, from/to clauses</td>
<td>Are you interested in how the data values relate/compare to each other?</td>
</tr>
<tr>
<td>Optima</td>
<td>majority, minority, least, most, greatest, biggest, smallest</td>
<td>Are you looking for maxima or minima within the data?</td>
</tr>
<tr>
<td>Trends</td>
<td>What, from/to clauses, distribution, generally, movement, change, time</td>
<td>Are you interested in the way your data changes or behaves over a time period?</td>
</tr>
<tr>
<td></td>
<td>period assessment</td>
<td></td>
</tr>
<tr>
<td>Relationships</td>
<td>What, How, from/to clauses, multiple data sets, depends</td>
<td>Are you interested in how some of the data sets relate to each other or affect the values of other data sets?</td>
</tr>
<tr>
<td>Aggregation</td>
<td>grouping based on data store field</td>
<td>Are you interested in classifications within some data sets?</td>
</tr>
<tr>
<td>Distinguishing</td>
<td>specific inclusion and exclusion clauses</td>
<td>Are you interested in individual data values within the data sets?</td>
</tr>
<tr>
<td>Calculations</td>
<td>sum, difference, total, average, median</td>
<td>Do you need to perform numerical calculations on data within or between data sets?</td>
</tr>
</tbody>
</table>

**Figure 2.11 - User Tasks as defined by Salisbury (2001) as cited by Pilgrim (2003)**
Coloring coding, textural annotations and use of symbols/metaphors have been the most widely used visualization techniques to represent semantic information on 2D and 3D settings (Yang, 2014). In addition to color, text and symbols, researchers also explored other techniques to represent multidimensional data like altering visual attributes of building components in 3D views to display multiple project datasets (Song et al., 2005), using size of geometrical primitives to represent sensor data (Hsieh & Lu, 2012), textual annotations and graphical augmentations in virtual environments (Virtual reality-VR and Augmented Reality-AR) to present a reality continuum\(^\text{16}\) of the construction processes (Bowman et al., 2006; Cheng & Teizer, 2013) and use of heads-up displays and transient geometry to provide auxiliary information on high-fidelity 3D views (Hand, 1997; Hailemariam et al., 2011).

Considerable research has also been done on visualizing building energy and resource consumption data (water, gas, etc.). Most of the work in this regards explored visual tools that incorporated dashboard like interfaces (Yang, 2014), using mostly analytical information visualization techniques like graphs, charts, time-series and tables to show energy use information to building operators and decision makers (Piette et al., 2001; Marini et al., 2011; Lehrer, 2009; Lehrer & Vasudev, 2011). Hoff and Hauser (2008) also used iso-lines, line-flows and heat maps to demonstrate energy consumption of larger areas and also integrated geographical data to illustrate consumption variation over certain areas. Other researchers have also experimented with self-organizing maps, neural networks (Duarte et al., 2011), direct render and transient geometry

\(^{16}\) An integration of augmented reality and virtual reality visualizations to produce a continuum between virtual and real world environments, see Milgram & Kishino (1994) publication for details.
(Hailemariam et al., 2010), carpet maps (Raftery & Keane, 2011) and floor maps (Itoh & Kawano, 2015) to visualize energy related data but geometric and spatial contextual information was not typically included in these studies (Yang, 2014).

Limitations in presenting spatially contextual geometric information of traditional visualization techniques have given rise to adoption of 3D visualization techniques – enabling building operators to visualize and analyze complex data (Pilgrim, 2003). 3D visualization specially in context of geometric information plays an important role in reducing the gap between the virtual representation and the actual object. Since humans are visual beings (perceptually tuned to respond to visual stimuli), "it is easier to convey the information to the observer if the information is represented by being mapped to the familiar physical space" (Gershon & Eick, 1995, p. 39).

Building information models (BIM) have gained considerable traction in terms of representing building physical and functional aspects as an integrated database of contextual information facilitating visualization of multiple performance parameters including architectural, structural, energy, acoustical, lighting, etc., (Eastman et al., 2011; Fischer, 2006; Asl et al., 2015). However, most of the research in this regards have mainly built on BIM’s visualization capabilities to display facility information (Motamedi et al., 2014; Akcamete, 2011; Chen et al., 2013; Su et al., 2011; Lin & Su, 2013). Given the inherent 3D geometrical characteristic of BIM, considerable research has focused on presenting information directly on the 3D model (Milne et al., 2001; Castelo, 2012; Maile et al., 2007), with very limited exploration of other interface elements to present performance information (Yang, 2014). Typically, semantic information is displayed over 3D geometry using color coding, textual annotations and symbols/metaphors (Golparvar-Fard et al., 2009; Song et al., 2005; Castelo, 2012; Hseih & Lu, 2012).
Recent studies by Pilgrim (2003) and Yang and Ergan (2014), however, noted that 3D visualizations may not be the visualization “panacea” as being hyped throughout the construction industry and may have to be augmented with other interface and visualization techniques to overcome certain shortcomings inherent to the 3D visualizations. For example, one of the shortcomings is that the front surfaces of a 3D geometry may occlude its rear/back surfaces and some of the mapped data may not be directly visible to the user. Pilgirm (2003) provide potential solutions to resolve this occlusion problem within a 3D geometry, Figure 2.13. The effectiveness

Figure 2.12 - Example of semantic information being displayed over 3D geometry: a) Use of textual annotation to provide energy usage information, b) use of colors ranges to describe the same data (Castelo, 2012), and c) Use of colors with iso-surfaces to provide energy.
of each technique highly depends on the complexity of the geometry, mapped data and purpose of representation (Pilgrim, 2003). If the main purpose is to understand and interact with both geometry and mapped information simultaneously, different combinations of these techniques may have to be adopted in order to offer enough flexibility to building operators to accommodate different building O&M scenarios.

2.4.3.2 **Visualization Techniques to Encode Spatially Contextual Semantic Information:**

A typical building requires multiple explicitly developed information models, in order to visualize both spatial/geometric (architectural, structural, site plan, etc.) and abstract (sensor, environmental, weather, etc.) data and provide holistic understanding of performance parameters.

![Figure 2.13 - Potential solutions for surface occlusion problem of a 3D geometry (Pilgrim, 2003)]
Tauscher et al. (2011) defines three methods to map and integrate semantic information over multiple models, i.e., blending, embedding and interaction. Where blending combines information from two different streams of information and represent them through visual attributes (color, size, position, etc.), embedding displays information from multiple sources in the form of secondary views (navigation maps, annotations, etc.) or facets (Wilkinson, 2005), interaction is similar to embedding where multiple streams of information is displayed but do not share a single rendering space but rather are triggered through user’s interaction with the visualization (pop-ups, heads-up display, etc.). According to Yang (2014) these three methods represent a higher level taxonomy of visualization techniques to map semantic information over geometric models with the potential to support other visual techniques that may enhance such mapping. She proposed a list of visualization techniques summarized in Table 2.3.

Categorical data which can be grouped together in a meaningful manner is usually represented using color coding, pattern coding or and symbols/metaphors (Roh et al., 2011; Yang, 2014). These techniques have been previously studied to retain and at times enhance user perception of the data even when mapped on complex 3D surfaces (Hsieh & Lu, 2002; Pilgrim, 2003; Rheingans, 1999). Animation is a valuable visualization technique that is often utilized to display temporal data (time dependent data); users can view historic or progressive record of an even over the selected time period (Yang, 2014). In addition, to colors and animations, textual annotations/linked documents or even hyperlinks can be used to provide descriptive information about an event. Textual annotation is a common technique thoroughly studied in context of virtual environments (Schulze, 2010), to encode specific information directly in the spatial environment (Yang, 2014).
Table 2.3 - Categorization of visualization techniques to encode semantic information under Blending, Embedding and Multi-views, Interaction. (Yang, 2014)

<table>
<thead>
<tr>
<th>Categories</th>
<th>Visualization Techniques</th>
<th>Type of Encoded Semantic Information</th>
<th>Single or Multiple Object Visualization</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blending</td>
<td>Color Coding</td>
<td>Categorical, Scalar</td>
<td>Multiple Objects</td>
<td>Song et al. (2005); Roh et al. (2011); Hseih &amp; Lu (2012); Asen et al. (2012); Sampaio et al. (2009); Akcamete et al. (2011); Golparvar-Fard &amp; Peña-mora (2007); Golparvar-Fard et al. (2009)</td>
</tr>
<tr>
<td></td>
<td>Pattern Coding</td>
<td>Categorical</td>
<td>Multiple Objects</td>
<td>Roh et al. (2007)</td>
</tr>
<tr>
<td></td>
<td>Animation</td>
<td>Spatio-temporal</td>
<td>Multiple Objects</td>
<td>Huang &amp; Kong (2007); Gopinath &amp; Messner (2013); Doulis &amp; Vogel (2007)</td>
</tr>
<tr>
<td>Embedding</td>
<td>Symbol/Metaphor</td>
<td>Categorical, Scalar</td>
<td>Multiple Objects</td>
<td>Hsieh &amp; Lu (2012); Akcamete et al. (2011); Einsfeld et al. (2008)</td>
</tr>
<tr>
<td>Text Overlay/Annotation</td>
<td>Categorical, Scalar, Descriptive</td>
<td></td>
<td>Single and Multiple Objects</td>
<td>Huang et al. (2007); Lee &amp; Rojas (2013); Bowman et al. (2003); Irizarry et al. (2011); Shen &amp; Jiang (2012); Kim et al. (2012)</td>
</tr>
<tr>
<td>Chart / Graph</td>
<td>Temporal (Time-series data)</td>
<td></td>
<td>Single and Multiple Objects</td>
<td>Akcamete et al. (2011); Kim et al. (2012); Rohr et al. (2008)</td>
</tr>
<tr>
<td>Multi-viewing</td>
<td>Multiple types of data</td>
<td></td>
<td>Multiple Objects</td>
<td>Kim et al. (2012); Kuo et al. (2011)</td>
</tr>
</tbody>
</table>

Visualization techniques described in Table 2.3, are mostly used to map semantic data onto spatial models and may only support visual perception of a building’s performance without any indication toward highlighting any dependencies that may exist within the object assembly. Without any visual aide available, building operators often rely on their knowledge of the sequence of operations of various components and dependencies that exist within a larger system, to understand performance data and diagnose problematic issues. For instance, the heat pump of an HVAC depends on the temperature of the source water, which is coming from the boiler, in order to extract
the heat and transfer it to the circulating ventilation air in the building to provide optimum comfort conditions; knowledge of this sequence of operation and dependency between the system would allow operators to quickly find and diagnose faults. Node-link graphs or dependency graphs have been successfully used in various design and construction fields to provide connection details between different interdependent objects or datasets (Kim et al., 2007; Lucas et al., 2012). Dependency graphs is a very useful technique to visualize hierarchical relationships between multiple objects (Herman et al., 2000), Figure 2.14.

![Dependency graph](image)

**Figure 2.14 - Example of dependency graph used to model architectural artifacts using Dynamo (Miller, 2013)**

From the study of the above visualization techniques in the existing body of knowledge, six visualization techniques were selected that may inform the design decisions of the proposed interface. The selected techniques are as:

1. Color/pattern coding and color gradients
2. Graphical symbols and metaphors
3. Textual annotation
4. Node-Link Dependency graphs
5. Balanced Occlusion and Direct Rendering Technique
6. Graph overlays

Another important aspect in terms of proposing an interface design is to study how humans perceive a certain visual element and interact with the virtual environment to perform an action (Yang, 2014). A considerable amount of research work has been carried out in the domain of Human-Computer Interaction (HCI), exploring various aspects that are concerned with designing, implementing and evaluating interactive systems (Dix et al., 2004). Previous research studies in the HCI domain have explored integrating various visualization techniques with computing interfaces (Bowman et al., 2003) that link the perceptual environment with the abstracted information (Yang, 2014; Bowman et al., 2003). According to Wassink et al. (2009) the success of any visualization depends on how the user perceives and interacts with it.

“[..] a good visualization for one user may be a poor visualization for another, because of the variance in user group characteristics and the differences in tasks to be performed. [...] Therefore it is essential to analyze what kind of visualization techniques should be used to support the tasks at hand and what types of interaction techniques best fit the particular user groups”. (Wassink et al., 2009, p. 2; Fikkert et al., 2007)
2.5 Human-Computer Interaction (HCI):

HCI has garnered tremendous interest since its inception in the 1980’s as a discipline highlighting the importance of human factors and experiences in interacting with computing systems. It seeks to understand and support the creative, cognitive and psychological aspects of human experience through intuitive design of interactive systems (Mackenzie, 2013; Carroll, 1997). A well accepted definition puts HCI as “a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them” (ACM SIGCHI, 1992, p. 6; Hewett et al., 1992; Dix et al., 2004; Preece et al., 2002).

The above definition can be dissected into four main HCI research areas: design, evaluation, implementation and influence of social and behavioral phenomena on user interactions. Although, all these concepts are equally important in realizing human-computer interactivity; interaction design would be primarily studied in more detail since it is the phenomenon that distills the knowledge and requirements from both human and machine perspectives to bring novelty and creativity to an interaction experience. Designing is “about developing interactive products that are easy, effective, and enjoyable to use-from the users' perspective” (Preece et al., 2002, p. 33). It not only encompasses the functional aspects but also addresses the cognitive and perceptual abilities of the users (Wickens & Hollands, 2000; Ashcraft, 2006; Goldstein, 2002), by ensuring usability and effectiveness of that system. In literature, interaction design is broadly discussed under two distinct categories: 1) Design of interactions as properties of system; where the main locus of interest is in exploring how users interact with technology (interface design), and 2) Design of interaction as the process of creating a system; which concerns with the processes
required to realize the above interactivity (Kjeldskov et al., 2012; Preece et al., 2002; Dix et al., 2004; Shneiderman, 1998). Key elements that define interaction design in a user interface comprise of:

1. Abstract concepts for interaction such as mental models, direct engagement, mapping, affordances, locus of attention, monotony, designing for action, etc. (Norman & Draper, 1986; Norman, 1999; Norman, 2002; Raskin, 2000; Laurel & Mountford, 1990).

2. Interaction Styles: such as command language, form filling, direct manipulation, gesture recognition, etc. (Preece & Benyon, 1993; Shneiderman, 1998; Preece et al., 2002; Card et al., 1999).

### 2.5.1 User Interface Design:

User interface can be termed as a representation of the system’s functionality; providing users the opportunity to interact with the computing system and carry out the required tasks (Beaudouin-Lafon, 1993). Treu (1994) defines a user interface as “the physical surface and facilities, between human user and computer, providing the medium through which they can connect and interact; the physical (visual, audio, tactile) means, methods, and patterns that support Human-Computer Interaction” (p. 24).

An interface is a connection between three interacting agents: the interface designer, a user and the system (Norman, 2002; Preece, 2002; Mandel, 1997) and consequently encompasses three discrete conceptual models: 1) a user’s mental model: is the user’s understanding of the system’s functionality, 2) designer’s

![Figure 2.15 - Conceptual Models Diagram (Norman, 1988)]
model: is his vision of system’s usability and function, and 3) systems’ image: is the physical and functional qualities of the system (Norman, 2002). Conceptual models based on user activities, spatial analogies (Norman, 2002), interaction metaphors (Carroll & Thomas, 1982) and paradigms (Preece et al., 2002) are helpful in terms of fleshing out the “behavior of the interface, appropriate interaction styles and the look and feel of the interface” (p. 40). These conceptual models and metaphors underlie almost every interaction between a user and a system, even if the user is unaware of it, and form the basis of interface design principles (Mandel, 1997).

2.5.1.1 Interface Design Principles:

“The needs of the users should dominate the design of the interface, and the needs of the interface should dominate the design of the rest of the system.”

(Norman, 1986, p.61)

A user’s experience interacting with the interface is quite diverse, complex and contextually dependent on various external (task) and internal (physiological and cognitive) stimuli and requirements (Dix et al., 2004; Karray et al., 2008; Mandel, 1997). This poses a considerable problem in terms of gauging the usability of user interfaces and quality of the user-experience. Many interface principles and guidelines have been proposed by researchers to facilitate interface design by defining implicit frameworks of user-experience goals and attributes, and by guiding design choices to enhance HCI practices (Chorianopoulos, 2008; Thimbleby, 1990). Three main distinctions can be drawn from the literature in this regard:

________________________

17 “User-experience quality depends on the application domain, the context of use, and the user characteristics and goals” (Nielsen, 1993).
1. **Standards** are mostly based on theories and are higher level of information, constituting both descriptive and predictive knowledge that helps clarify complex phenomena and support performance aspects (Shneiderman et al., 2009).

2. **Principles** can be taken as “abstract design rules” (Dix et al., 2004, p. 259) that are usually based on theoretical knowledge and experience, and are intended to provoke a richer and diversified thinking in designers about HCI design (Preece et al., 2002).

3. **Guidelines** on the other hand are more feature-centric. They address interface design on three broad practical levels: Physical (hardware), syntactic (sequence of interactions) and semantic (meaning of object and elements) (Mandel, 1997).

Many researchers have emphasized the need to model the interface according to what users need to see and do to achieve their tasks (Dix et al., 2004; Norman, 1987; Nielsen, 1992). The most famous proponent of this ideology, Don Norman (2002) proposed; visibility, feedback, constraints, mapping, consistency and affordance as the major heuristics/principles of a user-centered interface design. However, usability-based-principles tend to favor quantitative evaluation methods over qualitative measures, which many a time do not cater to more subjective elements like social norms, experience, etc. Hansen (1971) proposed HCI principles with a more qualitative undertone like know the user, minimize memorization, optimize operations and engineer for errors. Similarly, Gould and Lewis (1985) proposed, early focus on users and tasks, empirical measurement and iterative design as the three main principles for a user-centered interface design (Treu, 1994). Shneiderman et al. (2009) on the other hand proposed a more generalized approach by including; knowledge about the user and his skills, identification of tasks and selection of appropriate interaction styles, as prerequisite principles to the eight design principles referred as “eight golden
rules” (Shneiderman et al., 2009). Tognazzini (2014) further extended these principles by considering requirements of different graphical environment’s requirements (Web, mobile, wearable, etc.), see Table 2.4.

Table 2.4 - Summary of popular user interface design principles and heuristics

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<tr>
<td>Visibility</td>
<td>Visibility</td>
<td>Visibility of System Status</td>
<td>Cater to Universal Usability</td>
<td>Visible Interfaces</td>
<td>Visibilities</td>
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<tr>
<td>Consistency</td>
<td>Consistency: standardize</td>
<td>Consistency and Standards</td>
<td>Strive for Consistency</td>
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<td>Closeness of Mapping</td>
<td>Mapping</td>
<td>Match between System and the Real World</td>
<td>Design Dialog to Yield Closure:</td>
<td>Discoverability</td>
<td>Structure</td>
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<td>Error-Proneness</td>
<td>Constraints</td>
<td>Error Prevention:</td>
<td>Prevent Errors</td>
<td>Color</td>
<td>Tolerance</td>
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<td>Role-expressiveness</td>
<td>Affordance</td>
<td>Recognition rather than Recall</td>
<td>Permit Easy Reversal of Actions</td>
<td>Defaults</td>
<td>Affordance</td>
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<td>Abstraction</td>
<td>Simplify the structure of tasks</td>
<td>Flexibility and Efficiency of Use</td>
<td>Support Internal Locus of Control</td>
<td>Simplicity</td>
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<td>Hidden Dependencies</td>
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<td>Aesthetic and Minimalist Design: Help Recognize, Diagnose, and Recover from Errors Help and Documentation:</td>
<td>Reduce Short-Term Memory Load:</td>
<td>Efficiency of the User</td>
<td>Accessibility</td>
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<td>Viscosity</td>
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<td>Secondary Notation</td>
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<td>Reduction</td>
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<td>Premature Commitment</td>
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<td>Human Interface</td>
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<td>Diffuseness</td>
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<td>Objects</td>
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<td>Hard mental operations</td>
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<td>Aesthetics</td>
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<td>Progressive evaluation</td>
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<td>Explorable Interfaces</td>
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<td>Readability</td>
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<td>Autonomy</td>
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<td>State: Track it</td>
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<td>Anticipation</td>
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Since each interface design may present unique objectives and preferences, no single list of principles is complete and may require validation, refinement and appropriation based on specific design requirements (Dix et al., 2004; Shneiderman et al., 2009; Treu, 1994; Mackenzie, 2013). The underlying objective, however, should be to select appropriate principles that facilitate “simple, perceptually salient, elegant and usable” interface designs (Preece et al., 2002, p. 152).

2.5.1.2 User Interface (UI) Design Process:

Designing in general is an expressive, intrinsically dynamic process; diverse and contextual in nature that is tailored to the user’s needs. Yet any design must follow a structured framework, albeit iterative, to be successful and consistent in its implementation. In this respect, four main phases can be distinguished from the literature as constituents of interface design process: establishing user requirements, analysis, design and prototyping, and implementation (Dix et al., 2004; Preece et al., 2002; Treu, 1994; de Graaff, 2001).

According to Mandel (1997) an interface design is a cyclic process than traditionally practiced sequential “waterfall” approaches (Royce, 1970) for UI design, Figure 2.16(a). Preece et al. (2002) suggests that in addition to an iterative cyclic-approach an interface design should also be characterized by the focus on users’ involvement and needs with well-defined usability and user-experience goals, thus ensuring user-centered and consistent designs, Figure 2.16(b). By understanding the range of involved stakeholders, their skill sets and knowledge backgrounds; design goals can be aligned and directed by user requirements and domain context rather than the technical and functional constraints (Benyon, 2010; Alsumait, 2004; Van Welie, 2001).
Depending on the context of the investigation and quality of data required, several techniques like surveys, interviews, workshops, etc., can be used for gathering data, either individually or in appropriate combinations. In addition, focused groups, ethnographic studies, observations and videotape sessions have also been utilized in the past to gather consensual views and demographically specific requirements. The quality and objectivity of the collected information, however, is dependent on various factors and may lead to user requirements that do not provide a realistic overview of what users may actually need (Mandel, 1997; Norman, 1987; Carroll, 2000). Mandel (1997) suggests that in order to realize designs that not only cater to current user requirements but also satisfy any future needs, designers should use techniques that focus on answering key questions rather than gathering just problem-specific information (Stolterman, 2008). Aligning user requirements, with potential tasks present designers with opportunities to assess trade-offs with respect to various constraints, identifying implicit interaction patterns and appropriate interface elements required for the task (Alsumait, 2004; Preece et al., 2002). Designers can explore different design concepts with respect to variable use scenarios, draw

Figure 2.16 - Iterative design processes, a) A connected, closed loop design process (Mandel, 1997), b) An open looped design process with iterative phase development stages (http://www.dcndx.com, 2016)
implicit task requirements and utilize usability metrics to explore appropriate trade-offs (Contantine, 1996; Bevan & Curson, 1997).

### 2.5.1.3 Scenarios in User Interface Design:

Design of interactive systems is an ill-defined and iterative process (Rosson & Carroll, 2002). Problem-solving strategies may clarify various ambiguities but they may also indulge designers to pursue specific solutions without exploring other perspectives, root causes or knowing the context of system use (Cross, 2001). By explicitly describing work-oriented tasks, designers are able to understand how users perform tasks in their natural environment independent of any technological influence (Shneiderman et al., 2009). In this respect, scenarios and use-cases provide the most effective and efficient way of envisioning the context and the environment in which the user would use the system to carry out a task.

In software engineering, scenarios are often confused with instances of use-cases (Alsumait, 2001). Although both techniques focus on user-goals, the main distinction is that scenarios emphasize on user tasks while use-cases (Jacobson, 2004) stress more on exploring the user-system interaction itself (Preece et al., 2002; Cooper et al., 2003). Scenarios consist of “a description of a set of users, a specific work context, and a set of tasks that users perform or want to perform” (Nardi, 1992, p. 13) without any intervention of computing devices (Go & Carroll, 2004). Carroll (2002) distinguishes scenarios as, “The defining property of a scenario is that it projects a concrete description of activity that the user engages in when performing a specific task.” (p.385). Carroll (1999) proposed five key characteristics that highlight the importance of using scenarios in user interface and system design processes, see Figure 2.17:
1. Scenarios evoke reflection in the context of design work
2. Scenarios provide concreteness and flexibility to dynamic and ambiguous design situations
3. Scenarios afford multiple variations in resolution and perspective of design details
4. Scenarios can also be abstracted and categorized
5. Scenarios promote direct stakeholder participation to explore work-oriented user needs.

Scenarios can be expressed and communicated quite easily and flexibly using variety of media and forms. They can be presented in an informal, formal or semi-formal notation (Rosson & Carroll, 2002). Storyboards or visual mockups are often used to describe user scenarios using either textual or graphical mediums or both (Alsumait, 2001; Rosson & Carroll, 2002). Scenarios in the form of storyboards and mockups often lead to or form low-fidelity prototypes, facilitating evaluation, feedback and iterative development opportunities (Alsumait, 2001; Virzi et al., 1996).

Figure 2.17 - Approaches in scenario-based design (Carroll, 1999)
2.5.1.3.1 Scenario-Based Storyboarding and Prototyping:

Prototyping is a valuable technique of exploring design alternatives, envisioning and demonstrating interactions and evaluating the usability of user interface designs at various stages of design lifecycle. Designers develop prototypes to demonstrate different interaction strategies without actually developing the entire system. Prototypes are often distinguished as low-fidelity or high-fidelity depending on the degree to which a model of the system resembles the target system (Sauer et al., 2008). Storyboards and mockups both provide low-fidelity prototyping abilities. Storyboards are often referred to as “presentation scenarios” (Maguire & Bevan, 2002, p. 7): representing user behavior and task description through sequential frames of discreet events using either graphics or textual narrations. Mockups on the other hand are low-level representations of the system itself, reflecting general design concepts and details like screen layouts, visuals, colors, icons and controls, without providing any actual interactivity or navigation capability (Alsumait, 2001; Rudd et al., 1996). Both of these techniques provide a low cost and efficient means to demonstrate and communicate system interactivity.

Due to the relatively limited functionality offered by storyboards and mockups they are usually accompanied by task specific scenarios, which provides the context, goals and design rationale behind the interactions represented in the prototype (Cooper et al., 2007). Well thought-out and carefully orchestrated scenarios, used together may themselves function as a low-fidelity prototypes, exposing implicit design assumptions and facilitating design reviews and usability evaluations (Carroll, 1997; Karat & Bennett, 1991). Scenario-based prototypes provide contextually coherent broad design perspective as well as allow quick generation and evaluation of design alternatives by revisiting the underlying base-scenario for each task description.
2.6 Building Information Modeling (BIM):

AECO industry has long been plagued by its project-based nature (Taylor & Levitt, 2004), increasing complexity (Dubois & Gadde, 2002) and slow-pace in adoption of state-of-art technology compared to other developed industries (Gallaher et al., 2004; Froese, 2009; Froese et al., 2007) causing productivity issues (Teicholz, 2013), fragmentation and lack of collaboration (Egan, 1998; Sun & Aouad, 2000), and distraught project delivery systems (Riaz & Jaffery, 2013). To counter such short comings, innovative approaches and construction practices including integrated technologies, tools and processes like Lean Construction (Koskela, 1992), Integrated Project Delivery method (Fisher, 2004), Building Information Modeling (BIM) (Eastman et al., 2011), Augmented and Virtual Reality (Lee & Peña-mora, 2006; Golparvar-Fard & Peña-mora, 2007), have emerged over the past decade. Advancements in sensor and scanning technologies have also provided opportunities to capture high-quality as-built building information to further facilitate building operation, management and maintenance works (Akinci, 2004).

Among the above innovative solutions, BIM has emerged as a technological platform that is revolutionizing how we practice, communicate and visualize building information within the AECO industry (Fuller, 2009, Krygiel & Nies, 2008, Poirier et al., 2013, Succar et al., 2007). BIM can be defined as a “[...] digital representation of physical and functional characteristics of a facility, [which serves] as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle” (NIBS, 2013, p. 1; NBIMS, 2006). Succar (2005) however, notes that “the boundaries of BIM as a term-definition, set of technologies and group of processes is fast changing [...]”. As a term, BIM seems to have somehow stabilized now, but as a
set of technologies/processes, its boundaries are rapidly expanding” (p. 1). This is evident from the fact that BIM has grown from a design-specific modeling tool to being adopted almost across all building lifecycle aspects as a collaborative information-rich platform18 (Eastman et al., 2011; Azhar et al., 2008; Ashcraft, 2008; Becerik-Gerber & Kensek, 2010), Figure 2.18. Nicolle & Cruz (2011), describes BIM as:

“A BIM system is a central system that manages various types of information, such as enterprise resource planning, resource analysis packages, technical reports, meeting reports, etc. However, the main feature of a BIM is the 3D modeling system with data management, data sharing and data exchange during the lifecycle of the building”. (p. 15)

Although, Cahill et al. (2012) reported that BIM implementation beyond the design and construction phase is relatively “diluted”, there is a significantly growing interest in use of BIM to extend, coordinate and manage the information/knowledge from the design and construction phases to building O&M phase (Becerik-Gerber & Jazizadeh, 2012). According to Kensek (2015), BIM in this respect has a critical role to play by providing a reusable high-fidelity representation of physical and functional attributes of a facility in an information repository to building owner/operator to use and maintain over the entire lifecycle of the facility (Nicolle & Cruz, 2011; NBIMS, 2006). Numerous research studies have been carried out to evaluate potential BIM integration into facility operations and management processes (Volk et al., 2014), which can be

18 Succar (2009) defines information-rich platform as “a set of interacting policies, processes and technologies producing a methodology to manage the essential building design and project data in digital format.”
generally grouped under two major categories (Yang, 2014): 1) research on development of BIM-based frameworks, and 2) research studies evaluating facility information management using BIM.

For the purpose of this research, I looked at research studies that focused on BIM as an information management and visualization platform for O&M works, since they somewhat overlapped with the intended scope of research presented in this thesis. Examples of the studies include: Integration of sensor data with BIM (Liu & Akinci, 2009), BIM-based facility maintenance management system (Lin & Su, 2013), Real-time energy monitoring and FDD with BIM (Dong et al., 2012), BIM-based performance optimization (Asl et al., 2005), BIM-based facility energy management (Ahn, et al., 2014; Al-shalabi & Turkan, 2015), BIM and RFID based asset tracking system (Meadati et al., 2010; Shen et al., 2012), 3D-based facility maintenance and management system (Chen et al., 2013), Modeling and visualization building performance (Gursel et al., 2009), BIM for building maintenance (Motawa & Almarshad, 2013) and BIM-based approach to troubleshoot

Figure 2.18 - Potential applications of BIM in different phases of a constructed projects (Golabchi et al., 2013)
HVAC problems (Yang, 2014). These studies demonstrated the value and efficiency of model-based information repositories and how BIM can be integrated to optimize various building operations and management functions (Yang, 2014).

However, none of above the studies explored the visual representation value of spatially contextual semantic information in understanding of building performance, which shows the research potential of further exploring this aspect of using BIM. In addition, some of the studies also provide back-end information aggregation, indexing and dissemination processes involved in mapping multiple source datasets onto BIM schema, e.g., a multi-standpoint framework for technology development (Cerovsek, 2011), Capturing of Work order information (Akcamete, 2011), BIM transformation based on IFC (Liu et al., 2006) and fault-tree analysis (Lucas et al., 2012; Motamedi et al., 2014). Although, the scope of this thesis is not to provide a data mapping back-end structure for the proposed integration, these studies provide a grounded base and a departure point for this research.

2.6.1 Information Models to Map Building Performance Data on BIM:

Interoperability\textsuperscript{19} has been a serious issue in terms of information exchange among different AECO information tools, causing significant financial and productivity losses (Gallaher, 2004). BIM provides a potential solution to this problem by acting as a central information repository for semantic information of building objects across building lifecycle including geometry, associated

\textsuperscript{19} Interoperability is “the ability to manage and communicate electronic product and project data between collaborating firms and within individual companies’ design, construction, maintenance, and business process systems” (Gallaher, 2004)
properties, and relationships (Costa et al., 2013; Parsanezhad, 2015). Still BIM depends on other applications to speak its language in order to streamline a bi-direction information exchange process with them. Considerable amount of effort has been vested in developing common information models that can exchange information between BIM and other building services management applications like FM, HVAC, BAS and BMS and EMIS (e.g. IFC; COBie – (East, 2007); HVACie – (East, 2013); Yu et al., 2000; Liu et al., 2011). These “expert functionalities” (Volk et al., 2014, p. 113) are linked with a BIM model through Information Delivery Manual (IDM) frameworks and Model View Definitions\textsuperscript{20} (MVD) providing relevant information, facilitating data exchange and avoiding ambiguities (Volk et al., 2014), see Table 2.5 for a list of popular MVD for BIM functionalities.

Table 2.5 - List of MVDs for BIM functionalities in IFC2x3 format (Volk et al., 2014, p. 118)

<table>
<thead>
<tr>
<th>Model View Definitions</th>
<th>Acronyms</th>
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<tbody>
<tr>
<td>BIM Service Interface Exchange (Web Services)</td>
<td>BIMSie</td>
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<tr>
<td>Building Automation Modeling Information Exchange (Control and BAS)</td>
<td>BAMsie</td>
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<tr>
<td>Electrical System information exchange (delivery of electrical power within facilities)</td>
<td>Sparkie</td>
</tr>
<tr>
<td>Equipment Layout information exchange</td>
<td>ELie</td>
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<tr>
<td>IFC2x3 Coordination View v2.0 (Optional w/ Quantity Takeoff, Space boundary or 2D)</td>
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<tr>
<td>IFC2x3 Structural Analysis View</td>
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<tr>
<td>HVAC (Heating, Ventilation, Air-conditioning, Cooling) information exchange</td>
<td>HVACie</td>
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<tr>
<td>Lifecycle information exchange, with the refinement of Building Programming information exchange</td>
<td>LCie, BPie</td>
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<tr>
<td>FM Basic Handover with Construction Operations Building Information Exchange</td>
<td>COBie</td>
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<tr>
<td>Quantity Takeoff information exchange</td>
<td>QTie</td>
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<td>Spatial validation</td>
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<td>Water System information exchange</td>
<td>WSie</td>
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\textsuperscript{20} “The IDM framework defines the functionality-related exchange of process information in BIM […] which a MVD structures relevant information for efficient information flow between stakeholders in building related processes” (Volk et al., 2014)
2.6.1.1 Construction Operations Building Information Exchange (COBie):

The Construction Operations Building Information Exchange (COBie), was developed by the United States Army Corps of Engineers as a “specification for capturing design and construction information for facility managers and operators in a digital format” (Jawadekar, 2012, p. 20; East, 2007; Kasprzak et al., 2013). The IFC format COBie handover file can be directly integrated with BIM database providing a seamless mapping of relevant information. Additionally, the IFC MVD file can also be viewed and managed using non-BIM applications like Microsoft Excel (East et al., 2012; Parsanezhad, 2015). Although, COBie is designed to optimize information exchange to FM, it only caters to as-designed and as-built information and does not contain any provisions to record real-time information generated during building O&M phase like sensor information, maintenance records, energy / resource consumptions (Yang, 2014). Such information is quite significant for understanding, monitoring and troubleshooting building performance issues.

Several other information exchange models have been proposed to compliment and fill the current information gaps in the COBie format. HVACie and AEX (Turkaslan-Bulbul, 2006) are two such information exchange systems under development which may define the specifications for capturing and distribution of HVAC and related electrical system across building lifecycles (Hitchcock et al., 2013).

2.6.1.2 Industry Foundation Classes (IFC):

Industry Foundation Classes is the “data standard” developed and maintained by buildingSMART International (buildingSMART, 2016), used for exchanging geometrical and non-geometrical building information across building lifecycle phases (Parsanezhad, 2015). Since its fourth
iteration- IFC4, it has been also accepted as an International Organization of Standards (ISO) standard – ISO 16739 (buildingSMART, 2016). IFC covers all relevant building information in its resource layer including information regarding building equipment, sensors and controllers – which can be found under building controls domain and HVAC domain in IFC data schema, see Figure 2.20. Under each of the above its resource domains, IFC covers a wide range of generic information templates, that are quite valuable for mapping real-time information on BIM database for building performance monitoring and control activities. For example: location of equipment components (IfcObjectPlacement, IfcRelContainedInSpatialStructure), Sensor types (IfcSensorTypeEnum), Spatial zones (IfcSpatialZone), control relationships (IfcRelFlowControlElement) and connectivity relationships (e.g. IfcDistributionPort, IfcRelConnectsPortToElement) between components.

Figure 2.19 - Space composition in IFC, where a space is an that provides a certain function and can be grouped together to form a zone (ifczone), (http://www.buildingsmart-tech.org, 2016)

Despite having quite a comprehensive data template for building information not all the information is specified within the IFC schema (Yang, 2014) but a very important factor in IFC’s
iniquitousness as an information exchange standard is its openness to extensions and modifications. A considerable amount of researchers has extended various parts of IFC schema to incorporate their requirements to represent and communicate building information across different lifecycle phases (Cahill et al., 2012; Asen et al., 2012; Bazjanac, 2008; Bogen & East, 2011; Liu et al., 2006; Ahn et al., 2014).

To conclude, due to the relatively limited information available in support of building performance monitoring and control functions, and involvement of a wide range of research domains, the research presented in this thesis mainly utilizes established body of knowledge as the main departure point. However, lessons learned from the literature review were augmented with the findings of the case study to realize various features and visualization techniques used in the proposed integrated interface for building performance monitoring and control tasks.

![Figure 2.20 - IFC 2x4, Data Schema architecture](http://www.buildingsmart-tech.org, 2016)
Chapter 3: Lessons Learned from Building Operation Practices at CIRS

3.1 Introduction:

To understand how the building automation and management systems facilitate an operator’s understanding of a facility’s behavior and consequently shape O&M decisions, I carried out a case study of a high-performance academic building in a centrally operated university environment.

In this chapter, I first summarize building operation, maintenance and performance management practices prevalent in general at university level and then in particular at the case study building (CIRS). At both these levels, I studied the O&M practices in context of using building and energy management tools for O&M works. The collected data is used to highlight major discrepancies in current tools in regards to O&M works and was used as a baseline for developing explicit scenarios and use-cases that will form the basis of the envisioned interface. The results from this study may provide some direction for the future development of integrated performance visualization systems.

3.2 Background:

University of British Columbia (UBC) is a large owner-operated organization with almost 500 buildings spread over 993 acres of campus land\(^2\)\(^1\). Building Operations (BOps) department, located at University Services Building, is mainly responsible for operating and maintaining almost 405 hectares of UBC infrastructure that includes 225 core university owned buildings (810,119\(m^2\)

\(^2\)\(^1\) https://sustain.ubc.ca/our-commitment/campus-living-lab
gross floor area). With construction projects undertaken over UBC’s 100-year history, several buildings at the campus are of varying ages – with some vintage buildings even predating microprocessor based equipment control systems. Building systems in most of the UBC academic buildings have been periodically upgraded, retrofitted or renovated through various initiatives like the Building Tune-up program in 2001, to keep pace with the advancements in the building O&M technologies. New buildings, on the other hand, are being commissioned equipped with modern state-of-art systems, on an ongoing basis. Due to various retrofitting initiatives and continuous induction of modern technologies over the years, four different BMS now exist at the campus. These systems are being used to operate and maintain different buildings based on the Original Equipment Manufacturer (OEM) installed equipment, control systems and communication protocols, see Figure 3.1. The systems are:

a. Apogee by Siemens
b. Metasys by Johnson Controls Inc.
c. EnteliWEB by Delta Controls Inc.
d. Enterprise Building Integrator (EBI) by Honeywell

22 http://www.buildingoperations.ubc.ca/about-us/
23 As part of Building Tune-up program, the ECOTrek initiative (2001-2008) saw retrofitting of 288 UBC academic buildings to reduce energy and water consumption, including installation of BAS and energy management systems (ECOTrek, n.d.)
In addition to BOps, which is primarily responsible for all core operation and maintenance (O&M) activities at the campus, a new Energy and Water Services (EWS) department was created by UBC for the execution of all energy, water and natural gas related projects and operational processes. As part of its long-term sustainability goals, UBC in 2001 initiated a campus wide energy and water infrastructure retrofit and restructuring program called ECOTrek. The main objective of the initiative was to provide comprehensive utility management infrastructure and framework for energy efficient operation of UBC’s building assets. The program resulted in installation of energy
sub-meters across 288 core buildings. The data from these metered buildings is made available through a publicly accessible database – ION historian, Figure 3.2.
Following-up on the success of ECOTrek, UBC\(^{25}\) implemented a *Continuous Optimization* program to monitor and optimize energy consumption of 72 of its core academic buildings. Part of this optimization was a $6 million project to upgrade and retrofit the facilities with an Enterprise Energy Management (EEM) system in partnership with BC Hydro’s *Continuous Optimization* program and technology provider Pulse Energy (now EnerNOC). Pulse Energy was selected to provide an Energy Information Management System (EIMS) to aggregate and present energy data from the sub-metered of the Core Academic Buildings (CAB) on campus in an understandable and actionable format, Figure 3.3.

![Figure 3.3 - Energy Information Management System (EMIS) by Pulse Energy](image)

Currently, all metered buildings are continuously monitored by UBC’s EWS unit, using both ION and Pulse Energy EMIS tools, to identify any deviation from the baseline. EWS also compare energy anomalies against BMS information and alert BOps of any system’s over-consumption or malfunction - which then investigates the cause at its end and propose diagnostics and remedial

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\(^{25}\) Project services provide primary renovation, renewal and modernization of university buildings, roads, and other infrastructure that have cost range between $50k-$1M (Tejeida, 2014)
actions. Both BOps and EWS departments have access to Pulse Energy interface and collaborate with each other concerning issues related to building system optimization, operational schedules, energy use efficiencies, maintenance programs, fault detection, diagnostic and performance data analysis, etc.

As one of the UBC’s core academic buildings, Centre for Interactive Research on Sustainability (CIRS) presents a unique position regarding its building O&M and performance management practices. Being part of the UBC campus, most of CIRS O&M activities are monitored and controlled through the Central Building Management System (CBMS) by BOps at University Services Building. Similarly, energy related information and processes are also overseen by Energy Planning and Innovation (EPI) group at EWS. However, as part of the UBC’s Living Campus Initiative26 CIRS is designed as a “Living Laboratory” - a test-bed for sustainable research work, integrated with 3000+ sensor and control points, monitoring building and energy performance data at component level resolution. Honeywell installed an enterprise level BMS to aggregate all data from these sensors; which is being monitored and controlled by a BMS specialist. This data is used to optimize operational schedules, reduce energy consumption and calibrate building systems.

26 The “Living Lab” initiative at UBC, is a vision to use the entire campus as kind of giant sandbox in which there is the freedom to explore—creatively and collaboratively—sustainable concepts utilizing all the resources available at campus including physical assets as well as academic capabilities. https://sustain.ubc.ca/our-commitment/campus-living-lab
3.3 Methodology:

Due to the complex organizational ecosystem present at UBC, the data was collected in two levels: 1) broader campus level for general O&M practices, and 2) project level with a specific focus on the use of BMS tools through a case study.

In this chapter the collected data is used to document and summarize prevalent O&M practices; while in the succeeding chapter, I analyzed the data to highlight gaps and problems in current BMS systems and their use and possible solutions to optimize these interactions.

3.3.1 Data Collection:

The author held a graduate office space at the case study building – CIRS for over a period of two years (2011-2013). Data on O&M and energy management practices was collected through various methods over this period. Both qualitative (interviews, contextual inquiries, shadowing) and quantitative (survey) data is collected to holistically understand O&M practices in the context of organizational setup and information flow for decision-making, building and energy management processes and use of technology at both campus and project level.

3.3.1.1 Collection Process:

A mixed-method two-phased approach was adopted. Phase-I involved collection of data through various methods:

1. **Formal and Informal Interviews:** I interviewed several UBC building operation and energy management personnel to understand their routine work practices and use of information for decision-making, Table 3.1.
2. **Observations and Contextual inquiries:** I observed the use of central BMS and EMIS tools at the Master Alarm and Control Center (MACC) by different building operators and energy managers to troubleshoot building performance issues. I also observed and contextually inquired the BMS specialist at CIRS in his use of the Honeywell BMS tool.

3. **Document review:** Numerous documents including policies, technical guidelines, procedures and drawings, were examined to understand and relate observational data with UBC’s standard procedures. I also studied BMS manuals, drawings and instrument specifications for CIRS to have a better handle on system operations and functions.

Phase-II involved a survey-based investigation of practitioners on the specific use of BMCS and EMIS tools for their routine O&M and energy management work practices. The survey was designed to explore both general and technical problem sets, identified from the initial observations and the interview sessions to obtain quantitative data to support prior empirical observations.

**Table 3.1 - List of interviewed personnel, with their departments and respective roles**

<table>
<thead>
<tr>
<th>Department</th>
<th>Interviewee</th>
<th>Responsible for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre for Interactive Research</td>
<td>CIRS Program Manager</td>
<td>Project management of post-commissioning and building operations</td>
</tr>
<tr>
<td>(CIRS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BMS Specialist</td>
<td>BMS monitoring and Control</td>
</tr>
<tr>
<td>Campus Sustainability</td>
<td>Climate and Energy Engineer</td>
<td>Building energy monitoring and management</td>
</tr>
<tr>
<td>Building Operations</td>
<td>BMS Supervisor</td>
<td>BMS programming</td>
</tr>
<tr>
<td></td>
<td>Head Maintenance Engineer</td>
<td>Building Operations and Maintenance works</td>
</tr>
<tr>
<td>Energy and Water Services</td>
<td>BMS Manager</td>
<td>BMS programming and management</td>
</tr>
<tr>
<td></td>
<td>Energy Conservation Manager</td>
<td>Pulse and ION energy data analysis</td>
</tr>
</tbody>
</table>
3.3.1.2 Participants:

In the initial informal Phase-I of the study, two (02) participants, at decision-making positions (management level), were selected to get a higher level understanding of the O&M practices at UBC. Both participants reported a direct or indirect use of building performance information from BMS and EMS systems to make optimization and policy level decisions. These preliminary interviews were designed to be more exploratory and open-ended and covered three broader topics: 1) Hierarchical Flow of information, 2) Use of BMS and EMS tools for O&M works, and 3) Interpretation and use of performance information for decision-making.

Based on the information acquired through preliminary interviews, four (04) more participants were selected, who are a bit more directly involved in using BMS and EMS systems for routine O&M works at UBC. Out of these four participants, two are the managers of their respective department, one is the lead operator at the command center, whereas the forth one is the lead operator of the BMS at CIRS.

Due to the integrated nature of building operation group at UBC, only a small set of experts are involved directly with using BMS and EMS tools for O&M works. Therefore, in phase-II, the survey was distributed through electronic mail to carefully selected seven (07) participants including some from previous interviews. Same criteria as the interviews were used to select the pool of participants for the survey. Out of these seven selected participants, only three replied with genuine responses and their data used for analysis in conjunction with the information collected earlier in the study to get a clearer understanding of O&M practices at CIRS. Other four (04) participants requested to respond through a group based interview session. Since the data collected
from that interview session did not meet the rigor of the survey, it is excluded from the analysis part but is used to elaborate various problem sets in using BMS and EMS tools for O&M tasks, discussed in Chapter - 04.

3.3.1.3 Phase-I Interviews:

As mentioned earlier, the interviews were designed to be exploratory; leading to descriptive – qualitative information rather than one answer, quantitative information. Each session was initiated by describing the scope of the research, followed by simple questions to ease the participants in providing information of their routine work. More technical questions were asked at strategic points of conversation that would elicit the participants to give elaborate answers often leading to the observation of the experts using the BMS tool to carry out tasks. Examples of some of the introductory questions include; “what is the first thing you check after logging into your system in your daily routine?” “Which part/feature of the interface do you find yourself using the most?” “How long does it take you to figure out what is wrong just by overviewing the alarm page?” “When you receive an inquiry/trouble call, how do you proceed with it?” “How easy is it to generate reports of different performance parameters?”

The exploratory leading-questions mostly depended on the earlier responses authors received and included questions like: “…then how would you dig down to the building space from the alarm menu to figure what is wrong and where?” “… Did the system helped in any way figuring out the problem?”, “… were you able to control the sensor from this menu?”, “…does the system help generate comparative analysis between performance parameters or previous performance reports?”.  

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3.3.1.4 Phase-II Survey:

In addition to interviews and contextual inquiries, a user-survey was developed to gather qualitative information from user groups who are highly familiar with building and energy management and have the first-hand experience in analysis and interpretation of performance information for decision-making. The survey questionnaire included multiple choice questions, with some questions designed to urge the participants to explain their selected choices briefly. The questionnaire was designed to conditionally lead the participants through progressively specific questions regarding their use of the building and energy management system (BEMS) interface. The survey started with participants describing their experience, role and involvement in using the BEMS tools. Subsequent questions progressively inquired the participants about the effectiveness of these tools in their routine works or the specific interface elements/features that are most useful in carrying out their intended tasks. The final question required the participant to describe a task scenario where they felt the system fell short of providing them with the required information.

See Chapter 4: for a detailed analysis of the collected data.

3.4 Case Study of Current Building Management Practices at UBC:

This section summarizes the findings of Phase-1 of the research case study. To understand the overlapping interrelations between campus level O&M practices and building level performance management, I examined the prevalent O&M practices from three perspectives: technological utilization, information flow and decision processes, an organizational context, Figure 3.4. The need for an organizational context in understanding current practices at UBC can be highlighted by the fact that different building functions are monitored and controlled by separate organizational
departments with overlapping management hierarchies, see Figure 3.6. In particular, I studied: (1) performance monitoring and control processes, (2) Use of BMS and EMIS tools for operation and management tasks, and (3) information flow.

In this section, I would first describe the organizational context of building and energy management practices at UBC and then specifically discuss how technological systems are being used in this context at project level. I would further highlight the role of different organizational departments responsible for carrying out different aspects of building operations and management and how their role distills down to project level decision making.

Figure 3.4 - O&M practices from technology, information and process perspective in an organizational context, adopted from the TOPICS framework proposed by Staub-French et al., (2011)
3.4.1 Organizational Context:

As already described in section 3.2, UBC is a large academic institute with over 500 buildings on campus, including 225 CAB which are operated and maintained by the university itself. There is a complex network of interrelated organizational departments that are involved in various facets of daily operations of campus facilities including asset stewardship – commissioning of new buildings, Infrastructure development – which caters asset development\(^{27}\), space inventory, facilities information systems and records, campus planning and development and utility and service distribution. Routine O&M works of all built assets are handled by Building Operations department (BOps)\(^{28}\), whereas all energy and utility related services throughout the campus come under the stewardship of EWS unit. Both departments are highly interconnected with various overlapping and at times interdependent functional domains.

In an effort to centralize operations and utility services across campus, UBC recently brought different teams of professionals from other departments\(^{29}\) under EWS department. This meant that various functional operations, which were otherwise handled in separate departments are now being catered centrally at EWS. Under this new restructuring Energy Planning and Innovation (EPI), a specialized group within EWS, is now responsible for all energy and resource conservation projects including performance monitoring and control of HVAC systems across campus.

\(^{27}\) Infrastructure development department provides services like renovations, maintenance and upgrades for projects of monetary value between $50,000 and $2.5 million, any projects above $2.5M are carried out by UBC project services or UBC property trust.

\(^{28}\) BOps handle all maintenance, renovation and upgrade projects of monetary value of under $50k – with projects exceeding this constraint referred to infrastructure development or UBC project services.

\(^{29}\) The EWS team consists of existing staff members from UBC’s Building Operations and Campus and Community Planning departments, with governance enhanced by an advisory board (http://energy.ubc.ca/ubcs-story/)
Building Operations (BOps) on the other hand, provides overarching O&M services throughout the campus’s core academic buildings through a network of four different OEM building automation and management systems: Apogee by Siemens, INTELIweb by Delta Controls, Metasys by Johnson Controls and Enterprise Building Integrator (EBI) by Honeywell, Figure 3.1. A team of building operators at MACC identify and respond to routine maintenance trouble calls by looking up building performance data from the relevant building management system in the CBMS interface or by remotely accessing BMS of that individual building. After identifying the issue either through the BMS system or by sending field staff at the location, appropriate measures are taken to repair, upgrade or replace the faulty equipment. Issues which tend to be difficult to diagnose through BMS interface or even through field inspection are forwarded to the BMS specialists at EPI for further consultation and diagnostics of the issue.

Figure 3.5 - Distribution of Buildings controlled by different Building Management Systems (BMS) at UBC, (http://energy.ubc.ca/, 2016)
BMS specialists at EPI are responsible for monitoring and analyzing BMS data to detect and diagnose technical problems at instrument level including sensor calibrations, error checks, optimization of operating schedules, communication errors, controller configurations, etc. Detected problems are either handled in-house (reprogramming or calibration) or referred to BOps for field related repair or replacement works. In addition to system-level performance monitoring, energy conservation team at EPI also regularly monitors energy consumption data of core academic buildings. Data from the ION meters and Pulse EMIS is analyzed, and related issues are communicated to either BMS specialists to optimize operational schedules, sensor tolerances, etc., or BOps for any field related maintenance works, as required.

The BMS at CIRS is also integrated with the CBMS and all the performance data from CIRS is accessible to BOps at MACC. However, the unique aspect of CIRS is that it is a living-lab research building and the data collected through the BAS is also used for research and system optimization. It has its own Central Operations Center where a dedicated BMS Specialist (dBS) monitors and controls all performance related data. Any faults or alarms associated with operational functions are communicated to the BOps by the dBS for field evaluation and maintenance works. Similarly, energy consumption data is monitored and analyzed at CIRS, and any changes to the BMS schedules, system calibration or controller programming are handled by the dBS but also communicated and logged with the EPI as part of the information record process. Any operational issues detected by BOps and EPI on their end are communicated to the dBS so that appropriate measures can be taken to rectify them.
After examining building O&M and energy management practice from a higher-level organizational perspective, a more focused discourse would be taken in the next section exploring technological and procedural aspects of information flow for fault detection and diagnostics.

3.4.1.1 Building O&M Process and Technology:

Most of the maintenance carried out at UBC campus is reactive in nature. Reactive maintenance means that UBC building operators do not continuously monitor, track or control performance parameters of the built facilities but refer to building information once a problem is reported (by an occupant or tradesperson in the field) or if an alert is issued by the system signifying a breach of a control threshold. In such practice, reporting of an issue is the primary trigger that may initiate

Figure 3.6 - BOps, EWS & CIRS relationships in terms of building performance monitoring and control information flow.
performance evaluation, information analysis and fault detection actions, from building operators.

At UBC building related issues are generally reported in the form of:

1. **Trouble Calls:**

All issues regarding equipment functions, building performance or occupant discomfort are reported to BOps Service Center, which filters such reports and issues work requests to appropriate personnel. Depending on the complexity of the problem, building operators may forward the work request directly to a tradesperson – which can receive this work-order on a mobile device, or forward it to BMS engineer for further investigation/ triage using the BMS interface, see Figure 3.7. A UBC climate and energy engineer describes this process as:

“[let’s say an occupant is in an office] and it is warm all the time, [he] will put it in the trouble call. […] The trouble calls relating to HVAC goes to Building Ops. They are supposed to do their own triage, look at BMS and loot at few other things. Let’s say if the occupant calls [and reports an issue], they may call him to confirm and get some more info. May be someone needs to come to have a look at it. And will figure out what should be done. If it’s a trade, the trade goes out. If it is a programing issue, it goes to BMS guys. If neither [could find] an issue and if it is a major repair work or it has to be retrofit or be replaced, then we need to request for upgrades. [Issue reports are like tickets] when issue is resolved, we close the ticket.”

2. **System Alerts and Alarms:**

Building systems and equipment are usually operated using automation schedules. Many critical components including heat pumps, air ducts and air handling units, are programmed in the BAS with control thresholds and alarms are generated if there is any deviation in operational functions
of any of the components. For example: controllers in a heat pump are pre-programmed to open or close valves at a certain set point temperature of the circulating water; sensors may issue an alarm if the water at the source side is received at a lower temperature than required, indicating that there might be some problem from the input end, maybe the boiler or a leak, etc.

Figure 3.7 - Information and decision flow diagram for trouble call resolution, adopted from (UBC, 2011)
All four BMS at UBC have pre-set alarms to indicate system faults. The alarms are displayed directly in the interface in the form of visual cues (flashing color coded messages) or as curated alarm tables. Additionally, all the BMS systems are configured to communicate critical alarms (major equipment failure/ power outages/ system overload, etc.) through emails or text messages to relevant personnel. Depending on the nature of the issue, building operators may follow trouble call procedure, Figure 3.7 and issue work request to a tradesperson or refer it to BMS specialist for further investigation, Figure 3.8.

![Flowchart](image)

**Figure 3.8 - Information and decision diagram for BMS related issues, (UBC, 2011)**

After confirming the root cause of the concerned issue, building operators forward pertinent information like fault diagnostics, timeline, priority, location and description of the issue, to the relevant trade. Depending on the complexity of the problem, the tradesperson may either fix the issue right away and close the work request or he may request further information about the issue.
Most tradespeople have extensive experience working with different building systems at UBC and are familiar with the building layout and comfort requirements of the occupants. However, for more complex problems a tradesperson may require information like standard operating procedures (SOP), manufacturer information or system manual, warranties, electrical or plumbing connections and threshold-control parameters. Currently, all of this information is not available with BOps at University Services; it is not even available in a single location. The tradesperson may have to spend considerable time searching and acquiring the required information from UBC Records, in order to fully understand the system and procure proper repair parts. As Head Maintenance Engineer (Automation) pointed out in the interview:

“There is not much documentation of the buildings available with the building operators, few buildings have manuals and other information but most of the buildings have only drawings to go with. [Most of] the diagnostics are made as per the experience of the operator, so it’s of quite importance that we have very experienced personnel that go and check the system and maintain them.”

Once the tradesperson confirms the problem and figures out the repair strategy, he notifies BOps of the proposed remedial action. He may also require the building operator to override the BMS controls to stop current operation of that particular component for some time. Building operators can override various functions of the equipment remotely through the BMS interface and may also flag particular repair work so that other operators would be notified of the issue and there would be no accidental activation of the system during its maintenance.
3.4.1.2 Building Management System (BMS):

Building automation and management systems are extensively used by BOps personnel to operate, monitor and control various building functions. As already discussed, UBC has four different and autonomous BMS installed. In line with UBC technical guidelines – 15901 (UBC technical guidelines, 2015), all BMS installed in individual buildings are configured as stand-alone systems capable of real-time monitoring and control of building operations, but are also integrated with the Central Building Management System (CBMS) at the MACC and ACC\(^{30}\) in the University Services Building for remote accessing. All current BMS interfaces are available to the building operators on their Operator Workstation (OWS) at MACC, through native BACnet\(^{31}\) local area network (LAN)\(^{32}\). Out of the four BMS, Siemens Apogee system is the oldest and most predominantly used BMS at UBC campus. Performance data from other management systems is stored in a central database server and mapped over Apogee’s interface graphics to provide a familiar user-experience for the building operators. As one of the interviewees reported:

"The graphical file is an entity outside the BACnet network and it is taken as an image and then the graphical nodes are connected with the dynamic information from the control points. Because Siemens was chosen as the front-end software [for CBMS], there is a server that collects information for the Siemens, and it also collects information from other systems and translates it into the Siemens front-end". (BMS Supervisor)

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\(^{30}\) MACC: Master Alarm and Control Center; ACC: Auxiliary Alarm and Control Center (Remote)

\(^{31}\) “Native BACnet” implies that the devices only communicate using BACnet protocol.

\(^{32}\) Management Level communication LAN utilizes UBC enterprise Ethernet/ IPNetwork for communication between remote building BMS installations and the central monitoring and control equipment, Section 25 05 00, (UBC Technical Guideline, 2016).
Building operators at MACC can either log into dedicated OWS to access individual BMS interfaces or they can log onto the CBMS OWS to access integrated Siemens Apogee interface and identify concerned issues. However, since Apogee is a proprietary software designed for Siemens OEM equipment, it has some limitations in terms of integrating all features and information datasets from other BMS. Often such information is visually represented on the interface as generic nodes and may not represent as-is condition of the data point or the associated object.

Building Operators usually have to be quite familiar and at time even experts of various types of equipment and systems installed across UBC campus in order to understand and properly detect and diagnose faults using the current CBMS. One of the interviewee attributed the complexity of the modern systems at UBC, as the main reason behind the need to have experts using BMS:

“The problem is that the systems are getting so complex that the operators working on the BMS system [needs to understand the system in order] to understand what they are viewing on the BMS interface and how the [data displayed] corresponds with the physical objects in the building and understand what’s happening”

The majority of building operators at BOps working on the BMS systems come from building the workshop or from the field, where they have hands-on experience working on the equipment and understanding various aspects of problems that may arise on that particular component. Since most of the building operators are already savvy with the equipment and system functions of campus buildings, their reliance on detection and diagnostics is based more on their previous experience than the information displayed by the BMS interface. “This approach is heavily dependent on
personnel’s memory that currently cannot be stored, shared or transferred automatically” (Cavka et al., 2015, p. 1281), thus putting a lot of cognitive load on the building operators to recognize problems by recollection as well as making them a huge resource investment on part of UBC.

“The information [knowledge of operating and maintaining various systems] is usually earned through working experience by working directly on the systems and is not transferable immediately to any new operator. Usually the operators working on various aspects of the building equipment, develop expertise about the systems and understand the diagnostics once the problem arises, but such expertise is highly individualistic and cannot be transferred to other operators or operators replacing the concerned person. This makes the operator indispensable and creates a problem if the said operator is not available to work. Any newcomer would have to go through a rigorous learning curve in order to fully grasp the work sequence.” (Head Maintenance Engineer)

Since most of the maintenance work at UBC is reactive in nature, building operators usually interact with the BMS interface to monitor performance in response to problem reports. I found from the interviews and observations that most of the BMS interfaces being used at UBC, severely lack in presenting information in context of the location, dependency or causality of the fault in concern. Building operators usually start their day by just reviewing the alarms and trouble reports in the BMS interface, identify significant issues and collect relevant information needed to rectify the problem to resume normal operations of the facility, see Figure 3.9. Alarms in the CBMS interface are organized with respect to the criticality of the fault and can be assigned to alert a relevant trade person directly or analyzed for an optimized solution. Building operators usually use the information to identify maintenance, repair or retrofitting related works. Other issues
related to system configurations, BAS programming, calibrations and control schedules are forwarded to a team of BMS technical specialists at EPI for further processing.

“[Building operators are quite knowledgeable in] various operational aspects which are [usually] fine-tuned by the operator working on those systems like static pressures and balancing input and output flows of the valves [using BMS interface]. [However], you need to have a specialized knowledge if any catastrophic failure occurs in sophisticated building systems. The building operators only deal with the front-end of the system, BMS specialist work with any changes to the graphics and tolerances.” (Head Maintenance Engineer)

BMS technical specialists monitor and review the data being collected by the BMS, in the form of trends or historic operational records, to identify root causes; whether it is an anomaly, a
reoccurring problem, is it associated with system defect or a control programming error? etc. All operational decisions in terms of controls programming, operational schedules and threshold parameters, are carried out by the BMS technical specialists. One of the interviewee during a contextual inquiry session described a typical scenario that a specialist may have to deal with on daily bases, Figure 3.10:

The pump that feeds the water to the source side had failed and we couldn't run the compressors [...] the gap in the data shows that it was not running. The yellow line is for the compressor control data and yes it is showing that the compressors were not working at that time. The blue and white lines are showing the backup electrical room temperature. The temperature trend shows a rise and it lowered when someone went into and put another fan to cool off the place and it practically sat over the night and it cooled off and then the pump was replaced and you can see from the interface that the fan was replaced by the normalization of the trend line. (BMS Specialist)

BMS technical specialists require high-fidelity visualization of building behavior and performance with contextual information like space geometry, physical attributes (size, orientation, shape, etc.) of equipment, dependencies (which space a system serves or which equipment is dependent on another system) and chronological performance data (an equipment showing consistent energy usage even over weekends), to effectively identify and diagnose performance issues. Current BMS interfaces map performance information (usually numeric data) over 2D representation of the equipment and building systems, which at times is not detailed enough to include contextual information or relate physical attributes through visual presentation. I also learned that accurate and detail-on-demand information, especially information regarding sequence of operation for building systems is quite important for BMS users as reported by one of the interviewees:
“Proper sequence of operations [should be available in a BMS], so that operators can read the information and judge that this is what it is supposed to do and that is what’s happening, what are the tolerances of the information pertaining to that component.”

Figure 3.10 - BMS Specialists may have to analyze multiple performance factors (environment, occupancy, control parameters, etc.) and evaluate historical performance trends in order to figure out complicated programming issues.

Another aspect of understanding whole building performance is to consider energy consumption of building systems as an integrate performance parameter, not just as a separate metric describing an isolated occurrence. Considering energy consumption patterns along with the operational functionality of building systems may provide operators with a deeper insight into that system’s
performance, highlighting any tell tail signs of potential degradation or even failure. Degradation effects from aging, excessive use, weather wear and tear, and changing occupant requirements may not be evident from routine operations but may be highlighted by analyzing energy consumption patterns of that equipment. Additionally, BMS operators can change operational schedules, control parameters and set point thresholds of various equipment in a building to optimize their operation by analyzing their energy trends and consumption patterns. For example, if a building is consuming a constant electrical energy load of 60 MWatts/hour irrespective of occupancy level. BMS specialists can review the operational schedules of that building and program the equipment so that heating is provided to only those areas where it is required. They can also revise the threshold parameter, control temperature set points and optimize comfort conditions based on the interpretation of the energy data.

3.4.1.3 Energy Management System:

Energy management and control is one of the most important tasks in optimizing building operations and maintenance activities (Al-shalabi and Turkan, 2015). Poorly maintained and operated buildings lead to significant energy usage through inefficient equipment and systems or wastage from mismanaged spaces. This is observed even in cases where building automation systems are available to assist building operations (Underhill, 2013).

33 The poorly operated and maintained buildings face significant energy wastes of 5% to 20%, even when they have building automation systems. (Underhill, 2013)
As already described in the background section – 3.2, all Core Academic Buildings (CAB) at UBC have been installed with energy sub-meters\textsuperscript{34} at building utility level as well as to monitor critical equipment consumptions (main chillers, TRIUMF cyclotron, etc.). This was carried out as part of UBC’s “continuous optimization” program under ECOTrek initiative, with the ultimate goal to achieve 12% overall energy use reduction by continuously monitoring and optimizing energy performance of its CAB. Energy meters are programmed to monitor energy consumption, demand, power quality, costs and equipment status (if sub-metered at equipment level) and are connected to the central operations software, ION Enterprise, via Ethernet cables on a LAN. The data from all these meters is stored in a central Sybase SQL database server and is publically accessible through a front-end Open Database Connected (ODBC) interface ION Historian\textsuperscript{35}, providing opportunity to monitor real-time and long-term trending of energy and water consumption data of CAB, see Figure 3.11. While ION Historian is only a front-end visual display of energy meter data and was not intended as an energy visualization tool, it typically displays real-time energy data only and historical data needs to be abstracted for further analysis and energy performance evaluation. The interface allows easy data abstraction in the form of Excel spreadsheets.

In 2010, as part of the “Continuous Optimization” program UBC initiated a $6 million project to upgrade, retrofit and monitor 72 of its 225 core academic buildings with an Enterprise Energy Management (EEM) system in partnership with BC Hydro and technology provider Pulse Energy (now EnerNOC). Pulse Energy provided the EIMS to aggregate, benchmark and present energy

\begin{footnotesize}
\begin{enumerate}
\item The meters are programmed to monitor consumption, demand, power quality, billing, and equipment status.
\item http://energy.ubc.ca/community-services/ion-system/
\end{enumerate}
\end{footnotesize}
data from ION meters of the participating CABs in a more visually appealing and intuitive format. Since Pulse acquisition hardware is linked to the building’s utility input lines, the software is able to track the exact amount of energy being consumed at any given time, analyze it, and provide real-time visualization of the data, along with a performance overview of that building overtime. The aim of moving from ION Historian to a more intuitive dashboard style energy information visualization was to provide building operators with an actionable intuitive tool; enabling them to maintain and optimize buildings through real-time performance monitoring and response (sustain.ubc.ca, n.d.).

Pulse Energy back-end software automatically aggregates energy consumption data of a building over a period of a year and analyzes it in relation to various environmental factors to determine an energy consumption baseline\(^\text{36}\), see fig-3.4.3.2. A typical “demand” curve is established based on the baseline configuration, where the demand is the rate of energy consumption (Power) at a time interval. Pulse Energy tracks actual energy demand at periodic intervals and compare it to the typical demand curve to evaluate performance deviations, see Figure 3.12. The primary metrics at UBC for measuring and monitoring energy consumption across is Energy Use Intensity\(^\text{37}\) (EUI) and all information is measured and reported using this metrics.

\(^{36}\) Baseline in Pulse is based on historical behavior and correlates with weather conditions, time of day, day of week, month, season, and other available variables such as occupancy rate. (ca.pulseenergy.com/help)

\(^{37}\) Essentially, the EUI expresses a building’s energy use as a function of its size or other characteristics. It’s calculated by dividing the total energy consumed by the building in one year (measured in kBtu or GJ) by the total gross floor area of the building (https://www.energystar.gov/)
Figure 3.11 - ION Historian’s different visual display windows, 1) Main layout showing building meters over a geographical map of UBC, 2) Dashboard style real-time energy information panel, 3) Electric meter schematic diagram with control information, 4) Energy and demand log updated every 15 sec., and 5) Energy consumption trend graph.
A demand curve signifies a “Business as Usual” operational scenario for any building, any deviations from this typical curve may indicate that the building is not performing as per its normal operational conditions. Pulse Energy considers these deviations as anomalies and issues an alert message - usually sent to the energy engineers and BMS specialists via emails, indicating performance deviations.

Figure 3.12 - Example of Pulse Energy Baseline
(ca.pulseenergy.com/help)

Figure 3.13 - Actual Vs. Typical Electrical Demand (kW) of Earth & Ocean Sciences Building retrieved from UBC Pulse Energy dashboard with permission on March 2016
Once the alert is issued by Pulse, the energy engineer acknowledges the alert and gives his immediate interpretation in the form of a note on that alert. This tells the software that the issue has been analyzed and acknowledged and the alert status is lifted off from that particular building. Since many building systems are operational during off-working hours at the university, it is quite important that the person responding to the issues alert acknowledges it, so that other engineers or BMS specialists are aware of the response and do not spend additional time on analyzing the issue. Pulse issues alerts for every threshold deviation, with many alerts issued due to changes in operating schedules or misconfigured control parameters. The responding engineer analyses the alert issued by the system according to the criticality of the deviation.

Figure 3.14 - Engineer’s response on the threshold alert issued by Pulse EMIS, retrieved from UBC Pulse Energy dashboard with permission on March 2016 (ca.pulseenergy.com)
From the interviews and SOP documents, I found that there are four major types of deviations that energy engineers needs to monitor and analyze before reporting it to either BMS or BOps personnel.

1. Expected One-off Deviations: “These deviations could be due to an out-of-season equipment test or an afterhours event that required the operation of the building’s HVAC or lighting systems and are expected by the energy engineers” (UBC, 2011, p. 8). Sometimes they can even show positive results, as in the case of generator tests, where actual energy is less than baseline energy profile.

2. Unexpected One-off Deviations: These deviations are usually quite significant and are associated with major equipment fault or system failure. These deviations may require analysis of BMS data as well as operational and maintenance schedules of that equipment.

3. Consistent Consumption: “These deviations typically are subtle and associated with a change in building system control either by changing a parameter in the BMS or manually changing a control feature in the mechanical room, such as the position of a throttling valve” (UBC, 2011, p. 8). Excessive energy consumption due to leaks in heating/cooling equipment may also show consistent deviation from baseline values. These deviations need to be analyzed carefully since Pulse Energy would update its baseline by aggregating this over-consumption data if it persists for a period of a year.

4. Consistent Reduction: These deviations are also subtle and are usually associated with the change in use of the building, optimized schedules, efficient equipment or occupancy behavior changes. Actual consumption profile which is consistently negative can reinforce positive changes in the energy usage of the building.
Once the energy engineer detects what kind of deviation the software is showing and locates the root of the problem, he forwards the data to BMS specialists to re-configure the controls or the building operators to issue a work order for repair/maintenance works. One of the interviewee described the whole process as very iterative and cumbersome. As both energy management and building management systems collect and disseminate data separately, operators often have to go back and forth between interfaces to try to find and match a certain energy consumption spike with the probable equipment that were operational during that time in a building and may have triggered that energy spike. Another interviewee described a scenario to elaborate this iterative process as follows:

Figure 3.15 - Information and decision flow diagram for energy exception reporting (UBC, 2011)
“So from the Pulse there was an alerts of an energy peak, we knew that a chiller was scheduled at that time and the software is registering a peak because the chiller went on. However, on the weekend we see another peak and the operators noticed that the energy was around 60kW, so it can’t be the chiller again. So they looked at their equipment list and try to find that what equipment uses that much energy and is left on in the building. What changed, so they were going through their manual and the BMS. So that [they can identify the equipment or fault in the schedule and] it won’t happen every weekend. So it is very iterative work based on their knowledge and their experience and the information available to them at that time”. (Energy Management Engineer)

Another challenge that building operators and energy managers face in detecting and diagnosing energy consumption related problems is that even if the building has equipment level sub-meters, the Pulse acquisition hardware is hooked to the input line of the building and thus provides cumulative energy consumption at the building level. At times, the software does not issue an alert even when there is something wrong with an equipment or component or if someone left the heating on in one of the rooms or have extra heating in their offices, because all other equipment is turned off and the overall energy consumption is below the baseline profile. As Associate Director of UBC’s Sustainability Initiative described:

“Pulse energy system is in practice right now, which looks awesome in theory but in practice, is not an efficient and effective monitoring device. It has limitations. If there is an anomaly per se, there is a chance it may remain unnoticed for the next 48 hours”.

During the interviews, I found that there is no way to know if one of the floors or zones are contributing toward majority of the building’s cumulative energy consumption like a computer lab or testing equipment. One of the interviewees reported that the real problem is the granularity of
the information being gathered, there should be further sub-metering of the buildings at least at the level of floor distribution panels to get a better picture of how energy is being consumed within a facility.

In reality you can’t relate this [building level energy information] to actual performance, if something is going wrong [at one particular equipment/space], but others are doing better, we cannot resolve that. The trend line will be the same. So the granularity [of the data] is not that great. (Energy Management Engineer)

Given the current limitation of the Pulse Energy system, energy engineers at EPI favor manually abstracting energy meter level data from the ION Historian system and analyzing the data externally in spreadsheets, see Figure 3.16. This according to the interviewees, provide them with the raw data directly from the meters without any filters or time normalization (pulse displays data updates every 15min.) and also allows them to access any sub-meters that are installed in a particular building. One of the interviewee describes the analysis and reporting process as:

“We abstract data directly from the ION historian portal in Excel sheets and use these sheets and the Excel data for measurement and verification of projects and for tracking. If a building appears to be off track by more than 10% we investigate through a) Verification that systems are functioning as intended through review of BMS trend data b) talk to the maintenance groups and c) talk to the user groups”. (Energy Conservation Manager)
I identified that energy performance and building system performance are being monitored and managed at UBC in a very compartmentalized manner. Information is shared between the two management factions on the need-basis and mostly in reaction to any problems or faults that occurred in their respective domains. I also found that energy is only being monitored and control at the building level with almost no information on equipment or system level energy consumption within the buildings. It was observed that it would be quite easier for both building operators and energy managers to detect and diagnose problems if the energy information is available in the BMS interface at the equipment level. Many interviewees showed interest in having contextual

Figure 3.16 - Quarterly Energy Consumption Analysis Report
information and documents pertaining to system functions, energy requirements and operational schedules in a centralized manner, so that problems can be resolved without excessive need to troubleshoot suspected causes. One of the interviewees described the short comings of current systems and practices in monitoring energy consumption as:

“Meter level readings are useful but have limited monitoring value; Spatial level readings when available will give us more informed decision-making capabilities as to where to put our resources and what areas have more energy usage than required. It will also provide us with a better understanding of why a certain deviation has occurred in a certain location, at a certain time. Right now, with meter readings, it just let us know that a spike occurred, but what and which space use caused that spike is un-known; at the end of our investigation, we may find that oh! Such and such person forgot to turn off the chillers. Which is quite a waste of useful resources and human power”. (Associate Director UBC Sustainability Initiative)

3.4.2 Project Context:

In the above sections, I investigated and documented various O&M and energy management practices and decision processes currently prevalent at UBC campus. I also studied different tools available to building operators for managing and controlling various operational and energy optimization functions of the campus buildings. Since all UBC core academic buildings are centrally managed (by BOps & EWS), performance monitoring and decision-making processes as well as the flow and use of information from CBMS and Pulse EMIS is generally applicable for all O&M and energy management functions of individual buildings.
The case study building presents a slight exception in application of general campus level O&M practices. CIRS has its own Central Operations Center that monitors and manages all system and energy level performance data through its stand-alone building management system. This particular aspect provided us with the opportunity to study the BMS interface in a somewhat isolated environment – standalone system monitored by relatively small dedicated workforce. It also allowed us to investigate how the visualization of performance information from the BMS alone, facilitates an operator’s understanding of operational situations and allow him to detect and diagnose different problems in the systems. In this section, I would summarize the findings of my study of the stand-alone BMS interface at CIRS and its visual presentation of the pertinent building performance information to the building operators.

3.4.2.1 Centre for Interactive Research on Sustainability (CIRS):

CIRS is one of the core academic buildings at UBC, Vancouver campus. It is a four-storey building with a net area of 61,085ft\(^2\) and is currently home to a mix of academic dry labs, meeting rooms, social and service spaces. It also accommodates various offices and labs, a 450-seat auditorium, cafeteria and a water reclamation facility. CIRS is also equipped with one of the most technologically advanced building systems at UBC including Photovoltaic panels, solar water heaters, advanced heat pumps and biomass co-generation systems.
CIRS was designed to be a “Living Laboratory” facilitating sustainable research through continuous performance monitoring and optimization of its operational functions and management activities (Robinson et al., 2014; Cavka et al., 2014). CIRS is a realization of a recent shift in Architectural, Engineering and Construction (AEC) industry approach toward intelligent facilities with increased performance monitoring and control capabilities in an effort to achieve greater energy efficiency and optimized operational performance (Chen, 2010).

*The CIRS building itself acts as a “living laboratory” that allows research and investigation of current and future sustainable building technologies [...], combined with advanced visualization and simulation technologies capable of communicating data through various means [...] to identify areas for innovation in sustainable technologies and practices.* (CIRS Building Manual, 2011)

The building is currently equipped with over 3000 sensors and control points, relaying performance data like occupancy, indoor environmental conditions (temperature, humidity, CO$_2$ level, Volatile Organic Compounds (VOC)), system operations - pump and fan temperature and
flow details, window status, water reclamation quality and status etc. (Cavka et al., 2014). All this data is being aggregated and managed by a stand-alone (although integrated to the CBMS) BMS by Honeywell called Enterprise Building Integrator (EBI). CIRS also houses a self-sustained water reclamation and treatment plant, which is fully automated and integrated with the EBI-BMS. Along with building systems, Energy and water consumption is also being monitored both at utility level and distribution level through sub-meters. Energy consumption data is managed through both EBI – equipment level energy sub-meters and Pulse Energy – building utility level energy meters. In compliance with the BMS Design Guidelines, both EBI and Pulse Energy data is being integrated with the Network Data Server (NDS) and is available to both BOps and EWS through central BACnet LAN at MACC.

In order to address understanding and realization of these complex synergistic-systems and design solutions among stakeholders and to streamline otherwise ad-hoc construction processes; the design team opted to produce Building Information Models (BIM) of architectural, mechanical and electrical designs. The combined model “allowed the team to coordinate details between disciplines and compare different combinations of systems and design strategies” (naturallywood.com, 2012, p.4). CIRS was the first building at UBC campus to be designed using BIM. However, the technology was quite new at that time and the models could only be prepared as design models and do not contain as-built or even construction related information. The current CIRS BIM, however, provides enough geometric and spatial information to be successfully used to demonstrate the envisioned potential integration of BIM as performance visualization platform.
The primary objective of CIRS is to be environmentally net positive, especially in terms of energy and resource consumption. All design solutions including high-performance building envelope, passive design strategies, high efficiency HVAC and energy equipment and state-of-the-art BMS were adopted to achieve this objective through a high-performance self-sustained built environment. There are multiple highly sophisticated systems that work together to serve various operational functions of CIRS. Almost all of these systems are integrated with the EBI-BMS, and are continuously monitored and optimized at the CIRS Operations Center (COC) through a sophisticated Building Automation System (BAS). Major building systems operating at CIRS can be categorized as:

1. Heat Exchange System
3. Lighting Systems
4. Water Reclamation system
5. BAS - Sensors and Controllers
6. Alarm and Emergency Generator system

Since CIRS was primarily designed to operate entirely on electrical energy, it is deemed implicit that all above systems use electrical energy and discussing energy systems as a separate category would be redundant at this point. Although, electricity is also utilized at the user-end in the form of plug loads, it is not integrated in the BMS but rather is monitored by the Pulse Energy EMIS at the utility level metering. CIRS also employ Solar Photovoltaic panels as supplemental energy
source but most of the energy generated by the solar panels is used to heat up domestic water, as the means to reduce off-grid electric consumption.

3.4.2.2.1 **Heat Exchange System:**

CIRS employs some innovative design solution to reduce its reliance on grid electricity for heating indoor environment. Firstly, CIRS is located strategically next to an existing Earth and Ocean Sciences (EOS) academic building, to recover some of the otherwise wasted heat from its exhausts. A heat recovery system captures the exhaust heat energy and transfers it to the CIRS heat pumps, which then heat the water used for heating floors. Access heat is returned to EOS as part of the net positive strategy. Secondly, a ground source geo-exchange field complete with integrated heat pumps and electric boilers supplements the heat energy required in addition to the EOS exchange for indoor comfort conditions.

![Figure 3.18 - Concept drawing of CIRS heat exchange system (cirs.ubc.ca)](image-url)
3.4.2.2 Heating, Ventilation and Air-Conditioning Systems (HVAC):

All indoor heating and cooling at CIRS is carried out using tempered ventilation air and radiant floor systems except for lecture theater where mechanical HVAC is provided. Indoor spaces are heated with ventilation air supplied through the under floor system and supplemented in certain areas by radiant baseboard heating (CIRS manual, 2012). Mechanical heating is provided by water-to-water heat pumps which extract heat energy from the CIRS heat exchange systems (section 3.4.4.2.1). The HVAC system at CIRS comprise of various mechanical sub-systems and control points that work together to provide the required indoor comfort conditions in the building. Major systems are listed as:

- **Air Handling Units (AHU)**
  - Recirculation Air Handling Units with Heat Recovery Coils (AHR)
  - Heat Recovery Unit (HRV)
  - Make-up Air Handling Units (MUA)
  - Fan Coil Units (FCU)
  - Air to Water Heat Pumps (HPWA)

- **Heating and Cooling Systems**
  - Geo-Thermal Ground Source Field, Heat Pumps and Electric Boiler
  - Hot Water Unit Heaters (UH)
  - Baseboard Heaters (BBH) and Force Flow Heaters (FFH)
  - Perimeter Radiation Heating Convectors System (RP)
  - In-Slab Heating System (MAN)
- Ventilation
  - Smoke Exhaust Ventilation
  - Washroom Exhaust Ventilation W-EXF with Heat Recovery Coil HRC
  - Exhaust Ventilation Systems
  - Operable Window System
  - Emergency Generation Ventilation System

![Figure 3.19 - CIRS HVAC & heat exchange equipment and energy flow diagram, adopted from Fedoruk (2013)](image)

3.4.2.2.3 Lighting Systems:

CIRS is primarily designed to be lit by natural light - daylight. However, depending on the use, illumination requirement and location of the indoor space, daylight is supplemented through artificial lighting systems. According to the CIRS manual, artificial lights in inhabited spaces like offices, have both daylighting dimming sensors and motion sensors to reduce energy wastage
In addition to these sensors, lighting control is also integrated in the EBI-BMS at the junction level, allowing COC to control lights of whole building zones.

### 3.4.2.2.4 Water Reclamation System:

CIRS utilizes reclaimed water for all its non-potable water requirements. Water is reclaimed by treating onsite collected water as well as water from the campus sewer system. CIRS uses a Solar Aquatic System (SAS) which is “an ecologically engineered system based on processes existing in nature that consume human biological waste to produce clean water” (CIRS Building Manual, 2011). The entire system is integrated with the EBI-BMS and every process stage continuously monitored and controlled by the COC to ensure adequate water quality in the return loop.

![Figure 3.20 - CIRS Water Reclamation System (cirs.ubc.ca)](cirs.ubc.ca)
3.4.2.2.5 Building Automation System (BAS) - Sensors and Controllers:

The underlying building automation system of the EBI-BMS at CIRS can be viewed as comprising of both physical control points (valves, dampers, etc.), and virtual control points (switches, flow gauges, etc.), which are all controlled either by physical configuration or virtual programming of the control point sensor. I listed few of the major monitored elements in Table 3.2, below.

According to CIRS Building Manual (2011), “An electric/electronic Direct Digital Control (DDC) system has been provided and installed by Honeywell to monitor and control the building mechanical systems for space comfort and to enable energy conservation. The control system receives information from various sensors and based on the system programming, energizes or de-energizes the controlled equipment and devices. Heating, ventilation and mechanical cooling equipment starts and stops and automatically to maintain various set points in the spaces as required for normal occupied and unoccupied periods”.

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<td>Air Temperature</td>
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<td>Temperature (Wet and Dry Bulb)</td>
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<td>Water Temperature</td>
<td>ºC</td>
<td>Humidity</td>
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<td>Carbon dioxide (CO₂)</td>
<td>PPM</td>
<td>Wind Speed and Direction</td>
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<td>Volatile Organic Compounds</td>
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<td>Valves (Mixing/Bypass)</td>
<td>Open/close</td>
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<td>Operable Windows</td>
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<td>Indoor Pressure</td>
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3.4.2.3 CIRS Building Management System:

Adoption of sophisticated building systems and control technologies allows building managers to understand discreet performance behavior of built systems and make complex control decisions to optimize their operational capacity. Building automation and management systems (BAS, BMS, EMIS) are used to monitor and manage different operational functions of built facilities including comfort control, fire safety, lighting, security and other equipment systems to one degree or another (Lawrence et al., 2012). However, in their study of expert users, Lehrer and Vasudev (2011) noted that despite the technological sophistication of current BMS and EMIS tools, they are still not being used to their full potential (CIBSE, 2000) given the “process of visualizing building information [from the BMS] for analysis, benchmarking and diagnostics, remains a time intensive, do-it-yourself undertaking” (Lehrer & Vasudev, 2011, p. 1) for many building operators.

Honeywell installed the main heating and cooling systems, fire and security alarm technology and all building control and sensing instrument along with the main BMS (Honeywell-Enterprise Building Integrator) at CIRS. EBI monitors and controls Honeywell’s as well as almost 80 other third-party systems, through a centralized management interface (Neary, 2012). I studied the EBI interface by observing and contextually inquiring the BMS specialist during several of his work routines along with various documentations available on the use and capabilities of the system. In this section, I would highlight different aspects of the EBI interface, pertinent features and how building information is visually displayed to the building operator.
3.4.2.3.1 Enterprise Building Integrator - EBI (Honeywell):

EBI is a state-of-art management and control system that aggregates system and energy performance information through a network of BAS -sensor and control points, provides visual display of system data, maintain two-way communication between BAS and management interface and provide system notifications through alarms and alerts. According to the Honeywell EBI operator guide (2010), a typical EBI-BMS essentially comprises of a server, point servers and controllers, Figure 3.21. All building performance information is stored at Honeywell’s data server onsite at CIRS – which processes data, directs system activities and relay programmed automation tasks. Point servers act as intermediate information storage – collecting information from the field (controllers) and relaying it to the main servers on-demand. All information communicated to and from the point servers is native BACnet, and is also made available to the UBC CBMS servers at MACC on-demand\(^\text{38}\). Controllers collect information directly from the sensors and actuators and continuously send it to the point servers for storage. All CIRS controllers in compliance with the UBC BMS Guidelines-15901, communicate information to both CIRS servers (continuously) and to UBC CBMS (on-demand) through UBC Ethernet LAN.

\(^{38}\) On-demand means that no point data is stored on the UBC CBMS, unless a trend or historic record is requested. All data however, is available to the BOps at MACC in real-time through the BACnet native LAN.
3.4.2.3.2 EBI Visual Interface:

A management level interface called Station, is available at Operator Work Stations (OWS) either as a stand-alone software program or through a dedicated Internet Protocol (IP) webpage. Station (interface) is essentially a control panel for monitoring and controlling various operational functions of the building and presents information through a series of display windows, with each window displaying a particular system or set of information with associated set of controls.

1. Login and Front Page:

The login and front page window for the stand-alone software and webpage interface are different. The software front window provides the user with a quick menu option, allowing easy access to various features of the interface from the front page. Webpage interface however displays a static

Figure 3.21 - System architecture of Honeywell EBI BMS (EBI Manual, 2011)
picture of CIRS on its welcome page and the user have to open the navigation panel to browse where he intends to go. Both interfaces display most critical alarm at the bottom of the window with date, equipment and component identification number.

2. **Main Menu:**

From the front page, the operator has to click onto the navigation menu in order to open the main menu window. From main menu window onwards, both stand-alone software and webpage interfaces are identical and provide user with essentially the same use experience. The main menu opens in a new tab on the menu-bar. The navigation menu tab remains visible on the top-left corner throughout the interface and acts as a home button to go back to main menu form anywhere in the interface. The main menu display presents the following information:

1. BMS controlled systems and equipment at CIRS
2. Floor controls and indoor sensors
3. Equipment level energy meters
4. System Architecture – Schematic diagram of BAS controllers in the building
5. Overview of ambient conditions – outside air temperature and relative humidity

The operator can select any of the buttons displayed on the main menu, which would open that particular system’s window. To select another system, the operator may have to return to the main menu, through the navigation menu tab. A pop-up option for the navigation menu is also available, which provides a floating pop-up window of the main menu options across the interface.
Figure 3.22 - EBI Interface with Alarm tab bar shown at the bottom; a) Webpage Front page, b) Standalone software front page (quick menu)

The highlighted boxes indicate alarm status, where the red box indicates most recent system alarm and cyan box implies a system alarm – lost communication, disconnection, etc.

Figure 3.23 - EBI main menu window interface layout
3. **System Information and Control Windows:**

From the main menu, the operator can opt to open any of the system information and control windows. Each window presents a schematic illustration of the main equipment with further illustrations of internal components being monitored or controlled by the BMS, shown at tentative locations within the equipment. Equipment illustrations are designed to represent the industry’s norm in presenting certain equipment and are reflective of the schematics shown on the construction drawings, see Figure 3.24. Performance information and operational status is mapped over the equipment illustrations in the form of tabs. Depending on whether the component is automated or configured for manual control, information tabs either display current performance information only (air flow rate, air temperature, status, etc.), or provide operators with interactivity to control the component’s operational parameters (turn on/off, temperature change, etc.), see Figure 3.25. Components with additional information or variable controls, display information icon (blue “i” icon) which an operator can click to open a pop-out window displaying further information and control parameters, see Figure 3.26.

Every major system information window has several tabs, each tab representing associated and dependent equipment, see Figure 3.25(c). An additional tab provides the sequence of operations (SOP) related to primary equipment window. Clicking on SOP tab opens a PDF document, Figure 3.27, describing the sequence of operations associated with the primary concerned equipment, e.g., if the main system window for an AHU is open, SOP document would reflect the sequence of operations associated with AHU but if the operator opens a Heat Recovery Unit (HRV) tabs within the AHU system window, SOP would automatically change and reflect the sequence of operations associated with HRV.
Any other relevant information in regards to a particular system is also displayed on the system information window, usually in a tabular form and as before, depending on the function, data tab can be static or interactive with drop-down menu for selection options. However, there is some inconsistency in display of similar equipment data, highly depending on the space it serves. For example, in the AHU-01 system information window, Figure 3.25(a), relevant information regarding the minimum set point room temperature of the served rooms as well as the schedule and alarm status is shown on the upper right hand corner of the window. However, in case of AHU-02 which essentially is the same equipment but serving another space, the upper right corner window now displays minimum and average room temperature as well as controllable (indicated by blue text) average room temperature near the skylights.

Figure 3.24 - EBI Illustrations based on Industry's schematic norms
Figure 3.25 - a) System Information Window (Air Handling Unit AHU-01), b) Tabs showing associated equipment and tabs, c) Auxiliary information (Data not shown in the main system information window)
Figure 3.26 - System Information Window (AHU-01) w/ addition component level information and control pop-up menu (Green text signifies information & blue text signifies control information – interactive)

Figure 3.27 - Sequence of Operation (SOP) document
All system and component illustrations are annotated describing various measuring units, part/component identification numbers as well as flow directions (air/water) in relation to any associated equipment, i.e., Exhaust Air (EA) to Heat Recovery Unit (HRV) or annotation describing shared components, i.e., AH-01 and AH-02 share EA and OA (outside air) ductwork, see Figure 3.25(a). However, such annotations are highly customized, describing CIRS specific elemental relations and are hard to represent in a more general model39.

Another aspect that I found during the contextual inquiry was that tabs presenting associated equipment change with respect to the concerned equipment being displayed, however, the original configuration shown on the system information window remains the same. I discussed this inconsistency in display of information in the interface in the analysis section in detail, 4.2.1.4.

Although, the schematic illustration describes various associated equipment, there is no intuitive visual relationship between them and a new user has to read several annotations, match them with other equipment before figuring out that exhaust air from the AHU-01 and AHU-02 goes through the Heat Recovery Unit, before being released to the environment. Also, I could not find any information regarding the location of these equipment and the space they serve, see Figure 3.25, from the interface. Although, building operators (from their work experience) are quite cognizant regarding where these systems are and what spaces they serve, but purely from the interface perspective such information is currently not available. However, such knowledge is earned

39 When mapping CIRS functions in Siemens Apogee CBMS, the system utilizes a static snapshot of the whole schematic display and then map dynamic system information in the form of nodes under the existing graphics. Any changes in CIRS equipment would mean that the whole graphics would have to be revised in the CBMS system and all information remapped, which is quite time and cost intensive process in itself.
through years of working on these systems and cannot be immediately transferred to any new user, as UBC Head Automation engineer reported:

“It probably takes an average of around 2-3 years to understand all the workings of the building systems [for any operator] of current high-performance buildings and fully understand various building functionalities and then make informed decisions using the BMS. This is so because some of the systems are so sophisticated that sometimes even manufacturers are having problems troubleshooting the systems”.

4. **Floor Information and Controls:**

In the main menu, there is a separate section of tabs for the floor controls, listing all the floors in CIRS. Opening up any tab from the floor controls section would bring up information of systems/instruments pertaining to that floor space. EBI displays this information mapped over 2D schematic layout of the building floor through data populated nodes and information tabs, see Figure 3.28. EBI displays three categories of information over the 2D floor plan schematics:

1. Room sensors – Temperature, Relative Humidity, CO₂, Volatile Organic Compound, Pressure sensors

2. Lighting

3. Windows

The information is displayed relative to the selection options and cannot be superimposed on each other to provide a consolidated view of all three options. An operator has to switch between the three options to overview the related information.
Administratively, CIRS is divided into three main zones: central, north and south. EBI also displays floor information based on this administrative division of spaces. So when an operator as interactive text chooses a certain floor from the main menu, the first window that opens shows a complete 2D schematic plan of CIRS, with the three zones highlighted overlay, see Figure 3.29. Clicking upon any of the zones open another window displaying blow-up 2D schematic of that
particular zone, with the relevant information and control tabs. However, to go back to the overall plan to select any other zone, operators have to go back to the main menu through the navigation tab and then repeat the process again.

Operators can view relevant information of any space by selecting “Room Sensors”, “Windows” or “Lighting” buttons on the right upper corner of the interface. Room sensor information (which is the default view) would remain in the display regardless of selection of any of the other buttons. However, by selecting lighting or windows button, EBI overlays lighting or window illustrations over the 2D floor plans, see Figure 3.29. In “Lighting” overlay, highlighted lights illustration

Figure 3.29 - EBI Level -1 floor plan window with zones

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signifies that the light is currently turned on, where as a darker illustration signifies that it is off. There is a catch, lighting status configuration is shown in the EBI based on the commands from the BMS system, e.g., if the operator commands the lights to turn on, they would appear to be turned on, in the BMS or vice-versa. However, lighting systems are equipped with motion and daylight sensors and if lights of a certain space are turned off by the motion sensor - because there is no body in the room, these lights would still be registered as turned on in the BMS. Graphics similar to lighting system are used to provide information about open or closed status of windows of a space, however, since the tempered ventilation system is integrated with the window actuator contact status, the BMS display is updated in real-time regarding any changes in window status.

Sensor information is displayed in the form of annotated nodes; T - temperature, RH - Relative Humidity, etc., shown at tentative location of their physical counterparts on the 2D floor plan. Temperature information is presented with both measured avg. room temperature and programmed set point temperature for a space (text in blue), see Figure 3.28. Clicking the set point temperature tab opens up further parameters that the operator can analyze and change to make sure the operational schedule and set point temperatures for that space are as programmed. Other than that, EBI displays real-time non-interactive information of all installed sensors installed in a particular space.

Several information nodes are also mapped over the 2D plan, annotated to describe their associated function. These nodes provide additional information of 03 types of functions: 1) operational parameter of an equipment serving that space, 2) Heating or cooling system used in that space, and 3) additional information of that space, see Figure 3.25 (a) (b) and (c), for how that information is displayed in EBI.
Similar to the system information window, floor information window also contains different tabs for space associated radiative heating controls, parameter summaries and sequence of operations, see Figure 3.30. Clicking on the *radiative control* tab opens a separate graphical window displaying radiative heaters in that space, with current and set point temperature information, see.
The EBI displays an illustrated image of the radiators, with regards to Hot Water Supply and Return directions. However, in open offices spaces where there are series of radiators, the graphic does not provide status information of any individual radiator, Figure 3.32/3.33. There is also no information about whether valves of any individual radiators are shut off by the user.

Figure 3.31 - EBI Floor information window w/ additional parameter displays:

a) Space associated equipment control parameters,
b) In-slab heating information,
c) Tentative illustration of a room with control information
Figure 3.32 – (a) & (b) are radiator control windows for Level-2 north wing. In order to access south wing data, the user has to go to main menu and select level-2 floor plan and then select the south wing, fig-3.33

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Figure 3.33 - (a) & (b) are radiator control windows for Level-2 South wing. User can select “Level 02–south” tab to go back to complete floor plan, this option is missing in the north-wing information window, fig-3.32
5. *Energy Information:*

As already discussed in the previous section, the electrical energy at CIRS is measured both at utility-end as well as through sub-meters at equipment (major) level. CIRS is also equipped with an array of dedicated BTU meters at major heat transfer equipment to monitor and manage the flow of thermal energy within the equipment and the building. EBI system monitors and displays both electrical and thermal energy usage through its interface.

Information regarding electrical energy consumption of CIRS systems can be abstracted by the EBI interface in two ways:

1. Import data from Honeywell data acquisition system in the form of Excel files
2. Directly read energy sub-meter readings at the system information windows

Electrical energy data can be extracted from the Honeywell EBI server by data acquisition system using Microsoft query in Excel, Figure 3.34. However, data extraction by this method only provides energy consumption at electric distribution panels without discriminating between spaces served or different equipment on that panel. Cavka et al., (2014) in their study of electrical energy consumption of CIRS, categorized seventeen electrical panels representing plug loads, seven distinct panels for lighting loads and nine panels for motor controls, heat pumps and mechanical equipment, see Figure 3.35.
Figure 3.34 - Data query procedure using Excel and energy meter results from EBI database

<table>
<thead>
<tr>
<th>Panel Name</th>
<th>Contents on Panel</th>
<th>Extra Functions on Panel</th>
<th>Annual (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIRS_ZV2M3C</td>
<td>Spare &amp; Moisture Detection Panel</td>
<td>NA</td>
<td>0.2</td>
</tr>
<tr>
<td>CIRS_ZW84C</td>
<td>UW-206EXF-3PL+H1&amp;H2-22 EXF-58-6 (future)</td>
<td>Spare &amp; L4 polarized glazing</td>
<td>1.35</td>
</tr>
<tr>
<td>HP_03</td>
<td>Heat pump 3</td>
<td>NA</td>
<td>19.655</td>
</tr>
<tr>
<td>CIRS_361A</td>
<td>Water Treatment Room (Access Door &amp; Pumps &amp; Honeywell panel &amp; HIGH BAY Lights)</td>
<td>NA</td>
<td>20.384</td>
</tr>
<tr>
<td>CIRS_B01_HL_BOILER</td>
<td>Boiler</td>
<td>NA</td>
<td>9.98</td>
</tr>
<tr>
<td>MCCENOP</td>
<td>Water treatment system</td>
<td>NA</td>
<td>47.81</td>
</tr>
<tr>
<td>MCEOM</td>
<td>cooling system load mainly</td>
<td>NA</td>
<td>78.21</td>
</tr>
<tr>
<td>MCCCENOM</td>
<td>heating system</td>
<td>NA</td>
<td>262.30</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>431.00</td>
</tr>
</tbody>
</table>

Figure 3.35 - Electrical energy distribution panels for mechanical equipment (Cavka et al., 2014)
Equipment level energy consumption can however, be viewed directly from the EBI interface by opening up the information pop-up menus shown next to specific components, see Figure 3.36.

Thermal energy information can be monitored by choosing “BTU meters” tab, directly from the main menu. Selecting the tab, opens a separate window presenting cumulative values of thermal energy, flow volume as well as supply and return temperature of the fluids. The data is presented in a non-interactive tabular form. The tabular sections do not follow the equipment hierarchy of the main menu but rather starts from the heat pump energy meters and display both source side as well as load side information of concerning equipment, see Figure 3.37.

Figure 3.36 - Energy meter reading in EBI of components from pop-up menu
6. Miscellaneous Equipment Information:

Information of all other building equipment other than major system like air system, water system and heat exchange system is categorized under miscellaneous in the EBI main menu. EBI displays pertinent information of these equipment as summarized tables, with both static as well as interactive (operator definable) information tabs. There is no information regarding any associated equipment or dependencies of these components of what space they serve. Miscellaneous category includes following list of equipment:
Equipment Description  EBI Interface Display

Fan Coils

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Description</th>
<th>EBI Interface Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan Coils</td>
<td>FC Summary</td>
<td>Sequence of Operation</td>
</tr>
<tr>
<td>Fan Coil</td>
<td>FC - 01</td>
<td>FC - 02</td>
</tr>
<tr>
<td>Room Temp</td>
<td>23.0 °C</td>
<td>25.0 °C</td>
</tr>
<tr>
<td>Room Temp Sp</td>
<td>25.0 °C</td>
<td>26.0 °C</td>
</tr>
<tr>
<td>Fan Control</td>
<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>Fan Status</td>
<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>Fan Alarm</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>EA Temps</td>
<td>26.2 °C</td>
<td>24.4 °C</td>
</tr>
<tr>
<td>Cig Call</td>
<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>Cig Valve</td>
<td>0.3 %</td>
<td>25.5 %</td>
</tr>
</tbody>
</table>

Force Flows

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Description</th>
<th>EBI Interface Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Flows</td>
<td>FFH Summary</td>
<td>Sequence of Operation</td>
</tr>
<tr>
<td>FFH</td>
<td>FFH - 01</td>
<td>FFH - 02</td>
</tr>
<tr>
<td>Room Temp</td>
<td>20.4 °C</td>
<td>19.4 °C</td>
</tr>
<tr>
<td>Room Temp Sp</td>
<td>18.0 °C</td>
<td>19.0 °C</td>
</tr>
<tr>
<td>Fan Control</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>Fan Alarm</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>Mgr Valve</td>
<td>0.0 %</td>
<td>6.0 %</td>
</tr>
</tbody>
</table>

FFH-01 - Stairwell 1
FFH-02 - Stairwell 2
FFH-03 - Stairwell 3
FFH-04 - South Lobby/Vestibule
FFH-05 - North Lobby Vestibule
FFH-06 - Lecture Theatre Vestibule North
FFH-07 - Lecture Theatre Vestibule South
## Baseboard Heaters

![Baseboard Heaters](image)

<table>
<thead>
<tr>
<th>BBH</th>
<th>BBH-01</th>
<th>BBH-02</th>
<th>BBH-03</th>
<th>BBH-04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temp</td>
<td>23.0°C</td>
<td>22.0°C</td>
<td>24.0°C</td>
<td>22.5°C</td>
</tr>
<tr>
<td>Room Temp Sp</td>
<td>21.0°C</td>
<td>21.0°C</td>
<td>24.0°C</td>
<td>22.0°C</td>
</tr>
<tr>
<td>Fan Control</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>Fan Status</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>Fan Alarm</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>Htg Valve</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

**BBH-01 - Women's Shower Room Level B Rm B1366**
**BBH-02 - Men's Shower Room Level B Rm B1374**
**BBH-03 - Men's Wash Room Level 1 Rm 1376**
**BBH-04 - Women's Wash Room Level 1 Rm 1366**

## Unit Heaters

![Unit Heaters](image)

<table>
<thead>
<tr>
<th>UH</th>
<th>UH-02</th>
<th>UH-04</th>
<th>UH-06</th>
<th>UH-07</th>
<th>UH-10</th>
<th>UH-12</th>
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<tbody>
<tr>
<td>Room Temp</td>
<td>22.1°C</td>
<td>22.6°C</td>
<td>23.1°C</td>
<td>22.6°C</td>
<td>22.1°C</td>
<td>21.5°C</td>
</tr>
<tr>
<td>Room Temp Sp</td>
<td>18.6°C</td>
<td>18.5°C</td>
<td>18.0°C</td>
<td>18.0°C</td>
<td>18.0°C</td>
<td>18.0°C</td>
</tr>
<tr>
<td>Fan Control</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>Fan Status</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>Fan Alarm</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>Htg Valve</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>UH</th>
<th>UH-13</th>
<th>UH-16</th>
<th>UH-18</th>
<th>UH-20</th>
<th>UH-21</th>
<th>UH-22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temp</td>
<td>23.2°C</td>
<td>21.8°C</td>
<td>21.7°C</td>
<td>21.8°C</td>
<td>21.8°C</td>
<td>21.8°C</td>
</tr>
<tr>
<td>Room Temp Sp</td>
<td>18.6°C</td>
<td>18.5°C</td>
<td>18.0°C</td>
<td>18.0°C</td>
<td>18.0°C</td>
<td>18.0°C</td>
</tr>
<tr>
<td>Fan Control</td>
<td>Off</td>
<td>Off</td>
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<td>Fan Status</td>
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<td>Off</td>
</tr>
<tr>
<td>Fan Alarm</td>
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<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>Htg Valve</td>
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<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

**UH-02 - Bicycle Storage Rm B1352**
**UH-04 - Basement Water Entry Rm B1202**
**UH-06 - Basement BVIS Rm B1204**
**UH-07 - Basement Mechanical Rm B1242**
**UH-10/12 - Bsmnt Storage Rm B1281**
**UH-13 - Loading Dock Storage Rm L362**
**UH-16/18 - Waste Water Treatment Rm 1321**
**UH-20 - North Roof Equipment Rm 5161**
**UH-22 - South Roof Mechanical Rm 5330**

**UH-21 - South Roof Equipment Rm 5381**
Sump Alarms

Emergency Generators

Smoke Exhausts
3.5 Conclusion:

The case study provided a holistic overview of the building operations, maintenance and performance management practices currently prevalent at UBC. It also highlighted the relational impact of the organizational setup, functional processes and technological tools on the flow and utilization of building performance information for O&M related decision-making. It was quite interesting to note that most of the building O&M practitioners at UBC, despite having access to state-of-art management tools, still make diagnostic decisions based on their prior experience with the system in the building. Additionally, a significant portion of the maintenance works is reactive, i.e., it is carried out in response to any faults or occupant complaints. This observation was also supported by the study of the management tools available at UBC. One of the main reasons for not having any proactive maintenance measures at UBC, is that the current BMS tools considerably lack in visually representing performance information in an understandable and actionable format. Building operators mostly rely on 2D schematics and analytical information output, without any spatial or relational context between the information streams or their respective sources. Additionally, there is no apparent connection between energy consumption and system performance management tools and the collected data is being analyzed by two separate organizational departments.
Chapter 4: Proposed Integrated Building Performance Visualization (iPViz) Interface

In this chapter, I present the synthesis of my findings and lessons learned from the research of relevant academic literature and the results of the case study in the form of a proposed medium – fidelity mockup prototype of an Integrated Building Performance Visualization (iPViz) interface. The proposed mockup is intended to present a vision of a BIM integrated building management system front-end interface that may facilitate understanding and optimization of building O&M performance through a contextually aware spatial visualization of building elements.

4.1 Design Process for the Proposed iPViz Interface:

The design process for the proposed interface followed the lessons learned from the literature review and analysis of the data collected through the case study (Chapter-03). Based on these lessons, task-based real-world inspired scenarios were developed, that informed and highlighted functional aspects of the proposed interface. The process involves three main steps: 1) identifying major interaction and visualization problems in current building management systems, 2) development of task-based scenarios that inform the usability of an integrated system, 3) development of a medium-fidelity mockup of the envisioned interface.

Data collected during the case study on use of Building Management and Energy Information Management Systems (BMS/EMIS) for building operation and maintenance works is analyzed in the next section to identify and categorize underlying problems that may exit in the current systems.
4.2 Data Analysis of Building Management System Use for O&M Works:

Data collected from both qualitative and quantitative research methods was analyzed and segregated into smaller meaningful chunks of information. Using constant comparison analysis technique (Onwuegbuzie et al., 2012), each chunk of information was compared to other chunks having similar content or meaning or purpose, thus making complementary themes or clusters of information providing insight on a particular aspect. By using this technique, I was able to identify various aspects related to the use of BMS interface in O&M practices, influence of visualization on cognitive inference, major discrepancies in current systems and real world scenarios to inform further integration opportunities.

4.2.1 Qualitative Data Analysis: CIRS – EBI BMS Interface:

Based on the exploratory interviews of Phase-I, various issues are identified and aggregated into groups. From the analysis of these information groups, I found that most of the issues identified have two recurring main themes: 1) Activity – when participants reported usability or usefulness issues with currently available interface elements, 2) Discovery – when participants wished to require certain interaction or features not currently available in the interface (Carroll, 2000). Both of these themes are complimentary and essential in any Human-Computer Interaction (HCI), since users usually “extract lessons from their experience to guide their work and improve their practice” (Carroll, 2000, p. 7).

The research objective was to understand an interface’s usefulness and usability in presenting required information and then use this knowledge as a departure for the proposed interface design. The data collection was designed to explore both activity and discovery in real scenarios from a
system interaction context. This context is important specially when investigating computer automated systems, as noted by Wei and Salvendy (2007):

“The growth of computer applications has radically changed the nature of [human jobs] in two aspects. First, through increased automation, the nature of the human’s task has shifted from an emphasis on perceptual motor skills to an emphasis on cognitive activities, such as problem-solving and decision-making. Secondly, through the increasing sophistication of computer applications, the job design in computerized work is gradually emphasizing the interaction between two cognitive systems [human and computer].” (p. 346)

Another thing that was kept in mind while analyzing the interview results was Human Information Processing (HIP) model (Norman, 1976). The model states that human problem-solving activity is greatly dependent on human’s short-term and long-term memory (ability to recall, retrieve and learn), the task environment (system) and the interaction layer (user interface) between the problem solver and the task environment (Newell & Simon, 1972). As the human interacts with a system through a user interface, the human’s understanding of the problem and his ability to strategize toward a solution, changes dynamically with each interaction event. Keeping this model in mind, I focused on understanding if there are instances/events where system is shaping certain action sequence, and if those action sequence are in line with general building operation, control and management practices. I was also interested to know if the system is actually overloading user’s memory with excessive information on screen and how could it be made better. What are the cognitive demands from the operator’s perspective to be able to fully understand and perform his tasks and take appropriate actions?
To analyze data from a HCI point of view, I took help from Don Norman’s theory of action\textsuperscript{40} and his proposed seven fundamental design principles as evaluation heuristics (Norman, 2002). According to Norman (2002), a good system should bridge these gulfs either by bringing the system closer to its user or bringing the user closer to its system. I am more interested to know how the system could be brought closer to its user. I first analyzed the data in order to from a higher level perspective of generalized O&M practices and then I analyzed the collected data from a HCI perspective to examine how operators understand building performance by interacting and visualizing information from the system. As Norman (1968) suggests:

\begin{quote}
\textit{“the information embedded in technological artifacts is as important to the achievement of a task as the knowledge residing in the mind of an individual who uses that artifact.”} (p. 36)
\end{quote}

I have formalized the results of the interviews, in accordance with the cognitive dimensions proposed by Green and Petre (1996) based on Don Norman’s theory of action (Norman, 2002). According to Green and Petre (1996), these dimensions are task specific and can be used to analyze performance of any system from the user’s perspective. There are fourteen cognitive dimensions in total, however, I only used the ones that directly address the issues identified during interviews, combined with Norman’s design principles (Norman, 2002).

\textsuperscript{40}“When people use something, they face two gulfs; the Gulf of Execution, where they try to figure out how it operates, and the Gulf of Evaluation, where they try to figure out what happened” (Norman, 2002)
4.2.1.1 Closeness of Mapping:

The first issue that was repeatedly discussed in various scenarios in the interviews was the need for contextual information in current systems. Contextual information is the information that “can be used to enrich the knowledge about the user’s state, physical surroundings and capabilities of the system in use” (Afyouni et al., 2012, p. 1). Green and Petre (1996) suggested that a good system should provide an adequate mapping between the problem world (real world) and system notation (digital representation of the real world), so as to make it easier for its users to make connections between the two worlds. Closer the mapping between the worlds, lower the cognitive demands on the user, hence easier for him, to contextualize the problem and make an informed decision (Alegre et al., 2016). From the interviews, I found that the BMS at CIRS lack in providing contextual information (closeness of mapping) in three major aspects:

1. The first major shortcoming in EBI-BMS is the lack of mapping of geometric/spatial information. The interface displays spatially relevant information like sensor readings of a room, open or shut windows or on/off lights mapped over a 2D schematic visualization of the building floor plans, 3.4.2.3.2 (4). There is no notion of space or spatial attributes in these visualizations; how high is the ceiling, is there an underfloor, window height, open offices or cubicles, stair orientation, architectural/structural elements in the space – which is important in understanding various operational scenarios and environment behavior in terms of occupant use (Afyouni et al., 2010). Looking at the current interface, building operators cannot ascertain (without any prior knowledge of the building) the location, size, orientation or layout of adjacent surroundings of building elements. A 3D geometric visualization of built spaces could allow building operators to relate different attributes of
building systems in a perceptual real-world environment, e.g., size of equipment in relation to the room, where is it spatially located—ceiling/under the floor/on the wall, other equipment in its surrounding space, etc.

2. The second thing that stood out from the interviews was the lack of contextual association of spatially relevant information. For example, faults alerted through the BMS alarm system provide only component description through tags, i.e., CIRS_RCW_Collection Tank_Failure_Alarm. There is no other information associated with this alarm that would indicate the sensor that triggered the alarm or the location of the equipment itself. The operator has to go to the main menu of the BMS interface, search for RCW_Collection_Tank, open the concerned tab and look for the component that triggered the alarm and then analyze the data and diagnose the problem. This puts a huge cognitive and memory load on the operator to try to find the equipment and navigate to the appropriate sensor information. Not only that, the system hardly provides any information regarding any previous reoccurrences of the same problem hence making it hard for its operators to make a quick judgment as to the severity of the situation.

According to one of the interviewee:

“The descriptions on my system are good, but they are not specific, for example they do not talk about the location of equipment. Honeywell needs to have a list of all sensors and exactly what room is the sensor installed. Not just the floor level, but also the room and exact wall location. May be a tabular form. Unfortunately, the system doesn’t give any more information than the tag on the sensor and can only say what (floor) level.”
Another one said:

“The equipment (pointing to the screen) shows isolated information aspects and does not always provide the contextual information of the equipment.”
3. The third aspect which combines the above two concepts is that, most of the performance information displayed by the BMS is concerning equipment functions, with no contextual mapping of any other influencing factors, e.g., occupancy, external environmental conditions, spatial attributes, etc. Such contextual information is quite significant for two reasons:

   a. To understand the building behavior (and change thereof) based on non-system (external) factors, e.g., temperature rise due to overcrowded space (occupancy) or energy spike due to plug-in high voltage personal heater (external event) or scheduled heating required in a space earlier than normal due to its larger volume or openable fenestrations (spatial attribute)

   b. In order to track and diagnose problems based on a holistic understanding of the building (consideration of all above factors) rather than just functional understanding of the systems.

In CIRS, there is a whole network of occupancy monitoring camera devices available all across the buildings, however, they have not been integrated into the BMS or even fully energized due to lack of funds, and undetermined scope and use of the data. Another example is that almost all artificial lighting systems have motion and daylight sensitivity sensors but the data from these sensors is not integrated within the BMS system, so whether the lights are on or off, if the electrical distribution panel for the lights in on, the BMS would show lights as on. As one interviewee said:

“The (building operators) can see [if] the light is on/off from the distribution panels, but they don’t have the capability to calculate how much energy is being used by the lighting on this floor. And that’s probably the level most buildings
are currently working here. I think we do see a lack here and we slowly are moving toward it where we actually do get the feedback to bring our buildings to the next level. You can’t say that UBC is doing everything – we are not there yet.”

4.2.1.2 Visibility + Controllability:

According to Green and Petre (1996) “The visibility dimension denotes simply whether required material is accessible without cognitive work; whether it is or can readily be made visible, whether it can readily be accessed in order to make it visible, or whether it can readily be identified in order to be accessed. Long or intricate search trails make poor visibility.” (p. 162)

From the interviews and contextual inquiries, I found that CIRS EBI-BMS interface has considerably poor visibility. For one, not all the building systems are integrated and visible in the BMS interface. Second, it is relatively hard to find sensor information directly through the interface. Several operators reported, relative difficulty in finding equipment sensors, their locations and other properties based on the information provided on screen. As one interviewee reported:

“Sensor location is not specified in the system. Thermostats are easy to find; they are always mounted onto the walls. Some temperature sensors [which] are hidden such as slab heating temperature sensors are hard to find.”

In order to understand, the flow and visibility of information within the CIRS BMS interface, I listed down all the major systems equipped with sensor or control points in the building, see Table 4.1. I am interested in finding out, how many of these sensors are integrated within the BMS, are
they visible in the interface and whether they can be controlled through the interface. It was found that almost all physical components (with sensors and controllers) are integrated with the EBI-BMS, except video cameras, so it makes sense if they are not visualized or controlled. Lighting systems although controlled through sensors and integrated with the BMS, are not controlled or even monitored within individual spaces but rather through the zonal electricity distribution panels of the building. An operator can override the status of lights in a building zone, irrespective of the proximity sensor status - the sensors are not part of the BMS visualization and therefore their status is not visible to the operator. Another aspect that is not integrated and visible to the operators is the energy consumption at building utility level or even at electricity distribution level. Data from electric energy meters is collected and visualized by Pulse Energy EMIS, which is a separate interface and not part of the EBI-BMS.

Another class of visibility is when the information is available and accessible but not readily visible to the users. According to Green and Petre (1996), for such cases, “the number of steps needed to make a given item visible” (p. 35) are important. The interface of CIRS EBI-BMS is designed in the form of tabs and windows; each containing separate set of graphics, performance information and control options. The interface navigation flow is centered around the main menu – a navigation tab directs the user from any point in the interface to the main menu. There is no provision for the operator to go backward or forward in the interface within a set of connected window tabs, he has to go back to the main menu and choose another system or a component tab to view the relevant information.

In order to locate and access a particular equipment performance information, an operator may have to go through several tabs; each opening a new window and hiding the previously opened
windows thus making the whole process somewhat complicated, highly disconnected and cognitively intensive. In scenarios like this, juxtaposibility – “the ability to see any two portions of the program on screen side-by-side at the same time” (Green & Petre, 1996, p. 35) becomes imperative. During the interviews, an operator was asked to show, how he would go about finding the root cause of an alarm that was going on his screen. To find what was wrong with a certain component, instead of clicking on the alarm itself, he had to first open a separate window, he then browsed through the navigation panel to see which component or system he wanted to monitor, according to the alarm’s tag. He proceeded to open the concerned window and only then was able to analyze the system information shown on a 2D visualization. This long thread of search through disconnected windows often makes it hard for operators to remember previously seen information, resulting into them going back and forth multiple times, ultimately causing delays when immediate diagnosis is required.

Another visibility issue that I found was the lack of information traceability in case of multiple operators accessing and changing performance control parameters in the BMS system. One of the interviewee told us that if someone changed system control parameters, the BMS marks such an overwrite with a different color, however, there is no record of who or when such a change was made and in response to what (an alarm, a repair work or change in occupancy use). The operator can identify the color coded visual marker of an overwrite based on his knowledge and previous experience working with that equipment. However, other operators or a non-experience person would not know what that color code means and why, when and who changed the control parameters from the interface itself.
<table>
<thead>
<tr>
<th>Monitoring device</th>
<th>Is the device currently working?</th>
<th>Is the device integrated with the monitoring system?</th>
<th>Is the device visualized in the system notation for operators?</th>
<th>Is the device controllable through the BMS online?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature sensors (Space)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Temperature controller (Equipment)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Volatile organic compound (VOC)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Humidity sensor</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Thermal Energy meter</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Window actuator</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Light (Proximity) sensor</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>CO₂ sensor</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Cameras</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Air Flow meters</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Water flow meter</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Electric energy meter (Equipment)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Electric Energy meter (building)</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Flow control valves</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Equipment controllers (fan speed, on/off switches, etc.)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
4.2.1.3 Information Dispersion – Diffuseness:

Diffuseness is one of the cognitive dimensions, defining “how many symbols or graphical entities are required to produce a certain result or express a meaning?” (Green & Petre, 1996, p. 11). The more dispersed the information is, harder it is to keep a mental model of all pieces of information in the working memory of an operator.

In terms of performance management at CIRS, the first and foremost instance of dispersed information occurs at the highest level; where energy and system level data is monitored and visualized using two different management systems. The onus of understanding and correlating the data from these systems is left on building managers by either mentally integrating bits and pieces of information based on their knowledge and experience or by extracting it to external programs (Excel, Tableau, etc.) for analysis and evaluation.

“It is difficult to pin point the spike in energy with the malfunction of an equipment. And it takes considerable time to relate the energy related anomalies with the building equipment functionalities.”

In addition of having separate systems for building and energy performance metrics, energy data is currently measured cumulatively from building utility energy meters and does not provide any indication or breakup of energy usage across building space or at equipment level. In their study of CIRS energy consumption Cavka et al., (2012) reported that “the BMS system is not configured to enable breakdown of performance results of different consumption measures within the building at 100% accuracy” (p. 4) and that breakdown of different utilities has to be carried out manually using mathematical formulas. This makes correlation of energy and equipment level data even more complicated and cognitively intensive. With current systems it is quite difficult to pin point
energy consumption contribution of different spaces and or equipment toward the overall building consumption pattern (Maile et al., 2012).

Another interviewee told us that he would prefer integrating all data into the BMS compared to the processes currently in practice at CIRS and other buildings at UBC.

“I personally think that managing at the meter level is a wrong decision, we should monitor at the BMS level. What is happening at the space level, when the performance is not up the mark, and then go into detail when needed. To me we should rely on BMS rather than relying on predictive algorithm, in which case if there is a spike, it could take someone 48 hours to notice or anything, whereas in case we have a strong reliance on BMS, we could get alarm and get notified for something wrong and then we can dig deep into it to get to the root of the problem.”

Now even if I ignore for a moment, the information dispersed through the use of two entirely different software, I would find that operators still have to go through various windows (interface displays) in order to retrieve parts of relevant information. For example, operators have to query water flow temperatures in heat pumps to ascertain if the supply and return water are at correct temperature difference and the pumps are working at their desired efficiency. However, in order to find out how long has the pump been operating or when was it started, operators have to open pump historical trends and look at the timeline in the trend graphs. This kind of contextually relevant information should be immediately available to the operators on-demand, so that they do not have to spend a lot of time collecting, interpreting and understanding otherwise dispersed bits of information.
4.2.1.4 Consistency:

In HCI literature, one of the most significant aspects of usability of computer systems is “consistency” in user interfaces (Nielsen, 1989) as it leads to a smooth learning curve for the users. Green and Petre (1996) defines consistency as a particular form of guess-ability: “when a part of the system has been learned, how much of the rest can be successfully guessed?” (p. 20)

“Users should not have to wonder whether different words, situations, or actions mean the same thing. A particular system action-when appropriate-should always be achievable by one particular user action. Consistency also means coordination between sub-systems and between major independent systems with common user populations.” (Molich & Nielsen, 1990, p. 339)

As already discussed that EBI-BMS interface presents building performance information in the form of separate windows, where each major equipment window has several tabs representing associated and dependent equipment. The layout and mapping of these associated tabs is highly dependent on the selected equipment and may change from the original set of tabs to a new set of equipment relevant tabs with the new selection. There is no reference to the previous layout or any hierarchy that would facilitate back-tracking to the previous window directly from the current window. This interface setup is highly inconsistent as it relies on user’s ability to remember the path and to maintain coherence within the changing interface environment, see Figure 4.2.

4.2.1.5 Secondary Notation:

Decisions on maintenance-related works are usually made based on various sources of “accumulated historical data, such as design drawings, inspection records, sensing data, environmental records, etc.” (Chen et al., 2013, p. 1). All these sources are supplemental
information that supports an operator’s understanding of the collected performance data. Presentation of any supporting information in addition to the main syntactical visualization is termed as “secondary notation” in an interface (Green & Petre, 1996, p. 11; Blackwell et al., 2001). In their daily routine works, building operators may need to refer to multiple sources of information, record maintenance tasks, log trouble calls, extract and analyze information, report writing, etc. Rather than providing functions to support every bit of associated information, interfaces are designed with secondary notations that a user can use in whichever way he likes and whenever it is required (Blackwell et al., 2001).

Lack of supplementary and up-to-date as-built information may have significant impact on operator’s ability to understand a facility’s performance and make informed O&M decisions (Kirkwood, 1995; Akcamete et al., 2009). Currently, all building drawings and manufacturer manuals and specifications are archived at UBC Records using various Electronic Records Management Systems like Laserfiche®, and can be retrieved upon request from a web portal, whereas all trouble calls, issue reports and maintenance logs are recorded in a services management tool – PeopleSoft® (Cavka et al., 2015). EBI interface does not have any direct link to any such supplementary information, with an exception to equipment SOPs, and operators have to retrieve any such information separately to analyze and diagnose O&M related problems. An interviewee pointed out that having an up-to-date sequence of operations within the equipment performance visualization is quite important, as it helps operators identify the control parameters of that particular equipment and its dependencies.
“It is necessary to have proper representation, but just having a proper representation isn’t enough, I think an integrated sequence of operation documents are more important.”

4.2.1.6 Details-On-Demand and High-Fidelity Visualization:

A problem with many of the current BMS tools is that users are provided with a very specific part of information of a very large and complex network of building systems and equipment. Being minimalistic is a good visualization attribute, however, it quite often produces a gap in users understanding of an equipment’s performance in context of the whole building or a larger system. Building operators may also require to compare and analyze data that is not located within the same display window, or may need to zoom-in or filter different aspects of information to get a better idea. However, it is quite cognitively demanding to navigate complex information structures and bring different parts of information into view and make relations between the two information sets (Jakobsen & Hornbaek, 2011).

“Quite often what happens is that for building managers is that they have harder time to determine exactly what is going on? As there is too much information to quite understand exactly. May be you need to have filters” (BMS Specialist – CIRS)

Since computer displays have limited screen space, and with tools like BMS interface which have high data complexity it is quite impractical to visualize everything at one time (Shneiderman, 1996).

“The details-on-demand technique provides additional information on a point-by-point basis, without requiring a change of view. This can be useful for relating the detailed information to the rest of the data set or for quickly solving
particular tasks, such as identifying a specific data element amongst many, or relating attributes of two or more data points. Providing these details by a simple action, such as a mouse-over or selection (the "on-demand" feature) allows this information to be revealed without changing the representational context in which the data artifact is situated”. (Craft and Cairns, 2005, p. 3)

Another aspect, is the visual fidelity of the information displayed. Current EBI interface, displays static graphic illustrations of the equipment and building layout schematics with dynamic information mapped over the static images. There is no provision for the user to overview, drill-down\(^\text{41}\), filter or zoom (Shneiderman, 1996) into different aspects of the display to get a better understanding of inner workings of the system. Numerous research studies have highlighted the need to have high-fidelity information that a user can drill-down, zoom or filter to gain a much more fine-grained understanding of user-level or equipment level performance. (Lucas et al., 1996; Stern, 1992; Jiang et al., 2009; Lehrer & Vasudev, 2011; Segel & Heer, 2010). A drill-down, zoom-to-relevant-detail capability of a BMS interface would allow the building operators to view finer details like user-level plug loads or overhead ducts or discreet sensors, from the same visualization without opening other information windows or interface elements.

\(^{41}\) “Navigation through the different levels of the data is called ‘drill-down’ (showing more detailed data) or ‘roll up’ (showing data on next aggregation level)” (Keller et al., 2007)
Figure 4.2 - Interface layout and Information flow within Honeywell EBI BMS.
4.2.1.7 Learnability:

Throughout the interviews, I was reminded by many of the participants that building O&M works is an experienced and knowledge based discipline. The process itself has a learning curve and operators need to “learn the ropes” in the field before they use the BMS interface. This knowledge, as pointed out by the interviewees, is not transferable immediately to any new operator. This makes the operator indispensable and creates a problem if the said operator is not available. The basic notion of computer tools is to facilitate human cognition by distributing cognition intensive tasks between the computer and the human user. If users are required to learn the tool itself and interpret the information, it would just add on to an already complex and cognitively intensive work task. Nielsen (2012) defines learnability as a quality attribute of an interface that indicates “How easy is it for users to accomplish basic tasks the first time they encounter the design?” (p. 1)

Given the complicated and inconsistent window-based (pages) design of the CIRS EBI interface, building operators have to learn the interface navigation layout and tab patterns in order to open relevant equipment’s information window. Some of the dependent equipment information is not even accessible from the main menu and has to be retrieved within the main equipment’s window tabs. For example, washroom exhaust system can only be accessed through Air Handling AHU-01 information tab, whereas Heat Recovery for Air Handlers and Earth and Ocean Sciences building (EOS) can only be accessed through the Geothermal loop window. Availability of context-aware information within the interface in response to user’s interactions, concerned object or query formulation, would significantly reduce the amount of time spent to understand and consolidate information (Afyouni et al., 2010; 2012; Hailemariam et al., 2011; Chou et al., 2001).
4.2.2 Quantitative Data Analysis: Survey of BMS Experts at UBC:

The main objective of carrying out a user-survey was to complete the rigor of mixed-method research process and to collect additional data that quantitatively supports the findings of the qualitative data. This allowed me to offset any weaknesses that may have appeared from my presence, during the interviews and contextual inquiry sessions. User surveys were not designed to acquire unique data but were used as a tool to acquire additional information that can support the results from the qualitative analysis and support the subjective views of the previous participants (Clark & Creswell, 2007).

"User experience (UX) research methods can provide both qualitative and quantitative measures of users’ attitudinal and behavioral responses to the product or service in question. While attitudinal UX research methods may be described as “what people say” and documenting their stated beliefs, its behavioral counterpart focuses on “what people do” with minimal interference from the method itself." (Lehrer & Vasudev, 2011, p. 16)

The first section of the user-survey was designed to capture the demographics of the BMS/EMS users at UBC. Since UBC is a tightly knit self-operated organization with handful of specialized personnel interacting directly with BMS/EMIS tools the survey results are not statistical representation of general practices but rather is a convenience sample to support the research study. Around 2/3rd of all participants had more than 10 years of working experience in O&M field, around the same number were direct users of BMS/EMS tools in one position or the other. Almost all the participants reported that they interact with these tools throughout the day spending around 4 - 6 hours daily, Figure 4.3.
Branching questions within the survey inquired participants about major sources of information (performance and otherwise) used by them to carry out their routine O&M works and what is the specific role of BMS/EMIS tools in that routine. Almost all the participants reported that most of the performance related information is gathered through trouble calls, while around 67% said they also use BMS/EMIS generated data and alarm logs to collect building performance data, Figure 4.3. However, almost all of them reported that they would refer to BMS/EMIS tools only if there is an alarm issued by the system or in response to a trouble call. Only one correspondent reported use of monthly utility bills as a source for building performance information. In a similar manner, around 67% (2/3rd) of the respondents reported that they use BMS/EMS tools for monitoring and fault detection purposes while the rest used the data to make administrative decisions, Figure 4.3.
In the follow-up section, I focused more on how building operators use the collected data to understand building performance parameters and what sort of data is more relevant to their routine work. Majority of the participants – around 67% – agreed that some familiarity and prior knowledge of the building systems/equipment is definitely required in order to operate as well as

Figure 4.3 – Results from the demographic section of the survey: a) Participant’s experience in O&M field; b) Experience working with BMS/EMIS systems; c) Information sources used by UBC building operators; d) use of BMS/EMIS tools to carry out specific O&M tasks. (N = 5)
understand the information from the BMS/EMS systems, however, there were differences in opinion as to how they utilize the information. In this regards, I asked the respondents to highlight the type of data that is most relevant to their daily works and which is essential in terms of understanding the building’s performance. While predictably, all the participants agreed that real-time and historic equipment status data is relatively the most frequently accessed information from the BMS for their routine O&M works, it was interesting to find out that most participants also found typically unconventional data like occupancy loads and building envelope status; to be very useful in terms of understanding building behavior and resource consumption, Figure 4.4. Another interesting aspect observed from the survey was that majority of the participants reported information like utility bills, change orders/ maintenance logs and normative data (monthly energy consumption, yearly equipment status reports), etc., is not overly useful for them in carrying out routine O&M tasks. This is somewhat conflicting with other research studies like the one carried out by Lehrer and Vasudev (2011); surveying seventy expert participants which reported 84% and 56% respondents finding normative information and estimated bills as useful in their daily works, respectively. Respondents of the study, also had a mixed response in terms of usefulness of building and system level energy consumption information for O&M works, which the authors presume, was mostly dependent on the line of work of participating professionals.
Since, there is huge range of BMS/EMS features provided by different vendors in their respective tools - depending on the requirements, nature of the facility and operational tasks and the sensor network; there is no one clear set of features that are available in all the tools (Kramer et al., 2013; Granderson et al., 2009). In the last section of the survey, I wanted to find out the set of BMS/EMS features which are most relevant to building operators in performing O&M works at UBC, by asking the participants to rate the usefulness of various features available in the BMS/EMS tools.

Figure 4.4 - Usefulness of BMS/EMIS data for understanding building performance parameters (N = 5)
Although, majority of the participants rated most of the features listed in the survey questionnaire as useful, almost all the participants agreed that operating schedules and alarms/notifications are the most useful and frequently used BMS/EMS features in their routine works, see Figure 4.5. Similar to previous question, there were mixed responses in terms of usefulness of features reporting energy consumption across building scale. Participants also reported a positive but mixed response in terms of having interactive controllability of building functions, which shows the usefulness of the feature but also highlights the lack of awareness of having such feature due to its unavailability in the currently available BMS/EMS tools. Interestingly 1/3rd of the participants reported no need for some otherwise quite important features in BMS/EMS tools including status of end-use plug load (Lehrer, 2009), integration with CMMS (Sullivan et al., 2010), event logging (Domingues et al., 2015). The author assumes that lack of interest in such features may be due to “on-need” based approach at UBC toward carrying out O&M tasks using BMS/EMS tools. As one of the interviewee suggested:

“[…] that’s probably the level most buildings are working here [at UBC]. I think we do see a lack here and we slowly are moving toward it where we actually do get the feedback to bring our buildings to the next level. You can’t say that UBC is doing everything – we are not there yet.”
Figure 4.5 - Usefulness of BMS/EMIS features in carrying out routine O&M works at UBC. (N = 5)
Although, the list of useful attributes and shortcomings from the survey, in using BMS/EMIS tools for O&M works at UBC corresponds with those from the interviews; the survey results provide a more generic overview of the prevalent practices of using the tools. However, from the results of the survey, I was able to glean the type of information and features which are potentially deemed useful by the building operators regardless of the fact that they are currently available or not in the tools being used at UBC. This is quite important as this kind of information could not have been collected through interviews and or contextual inquiries, since participants are not cognizant of not having such capabilities while using the tools. The results also highlighted the lack of interest among building operators of having access to energy consumption information across building scale, which signifies the current industry’s trend of having separate tools to monitor system and energy level information. Several previous research studies have however, established the need to provide both system and energy level information to building operators for a better understanding of building behavior.

The fact that some mixed and overlapping responses are seen in the results, indicates that different respondents in this sample of participants use different set of tools and belong to different aspects of building operation and management functions and may not be well suited to make distinction between interactive, controllable tools and those that only provide performance information.

4.3 Results of Data Analysis and Discussion:

Analysis of the collected data in regards to the use of BMCS/EMIS tools for monitoring and controlling building performance revealed various shortcomings in the current systems at UBC, in terms of providing understandable and actionable information to building operators. It was
observed that the current tools heavily rely on static 2D schematic drawings to relay building spaces and component assemblies, with most of the performance data represented in numerical, tabular or chart forms. The tools also showed very limited internal comparative, analytical and investigative capabilities; and building operators had to export most of the performance data for interpretation, analysis and reporting in other spreadsheet programs. In addition, the BMS tool only displayed equipment level performance information without any contextual reference to the occupancy levels across the building, ambient environmental conditions or any specific qualifications regarding operational schedules, functional and spatial requirements or control parameters of the built systems. Unavailability, unreliability and inaccuracy of performance information, specially of complex systems, can significantly impede an operator’s ability to efficiently understand and foresee potential faults, prepare preventive maintenance strategies and optimize operational functions of a facility (O’Donnell et al., 2013).

The research demonstrated the need to have better interactive environments that may enhance understanding and decision making capacity of building operators by providing context-aware controllable information visualization in a 3D geometric setting. The collected data was analyzed using established HCI interface usability heuristics and several overlapping and interrelated discrepancies were identified in the current BMS interface at CIRS. Some of the major discrepancies found during the research is summarized in Table 4.2.
Table 4.2 - Summary of interface discrepancies from the case study data analysis

<table>
<thead>
<tr>
<th>Interface Heuristic</th>
<th>Associated Interaction/information Visualization Problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closeness of Mapping</td>
<td>1. Lack of spatially contextual mapping between virtual objects and their physical counterparts, i.e., lacking in 3D representation of geometric objects.</td>
</tr>
<tr>
<td></td>
<td>2. No direct relationship between spatial and non-spatial data, i.e., between building component and its sensors/actuators.</td>
</tr>
<tr>
<td>Visibility and Controllability</td>
<td>3. Not all the systems/equipment are integrated or represented in the BMS interface.</td>
</tr>
<tr>
<td></td>
<td>4. The system fails to provide characteristic/auxiliary information like location, type, host, control parameters of components, sensors and at times even larger equipment/systems.</td>
</tr>
<tr>
<td></td>
<td>5. Energy consumption and system performance information presented through separate interfaces, with no interoperability.</td>
</tr>
<tr>
<td></td>
<td>6. Poor visibility of information due linearly tiered interface layout.</td>
</tr>
<tr>
<td></td>
<td>7. No provision of back-tracking to previously viewed information, i.e., the user has to go to main menu in order to select another option/equipment.</td>
</tr>
<tr>
<td></td>
<td>8. Unable to represent dependencies between different building elements, serviced spaces or monitored zones.</td>
</tr>
<tr>
<td></td>
<td>9. Lack in providing any traceability of information in case of multiple operators.</td>
</tr>
<tr>
<td>Information Dispersion</td>
<td>10. Different tools for energy and system level performance information.</td>
</tr>
<tr>
<td></td>
<td>11. Lack in providing variable granularity of monitored information, i.e., performance results cannot be monitored per space, equipment or even zone.</td>
</tr>
<tr>
<td>Consistency</td>
<td>12. Inconsistent linearly tiered interface layout, i.e., the window tabs change as per the selected equipment</td>
</tr>
<tr>
<td>Secondary Notation</td>
<td>13. No provision to embed or link supplementary information with the object it concerns like documents, manuals, work order, etc.</td>
</tr>
<tr>
<td>Detail-on-demand / high-fidelity Visualization</td>
<td>14. Lack of visual analytical abilities like overview, dill-down, zoom and filter.</td>
</tr>
<tr>
<td></td>
<td>15. No provision to compare different sets of information from different equipment.</td>
</tr>
<tr>
<td>Learnability</td>
<td>16. Non-intuitive interface layout and visualization – steep learnability curve</td>
</tr>
<tr>
<td></td>
<td>17. Non-accessibility of context-aware information within an object’s visual domain.</td>
</tr>
</tbody>
</table>

From the above discrepancies, I found that there are two primary problems that needs to be addressed at the foundational level of the proposed integrated interface, i.e., spatially contextual geometry and integration of otherwise segregated system performance and energy consumption data. Unifying both system and energy level performance information from EMIS and BAS, would significantly reduce the amount of time and effort spent by building operators in searching, relating
and analyzing relevant information for fault detection and O&M works. I hope that mapping of this unified semantic information in a spatially contextual geometric setting, would allow a more holistic overview of the building behavior and facilitate understanding by bridging the gap between data and user’s experiential mental model of the physical world (Hailemariam et al., 2010). In addition to these foundational elements, I further classified the observed problems into two groups; 1) those which can be solved by applying appropriate visualization techniques and 2) those which relate to the interactive user-experience of the interface, see Figure 4.6.

The above classification is purely based on the findings from the research study and as such are case-specific. They represent various features and interaction elements that were observed to be missing or not fully realized in the case study BMS and do not represent the full set of features that may otherwise be included in other commercially available management systems. The basic premise is to highlight the vision of interface/visualization elements that provide context-aware
spatial information of building systems and may potentially facilitate better understanding and controllability of building performance.

4.3.1 Functional Domains of the Interface:

The primary functions of the integrated interface identified from the research and literature review can be grouped into four areas:

1. Monitoring - provides a holistic overview of the building’s performance to help building operators understand operational aspects of the building (all systems are properly working), maintenance requirements (is there any issue or need to repair, replace or modify any system) and functional parameters (HVAC schedule, heating temperature, humidity levels, ambient factors, etc.). It also affords the opportunity to evaluate the results of any changes/repairs/modification made to the systems by the building operator.

Built environments have complex interdependent operational functions, with objects nested in multiple layers of shared utilities and characteristics (O’Donnell et al., 2013). Performance information of building objects is usually associated with two discrete semantic information hierarchies, 1) Spatial – as it is located somewhere in the building space and 2) System – as it may serve as part of a system or is served by a system/component or utility, see Figure 4.7. However, these hierarchies have closed looped nested interactions, since all system hierarchies (systems, components and sensors) are located spatially within a zones (areas) at a floor within a building (Costa et al., 2013; O’Donnell et al., 2013; Liu & Akinci, 2009). In order to capture and monitor these shared characteristics and information thereof in an effective manner; broader and semantically
sensitive visualization techniques are required that provide information based on the context of the building operator’s interaction with the interface and an object’s association with that interaction.

Figure 4.7 - Interdependencies between characteristic spatial and system based hierarchies of building objects

2. Control – provides building operators the ability to change, modify or restrict any operational function of the building directly from the building management systems. Most integrated BMS lack in providing control capabilities in the monitoring interfaces, causing building operators to use different interfaces for monitoring and controlling performance parameters.

3. Analysis – allows building operators to compare and evaluate different performance metrics and make inferences in regards to achieving performance goals. Analytical capabilities also allow building operators to understand fault scenarios, recurring issues or decide on maintenance strategies.

4. Result Reporting – is an important feature which allows building operators to share the findings of their analysis and investigation with other members of the organization. Reports
can be generated in both graphical, textual or tabular formats, depending on the type of
data to be shared and can provide both detailed transcript of the analysis as well as
summarized information about building performance, system operation and equipment
efficiency over a period of time (Crawley et al., 2006). An integrated system can further
enhance the understanding and contextual relevance of the result reports by inserting time
snapshots of the 3D visualization displayed in the interface and the interaction of the
building operator itself at that time instance.

4.3.2 Assumptions and Limitations:

The main assumptions of this research works are:

1. That the data sources required for implementation and demonstration of the interface test-
bed including as-built quality Building Information Model (BIM), weather data, energy
meter data, Building Automation System (BAS) sensor/controller data and Computerized
Maintenance Management System (CMMS) or Computer-Aided Facility Management
(CAFM) data is available for the case study building. In case of BAS, it is important the
that data from the sensors at user’s end like plug loads, occupancy loads, motion detection
and status of interaction with physical elements (windows, doors, etc.) is also available to
demonstrate variable information resolution and detail-on-demand aspects of the integrated
system.

The assumption is valid, in terms of its implementation potential, given that an as-built
quality BIM can be developed using COBie specifications as well as design and
construction models and drawings, BAS data is already collected at the facility and can be
easily integrated into the unified data repository, there is already an existing weather station on the building premises and UBC collects and disseminates all its related facility and asset management data through a central CMMS database software “PeopleSoft42” (Cavka et al., 2015, p. 1293).

2. The intricacies of mapping BAS, CMMS/CAFM and weather data onto BIM geometric profile has already been resolved and a framework for such integration is already existing.

3. The main users of the integrated platform are facility managers/building operators who regardless of being a novice or an expert, must have some background knowledge of building information in order to understand the data and make inferences.

There are some inherent limitations to this proposal, which are:

1. The proposed interface is only a demonstration and proof-of-concept of the envisioned integrated system. Implementation and evaluation of the proposed solutions is not within the scope of this work.

2. The components demonstrated in the proof-of-concept interface are only HVAC mechanical components. Although, the interface caters to the information of all the buildings systems, presentation of all the system visualization is beyond the scope of this thesis.

42 “UBC Building Operations has implemented PeopleSoft to manage the data of all its stores, purchasing and collected asset information on buildings, systems and select equipment” (http://www.buildingoperations.ubc.ca/, accessed)
4.4 Technological and Information Integration Feasibility:

The proposed Integrated Performance Visualization Interface (iPViz) requires some technological infrastructure to be developed and implemented. In this article, I will briefly highlight the technological feasibility of such a system. The main technological modules of an iPViz interface can be divided into two high level categories: 1) Physical hardware, which may include sensing and control instruments from the BAS, database servers, wired/wireless information exchange networks, etc., and 2) Software, which entails both back-end data acquisition, mapping and storage software as well as front-end analysis and visualization software. The main focus of this chapter is to explore the front-end visualization aspects of the iPViz system, however, I would also briefly look into the involved hardware and back-end data mapping processes that may potentially be involved in making the system feasible.

**Physical Hardware:**

Existing BAS network can be engaged to collect performance data for the propose system. There are over 3000+ sensory and control instruments currently installed as part of the Building Automation and Management System at CIRS. The current setup includes temperature, humidity, CO₂, Volatile Organic Compound (VOC), air and water flow sensing instruments, controllers, valves and switches, see Table 4.1 for the full list of sensing and control devices at CIRS. Currently, there are no motion detecting (available but nor operational) or end-use plug outlet sensors installed at CIRS. However, since the data from these devices is part of the comprehensive monitoring package; for the purpose of this research, it is assumed that such data is available at the time.
**Back-end data acquisition and mapping:**

Information and that too progressively up-to-date information is key to successful monitoring and control of building operations (Akcamete et al., 2009; Volk et al., 2014). In order to provide holistic and contextually relevant information to building operators the system requires a medium that is populated with updated as-built information from all the contributing disciplines (architectural, structural and mechanical, electrical and plumping (MEP)), and has the potential capability to acquire, map and update any further data manipulations (in real-time) onto its current information database framework. Although with current work practices, contractual implications and slow rate of technological adoption with in the Architectural, Engineering and Construction (AEC) industry such integrated as-built building information models have not been fully realized (Anderson et al., 2012; Irizarry et al., 2014), yet advances in developing data structuring and exchange formats like COBie, COBie2, IFC, HVACie, etc., have a huge potential in making data enriched as-built BIM a reality in the coming future. In addition, other computer-aided systems like CAFM, CMMS, are also being used to manage huge amounts of facility management and building O&M information over the operational lifecycle of the built environment. Integrating different streams of information from different building lifecycle phases is understandably both technologically and logistically challenging feat, however, there is a huge interest in the construction industry toward such integrated platforms and considerable amount of research work is being carried out to realize it (Irizarry et al., 2014; Yang, 2014; Yang & Ergan, 2015; Liu & Akinci, 2009; Lavy & Jawadekar, 2014; Golabchi et al., 2013).

Given that almost all the information and underlying sensing technology is currently available, albeit through different management to; the envisioned Integrated Performance Visualization
Interface (iPViz) would not require extensive technological modifications or workflow overhauls to be implemented. With properly developed and standardized BIM (COBie-based) of the built environment and an intelligently structured information mapping frameworks, the system can even be implemented with existing Building Management Systems (BMS) in the building, see Figure 4.8.

Figure 4.8 - Potential technological and information flow framework for implementing iPViz interface
In Figure 4.8, I envision four major streams of information that are required to be aggregated, interpreted, mapped, and communicated within a central integrated database server for the iPViC to be functionally realized. Architectural, Structural, and MEP geometric information can be collected in the form of IFC files from as-built - COBie based building information models. Although, COBie format of structuring information in BIM is not a necessity, it would be semantically much more challenging to fill in essential information at a later stage, that might have been left out if unstructured building information models are created by different stakeholders. Building operation data can be collected through BAS sensors, controllers, and meters that may already exist in a building. Metadata of these sensing and controlling devices can be aggregated based on several standard exchange formats like oBIX, IEEE 1451, SensorML, etc. (Liu & Akinci, 2009), which are compatible with and can easily be mapped over IFC (IFC4) schema (geometric metadata). Furthermore, operational data for various building systems, specially HVAC can also be easily integrated with IFC4 schema, since it is compatible with current HVAC information exchange formats like HVACie (Yang, 2014; Yang & Ergan, 2015). In addition to geometric and operational data, auxiliary information like weather data, occupancy data and documentation can be collected from existing data sources like weather stations, occupancy sensors, video cameras and document management systems respectively.

All this data can be aggregated, interpreted, and mapped in a central database using existing software packages like open source MySQL or more mainstream Oracle database administrator, Microsoft SQL, etc. An IFC interoperable visualization engine like the Autodesk Navisworks Application Program Interface (API) Software Development Kit (SDK) can be used to produce and display rich interactive visualization of the integrated database. An application integrator can
be used to integrate the visualization created through a visualization engine and the back-end database framework in a user friendly interactive environment, providing two-way communications, manipulation and control capabilities of both the visualization and the underlying metadata structure.

4.5 Front-end Visualization Interface:

Now that it is established that the proposed interface is technologically and practically feasible to implement, I would focus in this article on the main scope of the research work: front-end interface for visualizing building performance and control information. Since it is beyond the scope of this thesis to develop a functional prototype of the interface, I only developed a medium-fidelity digital mock up as a showcase and proof-of-concept of an integrated performance visualization interface.

4.5.1 Mock up Development Process:

The mock up development process started with initially defining the base structure of the interface, information display requirements, interaction flows and visual codes like colors, patterns, etc., through very low-fidelity hand drawn sketches and paper-based wireframes, see Figure 4.9. Once the basic structure and visual codes were finalized, I started developing medium-fidelity digital mock up.
Figure 4.9 – Low fidelity mock-up hand drawn sketches of the interface design elements (paper & white board)
I started by first studying the existing architectural and mechanical building information model to understand the level of detail of the modeled elements, associated information and the relationship that existed between the objects and the building spaces. The models were developed by Perkins and Will (http://ca.perkinswill.com) and Stantec (http://www.stantec.com/) respectively using Autodesk® Revit® 2009 software (Autodesk, 2009) and were handed over to UBC as part of the commissioning package; which is made available by UBC Records to students for research purposes. The models obtained from UBC Records (with permission) are only design based models with very little or no construction information embedded in the objects like sensors, electrical outlets, office furniture, etc. As a lot of these objects specially sensors and outlets were required to showcase different features of the proposed interface, they were added in the original Revit® models manually either by modeling them in Revit® or by importing them from open source model libraries like Autodesk Seek® (http://seek.autodesk.com, 2016). Both architectural and mechanical Revit® models were cleaned, i.e., unwanted objects, model lines, construction details, etc., were taken out so that only the elements required for the mockup are visible. Since Autodesk® Revit® does not allow manipulation of visibility and graphics of the modeled elements at object level, the finalized models were exported to Autodesk® Navisworks®.

I used Autodesk® Navisworks® to manipulate the graphical properties of the various objects, layers and building elements to represent dynamic interactions and visual cues as required to demonstrate the interactions within the proposed interface mock up. Graphical characteristics like layer transparencies, color coding, visibility and occlusion were manipulated to enhance legibility and visibility of nested and spatially overlapping objects. Since it was necessary to represent various
building components and elements within their real world locations (within walls, behind ceilings, under floors, etc.), a visual occlusion technique termed as “virtual x-ray” (Elmqvist, 2007, p. 1; Elmqvist and Tsigas, 2007) was mocked up in Navisworks by manipulating transparency settings of objects at different occlusion depths, Figure 4.10. Using this technique, I attempted to virtually represent different user interactions including zooming, selection, highlighting, etc. High-resolution images representing specific scenarios were exported from Navisworks® to another software for further processing. A UI design software Sketchapp® from Bohemian Coding® (www.sketchapp.com) was used to design various visual elements of the interface on top of the imported 3D graphical images. User interactions were captured by using images in a storyboard based on hypothetical user scenarios (see 4.6.1).

Figure 4.10 – Manipulation of object graphics in Autodesk Navisworks® to achieve dynamic transparency mockup
4.5.2 Mock – up Design:

One of main problems faced by building operators when interacting with complex building management systems is information-overloading; the challenge to comprehend and understand data saturated operational situation in an effective manner (Bahrami et al., 2007; Ehler & Aaslyng 2001; Yang, 2014; Yang & Ergan, 2015). Visual interfaces although highly effective in providing graphical representation of data, can at times also contribute toward overloading cognitive perception of the users if not designed and relayed properly (Papamichael, 1997).

In order to keep the interface simple, task-focused, and still be able to display all the relevant information in a spatially contextual manner, I had to utilize different combinations of visualization and interaction design techniques (semantic zooming, information cards and visual layers, etc.). In this respect, Lehrer and Vasudev (2011) in their study of energy visualization tools expert users, found that almost 84% of the participants favored having dashboard style interface layout whereas 71% expert users preferred using simple information cards to review routine performance information. Keeping this in mind, I based the design of the interface to display chunks of most pertinent information sets in the form of information cards while providing a dashboard like display of multiple but related information sets.

4.5.2.1 Structure of the Mock – up Interface:

Based on the findings of the case study and my observations, it was observed that building operators at UBC most commonly interacted with the BMS to review, respond, investigate or analyze reported building O&M issues. I wanted to highlight and optimize this interaction as much as possible through the proposed interface and used this objective as the basis for structuring the
interface layout and interaction sequences. In addition, I wanted to preclude the use of linear, sequential and disconnected view-based representation of performance information which is mostly prevalent in current BMS systems like Honeywell EBI. The proposed interface, therefore, is designed with only two interface screens and all the required information is available to the user on-demand basis. The two screens are Information Review (infoRev) screen and the main Information Visualization (infoViz) screen. A brief description of the interface structure and design elements in both screens is discussed as below:

4.5.2.1.1 Information Review (infoRev) Screen:

![Figure 4.11 - Layout of information panels in the Information Review (infoRev) Screen: a) The Alarms panel (covering the largest screen portion), b) Building Status and performance overview panel, c) Weather Condition panel, d) Login and title information panel](image)
This is the first page that the user interacts with after initiating the software. The Information Review (infoRev) screen is intended to provide an overall review of the most pertinent information about the building performance. It consists of three distinct information panels; a) Alarms, b) Building Status and c) Weather Information, Figure 4.11. The infoRev screen is designed to afford building operators the opportunity to review overall performance parameters of the building, familiarize with the alarms and trouble calls related to building operations and get an overview of the ambient environmental conditions without the need to login to the system. This in my view, would allow building operators to strategize, prioritize and get a precursor understanding to the prevalent conditions that they might have to analyze going forward.

1. **Alarms Panel:**

The Alarms Panel occupies a central position on the infoRev screen and has been allocated the largest portion of the screen to facilitate easier recognition and to reduce time spent on searching for required information, Figure 4.11 (a). All the alarms and alerts generated by the BMS as well as any trouble calls or request for maintenance reported by occupants and field technicians through the PeopleSoft® service system are displayed in this panel. An information card visualization style was adopted to display all the relevant information about an alarm or a trouble call in a concise format, which also serves as an entry point to a more detailed visualization of the concerned issue.

   a. **Alarm Info Card:**

The info card is designed to display the most basic information about the alarm/trouble call like its priority status (high, moderate, acknowledged and archived) and the date and the time the of the alarm at the very top of the info card, Figure 4.12. Along with the text, a color code was also
selected to visibly represent the different priority status levels of an alarm, see Table for detail. A colored tab is displayed in the right corner with the alarm or trouble call icons to provide a very visible visual indicator of the type and priority of the alarm card. A recurring icon also appears in the tab signifying that an alarm was issued by the same component or sensor in the past.

Figure 4.12 – Alarm info card panel; (a) blow-up view of the information card, with description of information visualization elements.
The card also contains the most relevant information about an alarm like its source, location, description and performance parameters of the faulty sensor/component at the time of alarm. The location text is accompanied by a small map pop-out providing location to the building in case the operator is accessing the system remotely. In case of a trouble call, the format changes to provide to display call related information like request type, location, description and data about who made the request, Figure 4.12 (a). A link is also available with the descriptive text to the original maintenance request form from the PeopleSoft® service system for the building operator’s review.

In addition to various visualization features, the card is also designed to cater user’s natural interactions directly. While the card slightly expands when a user hovers over it, a user can symmetrically expand a card to twice its proportions to enhance visibility of the information. The card can be directly interacted with by clicking on it. It prompts a login request signifying that the user wants to further investigate the concerned alarm. Upon logging in, the interface opens the infoViz display directly at the faulty component with all the alarm related information displayed.

Table 4.3 - Visual and interaction design elements to represent alarm status

<table>
<thead>
<tr>
<th>Alarm Status</th>
<th>Color Codes</th>
<th>Visual Feed</th>
<th>Symbols</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 High Priority</td>
<td>Color, Flashing</td>
<td>High priority alarms are highlighted by a flashing color tab along with the icon showing if it’s an alarm or trouble call</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Moderate Priority</td>
<td>Color, Static</td>
<td>Moderate priority alarms are highlighted by static color tab, with an icon for alarm or trouble call</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Acknowledged</td>
<td>Color, Static</td>
<td>Acknowledged alarms are highlighted with a lower frequency color along with an appropriate icon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Archived/Completed</td>
<td>Color, Static, Hidden</td>
<td>Archived alarms are not displayed for review by default but can be recalled through search</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Snoozed</td>
<td>Static, Dimmed</td>
<td>Alarms snoozed retain their original color code but stop flashing and are dimmed slightly to signify that the alarm has been snoozed for some time</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
To further facilitate building operators in finding and accessing alarm or trouble call information, the info cards within the alarm panel are searchable through key words from the search bar at the right top corner of the alarm panel. The search bar also supports queries with dates or months as input. Further, the alarms can be categorized using different filters facilitating building operators to view the information either; by date, by priority, by systems, by type or by status, in an ascending or descending order.

2. **Building Status Panel:**

The building status panel is located on the right side of the infoRev screen. The panel displays three main categories of performance information; 1) system performance, 2) energy and water performance and 3) Occupancy status, Figure 4.11(b), Figure 4.13(a).

a. **System Performance:** This section displays functional information of all the major equipment and systems operating at CIRS. It contains the most basic information about a system including if its active or not, the duration of its operation, when did the system started and if its inactive when did it last stopped. A system’s active and inactive status is further highlighted through color codes. This is intended to provide an overview account of the major systems, which can quickly double checked against their intended operational schedule.

b. **Energy and Water Performance:** This section is designed in a dashboard style and displays consolidated performance information of energy and water consumption across the building, in tabular and graphical formats. The operator can filter the information to view performance metrics of day, week, month or a year. Performance information is aggregated
(as per the selected filter) to display real-time consumption information: live, total-cumulative consumption, and total savings (as per the selected filter duration, i.e., if filter is selected as a day the savings would show against yesterday’s consumption figure and so on). A graph represents the tabular consumption figures over a time-series, providing further breakdown and consumption patterns over the selected duration.

c. **Occupancy Status:** This section provides an overview of the total occupancy in the building as a percentage of the total designed capacity as well as a graphical breakdown over a time-series. The graph is intended as an overview of the occupancy patterns in the building.

3. **Weather Information Panel:**

The weather information panel is located in the bottom right corner of the infoRev screen and provides ambient environmental conditions such as weather conditions including precipitation, relative humidity and wind speed/direction and outside temperature, Figure 4.11(c), Figure 4.13(b). Building operator can choose to view the weather data from different pre-determined weather stations across the UBC campus.

4. **Title and Login Panel:**

The top section of the infoRev screen contains the title information of the university, the building and the interface along with their logos, Figure 4.13(c). Login panel is also located within the title panel at the top right corner and building operators can put their assigned credentials to enter the main infoViz screen, Figure 4.11. The login information is envisioned to serve as an identity profile, and the interface can use the information to track all the actions, changes, notes and work
orders issued during session. It is foreseen that all this information can be recorded as information logs and can be associated to the building elements or spaces that the operator interacted with, providing a time based record of all the actions and decisions for future reference and analysis.

Figure 4.13 - Information Review (infoRev) screen information panels: (a) Building status information panel, (b) Weather information panel and (c) Title and logging information panel
4.5.2.1.2 Main Information Visualization (infoViz) Screen:

This is the second and the main performance visualization and control screen of the iPViz interface. Unlike the infoRev screen which a building operator can view and interact with without logging into the system, the infoViz screen is intended to only be accessible to authenticated personnel. The infoViz screen layout can be divided into four main panels; a) selection menu, b) performance visualization panel, c) dependency graph, and d) Heat maps, with the building visualization panel occupying the largest portion of the infoViz screen. The main design focus in developing the infoViz mockup was to highlight two main features that I foresee may facilitate better understanding of building performance and O&M functions; 1) a high-fidelity interactive 3D graphical visualization with dynamic transparencies (Elmqvist, 2007) populated with context-aware semantic information, 2) an interactive hierarchical graph – providing information of dependencies that exist between the spatial and physical elements of the building. I intended the infoViz screen to be a tightly integrated visual display by heavily utilizing brushing and linking visualization concept43 (Keim, 2002) to highlight different aspects of user interactions. By using these concepts, I envision that every interaction within any of the information panels would provide a connected response in each of the panels, e.g., selection of an element in the selection menu would highlight it in the building visualization panel, display the relevant node in the dependency graph as well as highlight the appropriate floor in the heat maps and the building key.

43 Linking and Brushing are different visualization technique that can be used in a way that “interactive changes made in one visualization are automatically reflected in the other visualizations. Connecting multiple visualizations through interactive linking and brushing provides more information than considering the component visualizations independently”. (Keim, 2002)
plan. A brief description of the structure and the visual and interaction design elements of the information panels is as below:

1. **Selection Menu:**

The selection menu is located on the left side of the infoViz screen and provides selection options of all building spatial and physical elements. The primary hierarchy of the selection menu is designed into seven major divisions: building/home, floors, zones, systems, components, sensors and meters, see Figure 4.7.

I designed the menu to display the secondary hierarchies in an incrementally sequential manner. To achieve this the menu is designed to dynamically display most relevant sub-hierarchy in an accordion slider style, see Figure, so that even with the user selecting a much lower sub-hierarchical element like sensor, the primary hierarchy remains visible providing context and an easier back-tracking and selection of other elements, see Figure. Given the sheer volume of spatial and physical components available at CIRS, users are also provided with the flexibility to query for required components, sensors or building spaces in the search bar located next to the home button at the top of the selection menu.

2. **Performance Visualization Panel:**

This is the main performance information visualization and control panel and occupies the largest section in the center of the infoViz screen. Since this section contains most of the information visualization and interaction elements, I wanted to off load as much graphics as possible and present a clean, decluttered environment to the users. All the information as well as the graphics displayed in this panel are intended to be context sensitive, meaning the level of semantic
information displayed varies with the changes in the size, orientation, visibility and context of the user’s interaction with the 3D visualization.

Figure 4.14 - Layout of information panels in the Information Visualization (infoViz) Screen: a) The selection menu, b) Performance visualization panel, c) Dependency graph panel, d) Heat Maps sliding panel and e) Toolbar
Interaction and information flow in the InfoViz screen

State-A
Uncollapsed view of the selection menu with the primary spatial and system hierarchical divisions

State-B
Dynamic display of most relevant secondary sub-hierarchy

State-C
Dynamic display of most relevant tertiary sub-hierarchy, with localized scrolling option

State-D
Dynamic display and selection of elements in the tertiary hierarchy, selection preview shown in the secondary and primary selection tab

State-A
Linked display upon opening the InfoViz screen. The views in the performance visualization and dependency graphs correspond to the selection in the selection menu.

State-B
The user selected "Floors" in the selection menu, prompting a floors information view in the performance visualization panel and selection and highlighting of all the space level dependency nodes in the dependency graph.

State-C
Selection of Level-2 prompted a graphical view of the 2nd level and highlighting of relevant nodes in dependency graph.

State-D
Selection of a particular zone in the menu, displayed the relevant graphical view and highlighted the spatial nodes in other views

Figure 4.15 - Interaction and information flow in the Information Visualization (inforViz) screen
a. **3D Graphics:**

Given the richness and complexity of graphic elements that are included in an integrated 3D model (combining architectural, structural and MEP components), it becomes a huge challenge to discreetly visualize each element let alone allow users to directly interact with them. To reduce the impact of occlusion and to retain the sense of depth and real world perspective in the 3D model, I heavily relied on the concept of dynamic transparency (Elmqvist, 2007) approaches, to vary opacity levels of various overlapping layers. By default, the building is displayed in a fully rendered graphics to the user, virtually portraying existing rendition of materials used in the building, Figure 4.15 (State-A). However, as the user starts interacting with the system, the graphical layers in order of increasing depth are displayed with varying transparency levels, giving a x-rayed or see through graphical perception to the users, Figure 4.15 (States B, C and D). In addition to dynamic transparencies, other visualization techniques like direct rendering (Hailemariam et al., 2010), edge detection (Lytle, 2011; Shin et al., 2001) and select-through, to color code highlighted objects, highlight and select objects over and under different layers respectively. This would allow the user to visualize and interact with objects that are otherwise hidden behind, under or within other building structural elements or components providing a much more real world experience and understanding of building behavior.

To minimize the cognitive and perceptual load on building operators in terms of distinguishing and understanding performance parameters while trying to recognize various building elements in a graphically intensive visualization such as iPviz, various filtering mechanisms were designed. Users can use these filters to selectively turn on or off different object layers as per their
requirement. The filters are provided on the right hand top corner of the performance visualization panel and include options to filter different equipment, energy systems, sensors and alarms as per user’s requirement, Figure 4.16(a).

We intended the high-fidelity 3D building visualization to be highly interactive, meaning users can zoom-in and out, rotate and view the building from any orientation. The amount and level of detail of semantic information associated with the building object would vary with the level of zoom, orientation and its visibility during the user’s interaction with the 3D graphics. Since the interface allows user to selectively zoom-in any space and have a virtually immersive first person eye-level view of that space, we designed a floating key plan view at the bottom left corner of the screen that would pinpoint a user’s current location on a 2D map of the floor. This is intended to provide users a context of their location at all times, which is otherwise difficult to maintain in highly complex 3D views.

Figure 4.16 - Different selection and visualization filters mechanisms in the performance visualization panel: a) Filter to display different visual and information elements, b) Data and time selection filter to view performance parameters over a specific time period.
b. Semantic Performance Information and Control Visualization:

In compliance with the earlier strategy to display consolidated complex information in a simple but unified manner, all semantic information and control features regarding building performance are represented in the form of information cards. However, unlike the alarm info cards, these information cards are highly context sensitive and display varying level of information intensity depending on the characteristics of the graphical visualization. Said that however, there are certain exceptions to the rule, for example information cards providing cumulative building level or floor level information are not contextually bound and display same intensity of information regardless of user’s manipulation of the graphical model. Similarly, information cards that are minimized by the are not intended to change by changes to model orientation or zoom level alone. We would try to capture the intent behind different configuration of information cards below, however, for better understanding of the usability of such a feature see Article 4.6.1.

b.1 Semantic Information Cards - Building and Floor Level Performance:

The building and floor level information cards are designed to provide cumulative performance data at much broader level. At building level, the information cards are designed to display more detailed information summaries than the one displayed in the infoRev screen, of the four major performance areas 1) HVAC, 2) Occupancy, 3) Energy, 4) Thermal Comfort. During the case study, it was observed that although building operators were familiar with over all condition of the building systems, they had no information about the breakdown of those performance metrics in terms of occupancy level, resource consumption, space utilization, component performance,
during the concerned period. The building and floor level cards were designed to provide much finer granularity of performance information.

Figure 4.17 - Information cards displaying performance information summaries at (a) Building and (b) Floor levels
Table 4.18 - Example of different semantic information visualizations displayed in the information cards based on the context of the query and visual characteristics of the 3D graphics. Example of the type and structure of semantic information displayed in a typical information card.
b.2 Semantic Information Cards - General:

In general, we designed the semantic information cards with the intention that all relevant information regarding associated with an object can be presented at one consolidated location, so that building operators retain spatial context of the situation at all times while investigating or analyzing performance issues. With this objective in mind, we designed the cards to contain different information tabs, with each tab representing specific type of semantic information associated with the object, Figure 4.18. As already iterated, the intensity of the semantic information in the info cards highly depend on the context of the graphical model and user’s interaction with the interface. In general, all major system/equipment information cards consist of six different information tabs: Alarms, Controls, Energy, Trends, Logs and Documents, with the default view set at “Controls” tab. Information cards of components and sensors consist of four information tabs: Alarms, Status, Trends and Documents, with the default view set at “Status” tab. In case of component and sensor info cards, there are significantly less number of controllers involved which can be directly controlled by the user from the status tab itself. Similarly, since there are few documents associated with the function of a sensor or a component, the document tab also serves as the logs tab and any manipulations or changes made to a component or a sensor’s functional aspects are recorded and displayed here.

Each card is identified through unique ID tags, which at the time of the mock up design were taken as provided in the CIRS BMS guidelines, however, the main intention is that these tags follow COBie information format to facilitate easier indexing, searchability and recognition. Info cards can be symmetrically expanded as per user’s convenience and are visually tethered to an associated
component through a dashed high frequency colored line, in any view of the graphical model. Given the tremendous amount of building elements, sensors and controllers available at CIRS, we designed the interface in such a way that all related info cards can be stacked together with only the most spatially closer component’s information on the top. All stacked info cards are clearly earmarked by the number of cards in the stack in a high frequency color and can expanded by the user by clicking on them.

3. Dependency Graphs Panel:

One of the major shortcomings observed during the case study was the lack of any information regarding various dependencies that different building elements share among each other. It was observed that building operators usually relied on their experience and past knowledge to figure out the dependencies shared among different components, or systems and components or even spaces and systems. The dependency graphs in the proposed iPViz interface are intended to fill this gap and provide building operators with visual cues regarding various dependencies that exist between building elements.

The dependency graph panel is located across the entire bottom length of the interface. It is divided into number of sections each representing floors in the building. Each section contains four different types of nodes representing zones/spaces, systems, components and sensors/controllers that exist within that floor. Every node has an input and output connection, where input represents the node being part or depending on another node and output represents that some other node is dependent on this node. For example: in Figure 4.19, the system node of AHU-02 is dependent on the Space node representing mechanical room (Output of 1242 node to input connection of AHU-
02), as AHU is located in mechanical room, whereas the Fan Coil unit FC-01 is dependent on AHU-02 supply air (output from AHU-02 to input connection of FC-01). The node is structured in a manner that if the operator is only looking at the dependency node, he would get all the pertinent information regarding that node’s object including ID tag, operational command, most relevant parameter (temperature, pressure, valve opening, energy in case of a space, etc.) and if there are any alarms associated with this object. The nodes are further visually distinguishable through selected color coding. As with all the visual elements in the proposed iPViz interface, we again mocked up the provision of searchable content by displaying a search bar at the upper corner of the dependency graph panel.

Figure 4.19 - Example of dependency graph, with blow-up view of connected dependencies and information node
4. **Heat Maps:**

Heat Maps are a visualization technique that employ color coding on 2D graphics to represent the intensity and importance of particular set of information (Benomar et al., 2013). Since most of the data visualization in the performance visualization panel is object-based, we felt that once a building operator starts interacting with the graphical model, he is only exposed to that level of information granularity and there might be a disconnect between the broader picture and the finer resolution of performance information. We used the heat maps technique to mock up a color coded display of real-time cumulative energy consumption at space level, with the intention that it would provide a glimpse of overall space level performance context to building operators at all times, Figure 4.20. A color gradient with their representative values is also given at the top of the panel. The energy heat maps are located on the right side, in a drawer style navigation panel which can be dragged in and out to show or hide the heat maps as per user’s convenience.

![Color Spectrum to show energy consumption range](image1)

![2D plan color coded to represent energy consumption as per color key](image2)

**Figure 4.20 - Example of heat map used in the iPViz interface to represent range of energy consumption information across building floor/areas**
4.6 Proof-of-Concept of Proposed Interface:

The proposed Integrated Performance Visualization (iPViz) interface is envisioned to aggregate, interpret and visualize performance information collected from existing information repository and management systems. It is intended as a solution to various problems observed during the research case study, however, since implementation and evaluation is out of scope of this thesis, it is rather difficult to demonstrate the capabilities of the proposal to appropriately resolve the observed problems in the form of a narrative. Carroll (1999) observes that “problems can only be definitively analyzed by being solved; […] the solutions must be implemented in order to be specified” (p. 1). However, designing is an iterative process and implementing every solution that might not even be appropriate or situationally functional in the real world, would be highly time consuming and expensive process. A much more direct and efficient method is to “explicitly envision and document significant user activities” (Carroll, 2000, p. 1) through task-based scenarios and then define specific solutions based on the situational context and user requirements in performing that particular task.

Scenarios are salient descriptions of how to execute specific tasks (Potts, 1995) in the form situational stories with a specific plot (Carroll, 1999). Every scenario comprises of an agent (user) interacting with the system with a specific goal, some abilities and in a certain context, performing certain action or set of actions in order to achieve that said goal. Specificity of the task and contextual background of the story affords scenarios to invoke reflection on user behavior and approach in terms of using the system, allowing resolution of interaction problems within the interface from a user-experience perspective. Storyboards or visual mockups are often used to
describe user scenarios; using either textual or graphical mediums or both (Alsumait, 2001; Rosson & Carroll, 2002).

Storyboards are often referred to as “presentation scenarios” (Maguire and Bevan, 2002, p. 7): representing user behavior and task description through sequential frames of discreet events using either graphics or textual narrations. Mockups on the other hand are low-level representations of the system itself, reflecting general design concepts and details like screen layouts, visuals, colors, icons and controls, without providing any actual interactivity or navigation capability (Alsumait, 2001; Rudd et al., 1996).

4.6.1 Scenarios:

As already described, there are two main ways building operators are informed of any maintenance, repair or operational optimization issues at UBC. The first one is through BMS generated alarms – which we discussed and demonstrated above, the second is through occupant trouble calls and field issued Request for Information (RFI). It is important that a BMS interface successfully executes all and any investigative, monitoring and control requirements presented to the operators, either through system generated alerts or through user prompted trouble calls. The first two scenarios would demonstrate iPViz’s visualization and interaction features that building operators can use to understand, analyze and control building performance in response to faults detected by the system and an occupant, respectively. The third scenario would demonstrate how iPViz can be proactively used to monitor, analyze and optimize building performance by providing context-aware information in a high-fidelity 3D visualization.
Figure 4.21 - Storyboard showcasing user's interactions with the iPViz interface as static frames based on the hypothetical “Alarm Scenario”
4.6.1.1 Scenario – 01: The Alarm Scenario

Bill is a BMS Manager at UBC Building Operations, currently assigned to look after operational aspects of the CIRS building. CIRS is a state-of-the-art modern high-performance building where almost all building systems are automated and operational aspects are usually managed and controlled through a stand-alone Building Management System (BMS). While out of office Bill receives an email alert notification from the BMS system notifying temperature increase in the CIRS lecture theatre. The fault detection and diagnostic algorithm of the BMS, detected the problem to be a malfunction in the fan coil valve control, but did not describe whether it is a hardware or software issue. Bill is quite familiar with the CIRS building systems but cannot tell from the alert what might cause the valve control to malfunction and needs to further look at the data to make some sort of decision. He has his office on the 3rd floor of the south wing of the CIRS building, from where he can access the iPVic BMS front-end interface on his Operator’s Station computer. Bill opens the software and is directed to the front page of the interface. He can see all the alarms displayed in the central information panel along with other information, Figure 4.22. He pauses to see if he can find the alarm that he got the email about but could not find it immediately and realized that the alarms were arranged by type; probably by another user since the system can be accessed remotely by other building operators. He changes the filter by date and saw the alarm on top of the list, being the most recent one, Figure 4.23. He wants to know if the valve turned off due to any temperature changes in the supply air and reads through the alarm card but found the data to be normal. He quickly browses over the other panel to see what is the outside conditions are like and if it has anything to do with this alarm, Figure 4.24.
Figure 4.22 – (1) InfoRev screen with all the alarms info cards, as viewed by Bill

Figure 4.23 – (2) Bill using the filter to sort alarm cards by priority
Not finding anything abnormal he clicks on the alarm, Figure 4.25, and is prompted to login before the system lets him in, Figure 4.26. Once logged in, the system directly shows a 3D layout of the lecture theatre, with the fan coil unit, relevant ducts and other sensors highlighted in the view, Figure 4.27. Bill looks at the information card displayed next to the fan coil unit, showing that the FC_01 controller is turned off but the BMS programmed command for the controller is displayed as “On”, signifying that the problem is probably hardware and not software programming. Bill can also see that the fan supply air temperature is much higher than the AHU supply air temperature, understandably because the coil is turned off.
Figure 4.25 – (4) Bill selects the alarm card, a location pop-up briefly appears giving an overview of the location of the building.

Figure 4.26 – (5) The system prompts Bill for a login before he can access the Information Visualization (InfoViz) screen.
Just to be sure, Bill enlarges the AHU information card showing control schematics, which was already displayed by the interface due to its contextual sensitivity to the alarm query, Figure 4.29. Everything looked fine at the AHU. Bill quickly clicks through the temperature and humidity sensors to see what is the comfort conditions are like in the lecture theatre, Figure 4.29. The temperature sensors show higher temperatures than the set point. He can see from the occupancy sensor that the lecture theatre is mostly unoccupied, with 3 or 4 people in it; currently no scheduled class but there is a class due later today.
Bill again looks at the fan coil unit information card and clicks on the trends to see what happened, Figure 4.30. The trend shows that the fan coil unit was working normally last 4 days, with the trend line dropping today. Still not able to understand the fault, Bill opens the logs to see if there was any information there. There was a note there by Arthur, one of the field technicians, on 5th May 2015 that the temperature gauge in the fan coil unit is due calibration by 2nd June 2015, Figure 4.31. Bill immediately understands that the gauge must have malfunctioned given it was three-week overdue calibration. Bill clicks on the documents tab and clicks on the “+” sign to show a pull out menu from which he selects “work order” and fills in the details and submits it. Couple of seconds later he gets an email, confirming that the work order has been issued and distributed to the relevant personnel, with the confirmation email being sent to Bill.
Nota bene.: The system automatically detects from the work order request that the alarm has been responded to and changes the alarm category from “high priority” to acknowledged. Once the valve is calibrated and the system detects that FC01 is functioning normal, it would archive the alarm into completed. The completed alarms can be viewed by the operators by choosing the archived option in the alarm tab of any component, sensor or system’s information panel.

Figure 4.29 - (8) Blow-up view of the information displayed on the temperature and occupancy sensor as viewed by Bill during his investigation of the alarm.
Figure 4.30 - (9) Bill checks the trends to understand the changes in the fan's operational performance over the duration.
4.6.1.2 Scenario – 02: The Trouble Call

In this scenario, I would attempt to demonstrate additional features of iPVis interface, by analyzing the same above described problem, but when it is reported by an occupant rather than detected by the BMS’s FDD algorithm, Figure 4.32.

Bill is a BMS Manager at UBC Building Operations, currently assigned to look after operational aspects of the CIRS building. CIRS is a state-of-the-art modem high-performance building where
almost all building systems are automated and operational aspects are usually managed and controlled through a stand-alone Building Management System (BMS). While out of office Bill receives a call from his colleague at Building Operation’s MACC, telling him that they received a trouble call yesterday regarding high temperature in the lecture theatre. The call was made by a student, who did not have access to the PeopleSoft® service request system, so Bill might be unaware of the issue. The data has now just been entered by one of Building Operation’s staff.

Upon reaching his office Bill opens the iPVic BMS interface on his Operator’s Station computer. The Information Review (infoRev) screen of the interface displays all the alarms and alerts including trouble calls in the central information panel, that have been issued in regards to CIRS’s O&M works, Figure 4.33(1). He can see the alarms displayed and quickly finds the trouble call info card flashing on the top. He drags one of the corners of the card to zoom it and reads the description of the trouble call. He clicks on the link icon to open the original information form from the PeopleSoft® service request and sees that the request was made by someone around afternoon, requesting cooling in the lecture theatre since it was too hot in there, Figure 4.33(2). Bill clicks outside to zoom out the card and then clicks on the card itself. He is prompted to login and once he enters his credentials, the system displays top perspective view of the lecture theatre, Figure 4.33(3).
Figure 4.32 - Storyboard showcasing user's interactions with the iPViz interface as static frames based on the hypothetical “Trouble Call Scenario”
Figure 4.33 - (1) The main infoRev screen showing the trouble call alarm (flashing) at the top with the filter selected by date, (2) The original PeopleSoft® service request and expanded trouble call info card as displayed on iPViz infoRev screen, (3) The login prompt upon clicking the trouble call info card.
He can see that the temperature readings show that the internal temperature is within the set point, though very close, Figure 4.34(4). He looks at the occupancy sensor data and sees that the lecture theatre is mostly unoccupied at the moment except for 3-4 people but has a class scheduled later in the day, Figure 4.34(5).

Figure 4.34 - (4) iPViz interface display of Lecture theatre cut away in the infoViz screen showing the red color coded fan coil unit as well as associated Air Handling Unit AHU-02 with associated sensor information cards. (5) The blow-up shows Bill's interaction with the sensor info cards.
Figure 4.35 – (6) The blow-up shows Bill’s interaction with the date picker menu, to view yesterday’s performance information. (7) The blow-up view of the InforViz screen displays performance information of 20th July 2015, a day back from Bill’s investigation time. (8) The blow up shows the “real time” button Bill interacts with to go back to the real-time performance visualization.
Bill selects yesterday’s date in the date panel, Figure 4.35(6) and looks at the information cards from yesterday, which shows that the temperature was quite high during the class, Figure 4.35(7). He comes back to real-time view, by clicking the “real-time” icon, Figure 4.35(8) and checks the AHU info panel to see if there is a problem with supply air temperature but everything checks out, Figure 4.36.

![Image](image_url)

**Figure 4.36 - (9) The view of the AHU-02 status and control information as displayed by the iPViz infoViz screen, along with the blow of the information displayed within the controls tab.**

He quickly browses the dependency graph at the bottom to see the status of the connected components and sensors, Figure 4.37(a) (10). He zooms the dependencies associated with the
AHU-02, Figure 4.37(b) (10) and finds that valve switch on the fan coil unit is shown as “Off” while the command by the BMS is still “On”, Figure 4.37(c) (11). He clicks on the dependency, which highlights the fan coil unit on the 3D display. Bill goes over the information on the info card which also shows that the valve control is turned off, Figure 4.37(d) (10). Bill opens the trends which showed a decline in the fan coil performance and a progressive hike in the temperature four days back, Figure 4.38(12).

Still not sure about the sudden decline in the fan coil unit’s performance, Bill opens the logs to see if someone changed command parameters, Figure 4.39(13). There was a note there by Arthur, one of the field technicians, on 5th May 2015 that the temperature gauge in the fan coil unit is due calibration by 2nd June 2015. Bill understands that the gauge must have malfunctioned given it was three-week overdue calibration.
Figure 4.37 – (10) The zoom-in view of dependency graph as displayed in the iPViz infoViz screen; (a) the normal view of the dependency graph; (b) blow-up view of the toolset available to the users for interacting with the dependency graph nodes; (c) blow-up view of the information displayed in the dependency nodes and Bill’s interaction with the FC_Ctrl node, shown by the node highlighting; (d) Fan Coil info card displayed upon Bill’s interaction with the dependency node in (c).
Bill calls Building Operations and asks them if they already procured for the valve switch calibration since the note by Arthur was shared with the BOps personnel. He is informed that he needs to issue a work order request in order to get the calibration since it was not done before based just on the note. Bill clicks on the documents tab and clicks on the “+” sign to show a pull out menu from which he selects “work order” and fills in the details and submits it. He gets a confirmation that the work order has been placed.

Figure 4.38 - (12) Fan coil performance information displayed by the iPViz interface as trends as a time-series graph.
Figure 4.39 - (13) The change log information as viewed by Bill through the “logs” tab in the information card of the fan coil unit.
Figure 4.40 - Storyboard showcasing user's interactions with the iPViz interface as static frames based on the hypothetical “Proactive Performance Monitoring Scenario”
4.6.1.3 Scenario – 03: Proactive Performance Monitoring

As iterated throughout the thesis, the main objective of proposing an integrated performance visualization interface is to understand how various interrelated functional aspects influence the performance parameters and if providing spatially contextual visualization could enhance their understanding, hence facilitating O&M decision-making process for building operators. In this scenario, I attempted to demonstrate how iPViz can be used to proactively monitor, understand and control various building performance parameters and how it can enhance building operator’s understanding of building behavior within a spatial environment, Figure 4.40.

As part of the new proactive maintenance program at UBC, Bill monitors different building operational functions at CIRS every Thursday morning, so that if he needs to optimize or repair something, he can do it on Friday and that the new week starts without any glitch. Bill opens the iPViz interface on his Operator’s Station (OS) computer and logs into the system, Figure 4.41(1).

![Figure 4.41 - (1) InfoRev screen of iPViz interface, with the login panel on the right corner of the title bar](image-url)
He had already gone through the alarms and trouble calls in the morning and just wants to look at how other systems in the building are performing at the moment. The system opens with a complete 3D building view, showing Bill the overall performance parameters of the whole building including system, energy, occupancy and comfort performance, Figure 4.42(2). Bill skims over the system performance to see if all major systems are functioning properly and if there is any major energy usage anywhere. In the energy information card, he sees that highest energy consumption in the building is being reported at second floor (Level-02) and that too from the user plug loads.

Figure 4.42 – (2) The first view of the iPViz InfoViz screen displays a rendered 3D graphic of the building along with the info cards of building level performance summary; the inset blow-up shows CIRS monthly energy performance summary.
He decides to investigate this surge and clicks on the second floor tab in the menu. The menu drops down to show all the monitored spaces at Level-02, whereas the 3D now shows the energy consumption levels per floor, Figure 4.43(3). This has been previously pre-set by Bill himself, so that the interface shows energy information as default display. He sees from the information card that North-wing of the floor is using the highest electrical energy across the entire floor.

Figure 4.43 – (3) Floor level information displayed in the infoViz screen upon selection by Bill. The blow-up shows the information displayed on the 2nd floor energy info card, where Bill can see that the zones in the north wing of the building are consuming more energy as compared to those of south wing.
Bill selects the second floor tab and the 3D visualization displays a perspective top-cut sectional view of the building at second floor, Figure 4.44(4). He can see from the view that the north wing is currently occupied by some students and they have also opened some of the windows.

Figure 4.44 – (4) InfoViz displays 2nd Floor top as a top view cut away perspective, with info cards displayed of the major components and sensors as per the graphical context (visibility). The blow-up inset shows the info cards of light systems, occupant, temperature and window opening sensors of the north section of the CIRS 2nd floor.
He uses the scroll on his mouse to zoom-in on the north wing, Figure 4.45(5a) and selects the supply air duct to see if the ventilation system is on, Figure 4.46(5b). The information card shows that supply air is turned off at the moment because the windows were opened an hour ago. He looks over to the weather info card and sees that weather outside is a bit chilly and yet someone has opened the windows. Odd as it is, he still wants to know what is causing such high energy usage in this area, he can see from the graphics that only the occupied portion of the lights are turned on and the info card for the lights is showing usual energy consumption, Figure 4.46(5b). He further zooms in and is prompted by the interface with the notification if he would want to take an eye-level view of the area, which he chooses.

Figure 4.45 – (5a) Zoom-in view of the north wing of the 2nd floor, with contextually more detailed information shown by the iPViz interface
Now he can see the space from a first person perspective and can immediately see that the plug sensor on the right hand side desk is reporting a very high level of energy consumption with the indication that an external device is connected, Figure 4.47(6). Someone might be testing an equipment, which he decides to inquire about later. Sorting this out, he turns the furniture layer off, for the space by right clicking a furniture article and opting to switch off the layer, Figure 4.48(7). He observes that because of the windows open, lower outside temperature and space being occupied the floor heaters are turned on, where the sensors detected occupants. Though, the internal temperature of the space still is below set point; he might have to go and ask the students to shut of the windows for a while. He checks the south wing, where things pretty look normal. He
shuts off the computer and goes off to see what the students have plugged in that is consuming that much energy, which he found to be some sort of experiment being conducted that uses outside air and tries to measure volatile organic compound that may infiltrate into the building. That is why the windows were open at that point.

Figure 4.47 - (6) Eye-level view of the north wing from its entrance. More detailed info cards are visible in context of the graphic. Blow-up inset shows the plug load info card as viewed by Bill
Figure 4.48 – (7) Bird's eye view of north wing with the furniture layer off and heating system selected from the filters. In the blown-up inset, iPViz displays contextually relevant information of the heating system; radiators with varying level of detail as per the visibility of the displayed graphics.
4.7 **Summary:**

In this chapter, I identified various discrepancies that exit in current building and EIMS by analyzing the results of the case study research, complimented by the lessons learned from the literature review. The identified problems were categorized into visualization and interaction related aspects based on how the current BMS interface addressed different building performance related issues. The proposed vision of a performance visualization interface is based on collected information from otherwise highly data intensive systems, and integrating it into a central data repository. To preserve rigor, I briefly explored the feasibility and practicality of such a system using currently available state of technology. Advancements in data collection, mapping and exchange protocols and a progressively developing penchant of construction industry toward integrating BIM into facility management and O&M functions provides solid technical base for the proposed vision. Although, given the current state of information fidelity of CIRS BIM, I had to make few assumptions that such technological infrastructure is available at the time of this research.

Given the complexity of technological systems and sophistication of collecting, structuring and mapping data from several sources; implementation and evaluation of the envisioned system is out of scope of this research work. However, I attempted to showcase the concept and the need of such a system by developing a medium-fidelity mockup of the visual and interactive features that address many of the problems identified through the case study. I summarized the concepts and intentions behind different design decisions in structuring and visualizing the information in the proposed interface. To eliminate information-overloading and reduce cognitive loads in trying to
find relevant information, the interface was designed with only two main visualization screens, accessible to building operators with varying level of authorization. Different solutions presented in each screen of the mock up interface were illustrated through graphical examples and snapshots, describing how the interface would visually and interactively present the information to the building operator. For example, 3D graphical static images from CIRS Building Information Model were used with dynamic transparencies and color codes to illustrate integration of 3D geometry from BIM and various visualization responses to user interactions with the model.

In the proposed interface, I attempted to address two core issues that were observed throughout the literature review and case study, i.e., segregation of energy and system performance information and lack of context – spatial or otherwise, in visually representing performance information for O&M works. I attempted to address the segregation of energy and system level information by associating energy consumption information at object level. This meant that performance information of every system, component or sensor would include energy consumption information, providing building operators better understanding of how that element is physically performing as well as its contribution in overall energy footprint of the building. The second core issue was addressed primarily by integrating BIM’s high-fidelity geometric model with the data collected from other information sources like BAS, CMMS, etc. Secondly, I envision the system to provide relevant information based on the context of the graphical setting as well as the nature of the query being investigated by the building operator through the interface. I designed the mock up interface screens specially the information visualization (InfoViz) screen to utilize and demonstrate this concept in its entirety. Visualization techniques like linking and brushing
(Becker and Cleveland, 1987; Kiem, 2002; Ware, 2004) were used to demonstrate this concept throughout the interface features.

I further explored the concept of providing contextually relevant information to building operators at all instances by using dedicated dependency graph in my interface mockup. The dependency graph is designed to present all building elements and their most basic information like IDs, status or alarms in the form of nodes, with each node residing in an individual panel representing location of building elements with respect to different floors. Each node is connected to different elements representing spatial and physical dependencies that exist between a building’s spatial and equipment hierarchies. Every interaction, manipulation within the 3D graphics is also represented in the dependency graph and vice-versa, intended to give building operators a grounded context of the situation at all times. The basic intention is to facilitate building operators through the interface by providing different variations of on-demand information. A highly data enriched 3D graphical representation has the potential to be cognitively overwhelming at times. Although I attempted to reduce such overloading by consolidating information in sand boxed cards, however, it is impossible to eliminate information overwhelming that is by nature characteristic in a 3D visualization. In such situations, dependency graph nodes can provide building operators a guiding point in finding and contextually analyzing relevant performance information.

In lieu of implementing and evaluating the interface, I presented various performance monitoring and controlling features of the iPViz interface through real world inspired task-based hypothetical scenarios. The scenarios were specifically designed to illustrate and emulate, a building operator’s interactions with the system to investigate, analyze and understand operational issues as well as
the proposed system’s ability to off load cognitive load from the user by providing on-demand as required information.
Chapter 5: Summary and Conclusion:

This chapter includes a summary of my research study, case study findings, lessons learned and the vision behind the proposed interface concept. In the following sections, I would briefly discuss content and findings from each chapter and they informed the direction of the research outcome.

5.1 Summary:

The main motivation for the research came from an observation that most modern high-performance buildings – even LEED-certified buildings, with integrated advanced automation and building management system, are not performing as well as their design intent (Newsham et al., 2009; Turner & Frankel, 2008; Scofield, 2009). During the discourse of my research, I found that this performance disparity in modern buildings, among other reasons, may be attributed to a lack of continuous monitoring and performance optimization practices during the operational lifecycle (Newsham et al., 2009). The problem in this regards, was found to be two-folds; first, most high-performance building automation and management systems (BAS, BMS) are so complex and provide purely analytical data, that it’s hard for building operators to understand the building behavior holistically and they may have to depend on field inspections and other sources of information to make informed decisions (Hailemariam et al., 2012; Akcamete et al., 2009). Secondly, the information required by the building operators is either scattered across different

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44 Other reasons may include an apparent industry-wide inattention toward Facility Management (FM) and building Operation and Maintenance (O&M) processes (Sucaar, 2009; Gallaher et al., 2004; Clayton et al., 1999), slow adaptation rate of established technological systems (Froese, 2009),
data sources (BMS, CMMS, IWMS, DMS\textsuperscript{45}, data archives, etc.) or is missing/unavailable or is not updated to represent the existing conditions of the building (design or construction only drawings, outdated manuals, etc.). Further, the analytical data presented by the BMS is without any reference to the spatial or relational context of the object or the information being presented, adding further confusion to an operator’s already cognitively intensive task of understanding the data.

Building Information Modeling; with its high-fidelity 3D geometry, semantic richness, information integration across lifecycle (Succar, 2009; Irizarry et al., 2014; Nepal et al., 2008), presented itself as the best potential solution for integrating and visualizing O&M semantic information in a spatially contextual environment. Through my research work in this thesis, I wanted to explore the potential of using BIM to develop a unified performance visualization interface, by integrating and mapping semantically rich data from other O&M sources onto its high-fidelity 3D geometry.

To further investigate the intricacies involved in such an integrated system, identify related state-of-the-art and to base my proposed interface solutions on grounded theories and established academic work; I carried out an exploratory review of the available relevant literature. This exploration was part of the main research objective to collect, review and present relevant literature that addresses integration and development of novel visual interfaces for building automation and management systems. Through a preliminary analysis, I identified four main academic domains that were most relevant and overlapped with my research focus: Building O&M, Building

\textsuperscript{45} CMMS: Computerized Maintenance Management System; IWMS: Integrated Work Management System; DMS: Document Management System
Performance and Visualization, HCI and BIM. An in-depth review of these research areas provided an opportunity to understand established theories, processes, and frameworks that relate to my research work. It also allowed an insight into more discreet knowledge areas like ambient intelligent, human cognition and perception, immersive realities and user-experience design, which was quite valuable in expanding my knowledge of various other nuances involved in an interface design. Lessons learned led to the development and refinement of many of the interaction and information visualization solutions that are presented in this thesis.

To understand O&M practices especially in the context of using BMS to monitor, analyze and control building performance information, I conducted a case study at a high-performance academic building (CIRS) at UBC. Through this case study, I wanted to understand; how building operators use and interact with the BMS in their daily routine works, what prompts such interactions, what is the level of information available in the system, how that information is presented to the building operators and to what extent it facilitates their understanding of the concerned performance scenario. To get answers to these questions, I documented the prevalent O&M practices by collecting data in two phases. In the first phase, I collected qualitative data of routine work practices by shadowing building operation personnel, informal interviews, discussions, and review of relevant documents. This was done at the campus level to understand the organizational setup and overarching goals, common work practices, available BMS, information requirements and performance management processes at a higher level and how they are distilled at the building level. From this initial study, I was able to identify the segregated nature of performance management at UBC; with different organizational teams monitoring and controlling energy and system related performance information using multiple displaced
management systems. In the second phase of my research case study, I focused specifically on the O&M practices in the context of using BMS at CIRS. I collected data regarding building operator's interaction with the BMS, information availability, adequacy and accuracy, the influence of the tool in the decision-making process, BMS interface features, etc., by shadowing a BMS expert, contextual inquiries of his routine work, and formal and informal interviews of building operations personnel. A user-survey was also carried out to preserve the rigor of the research process and to support the qualitative findings further with a more objective data.

Since the research discourse revolves around information visualization and integrated interfaces, the collected data was analyzed from a human information processing (Norman, 1976) perspective, using established HCI interface usability heuristics. Several overlapping and interrelated discrepancies were identified and grouped into two categories: 1) Visualization related issues and 2) issues related to user's interaction experience with the system. In addition to these discrepancies, two core issues were highlighted based on the lessons learned from the study: lack of spatial context and segregation of energy and system performance metrics.

The findings from the data analysis as well as the lessons learned from the literature review and my own observations during the discourse of the research study presented a very strong case toward exploring integration potential of a high-fidelity visual and information-rich platform like BIM with the performance monitoring and control capabilities of a building management system. Using BIM would provide a spatial context to the performance information as well as reduce the experiential gap between abstract (data) and tangible (physical) aspects of the building elements. Given the complexity of the system, information mapping and communication mechanism and
technical aspects involved in implementing such a system, I only developed a medium-fidelity mockup of my proposed interface design.

To demonstrate the potential use of BIM, I used the existing BIM model of CIRS and extracted static images of the building geometry to mock up the interface features using BIM visualization. Lessons learned from the literature review were instrumental in informing the design choices for the interface mockup. I designed the proposed interface to reduce as much information-overloading as possible by consolidating and presenting all the relevant performance data in an information card form. This design strategy was carried on across all the interface screens to provide performance data. A combination of high-fidelity 3D visualization and 2D graphical representation is used to provide spatial context to otherwise visually separated analytical data. Interactions were designed to minimize any perception disparity as well as to distribute cognition between the interface and the user, e.g., techniques, like linking and brushing (Kiem, 2002) were used to provide a unified display of information across all the interface panels.

Although evaluation was not part of the scope of this thesis, I did a quasi-self-evaluation of the designed visual and interactive features in the proposed interface against the findings from the study of current BMS system interface at CIRS. The proposed interface was successfully able to compensate for all the discrepancies that were observed in the analysis. Said that, the proposed interface is designed with the intention of providing a context-aware situation to building operators from a whole building perspective, whereas current BMS system provides a more equipment focused information and control capabilities to the operators. In the proposed interface, the operator may have to search for a specific equipment since the equipment is placed as a sub-hierarchy of space - though this effort is as cognitively simplified as possible, whereas in the
current system he has direct access to an equipment controls. These trade-offs are highly common in any design innovation and address to exceptions rather than generalized experience.

5.2 Future Work:

An obvious discourse after this research is to further develop and implement the interface using actual information sources and Building Information Models. This would highlight the amount of work and resources required to develop and furnish BIM models with the level of detail and associated information that is required to achieve the comprehensiveness and contextual awareness of the current model. Further research might also be required to explore and develop data mapping and integration structures as well as communication protocols that would allow a bi-directional mapping and manipulation of information from several different information management sources.

Evaluation of the implemented system would provide valuable insight to the most basic of the questions, whether such an integrated 3D graphical system is even required across the board by expert users. Or if integration of BIM would even provide the foreseen advantages in understanding building performance information and operational functions. It may also highlight various other facets of user’s interaction and information abstraction requirements currently unexplored due to unavailability of such systems. These new facets may instigate further exploration and research of Human-Computer Interaction (HCI) and visualization techniques.

Visualization techniques like augmented and virtual reality (AR and VR) (Golparvar-Fard & Peña-mora, 2007; Lee & Peña-mora, 2006; Irizarry et al., 2015) may also be explored to provide building operators a more immersive and real world experience in understanding building behavior, identifying performance patterns and optimizing operational issues based on more accurate data.
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