UNDERSTANDING THE PERFORMANCE GAP:

AN EVALUATION OF THE ENERGY EFFICIENCY OF THREE HIGH-PERFORMANCE BUILDINGS IN BRITISH COLUMBIA

by

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Abstract

The market shift towards high-performance buildings has been brought into question by growing concerns about the actual energy efficiency of these projects. Research studies have been pointing increasingly to performance gaps between the predicted (or modelled) and actual (or measured) energy consumption of certified 'green' buildings. Discussions about reasons for performance gaps have been recurring in the building industry and research alike.

This thesis investigates the energy performance gap of three high-performance LEED-certified buildings in British Columbia: the Centre for Interactive Research on Sustainability (CIRS), the Jim Pattison Centre of Excellence in Sustainable Building Technology and Renewable Energy Conversation (JPCE) and the District Education Centre (DEC). For each case study, an energy performance evaluation reveals differences between modelled and measured energy consumption. Based on an extensive literature review, the reasons for identified performance gaps are explored through expert interviews with key stakeholders that were involved in the design, construction or operation of each of these projects.

The energy performance evaluation reveals significant performance gaps in all three case studies, with one project out-performing and two under-performing the design predictions. The research highlights a lack of consistent metered-energy data at the system level. Based on these findings this study attempts to evaluate key sources of performance issues, in the context of the three case-study buildings. It shows that performance-gap reasons indicated in the literature occurred at all phases of the building lifecycle: starting at the planning/design and modelling phase, through the construction, commissioning and handover phases, to the building operation and occupancy phase. The results suggest that performance gaps are closely related to shortcomings in energy design concepts, development procedures, and operational practices that were applied in the three buildings.

The research emphasizes the importance of creating a greater transparency of development procedures and collaborative approaches to successfully design, build and operate high-performance buildings. The challenges faced by project teams to integrate innovative technologies calls for robust design solutions and methodologies that can be easily translated into implementation strategies and operation procedures that meet building management capacities.

Preface

This research was approved by UBC Behavioural Research Ethics Board, Certificate number H14-00666 and Project Name 'Building Performance Evaluation of Leading Canadian Green Buildings'.

Portions of Chapter 3 are based on work conducted as part of a collaborative research and development (CRD) project. The project was initiated by iiSBE Canada and implemented by researchers from the University of British Columbia, the University of Manitoba and Ryerson University, with support by Stantec and the Natural Sciences and Engineering Research Council (NSCRC). The UBC graduate student Ghazal Ebrahimi and Anne-Mareike Chu were responsible for collecting energy performance data and occupancy data among other performance data. I took the main responsibility to collect and evaluate energy performance data and occupancy data. Dr. Belgin Terim Cavka provided metered energy consumption data for the CIRS building. Rob St. Onge, Energy Manager of Okanagan College, provided access to energy consumption data for the JPCE building. Mark Tabet, Energy Manager of the Surrey School District, provided energy data for the DEC building with the consent of building owner representatives. Guidance for the project was received from Dr. Mark Gorgolewski, the principal investigator of the project, Dr. Murray Hodgson, Dr. Shauna Mallory-Hill, and Dr. Mohamed Issa. The results of this study are published as:

1. **Chu, A.**; Ebrahimi, G.; Scannell, L.; Save, P.; Hodgson, M.; Bartlett, K.; Terim Cavka, B., 2015, "Building Performance Evaluation for the Centre for Interactive Research on Sustainability", iiSBE Canada Report, iiSBE Canada, Toronto, Canada, January 26th, http://iisbecanada.ca/umedia/cms_files/Report_-_CIRS_Final_May_2015.pdf

2. **Chu, A.**; Ebrahimi, G.; Scannell, L.; Save, P.; Hodgson, M.; Bartlett, K.; Gorgolewski, M., 2015, "Building Performance Evaluation for the Centre for Jim Pattison Centre of Excellence in Sustainable Building Technologies and Renewable Energy Conservation", iiSBE Canada Report, iiSBE Canada, Toronto, Canada, January 26th, http://iisbecanada.ca/umedia/cms_files/Report_-_JPCOE_Final_Feb2015.pdf

3. **Chu, A.**; Ebrahimi, G.; Scannell, L.; Save, P.; Hodgson, M.; Bartlett, K.; Gorgolewski, M., 2015, "Building Performance Evaluation for the Surrey District Education Centre",

iiSBE Canada Report, iiSBE Canada, Toronto, Canada, January 30th, http://iisbecanada.ca/umedia/cms_files/Report_-_DEC_Final_Feb2015.pdf

4. Bartlett, K.; Brown, C.; **Chu, A.**; Ebrahimi, G.; Gorgolewski, M.; Hodgson, M.; Issa, M.; Mallory-Hill, S.; Ouf, M.; Scannell, L., 2014. "Do Our Green Buildings Perform as Intended?", World Sustainable Building Conference, Barcelona, Spain, October 28-30, http://iisbecanada.ca/umedia/cms_files/Conference_Paper_1.pdf

As part of the CRD project, Sylvia Coleman conducted six out of nineteen expert interviews that were utilized in Chapter 4 of this thesis. I conducted the remaining fifteen interviews. Dr. Leila Scannell, Dr. Craig Brown, and Sylvia Coleman provided key insights into the development of interview questions. Dr. Lisa Westerhoff helped with the framing of reasons for performance gaps. Portions of the occupancy and operation data were collected by UBC graduate students Ghazal Ebrahimi and Anne-Mareike Chu and Dr. Leila Scannell, UBC post-graduate student at the time, as part of the CRD project. I was mainly responsible for collecting the occupancy data for the CRD project and re-evaluated the data for the purpose of this research.

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AHU	Air Handling Unit
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BMS	Building Management System
BOMA	Building Owners and Managers Association
BPE	Building Performance Evaluation
BREEAM	Building Research Establishment Environmental Assessment Methodology
CBIP	Commercial Building Incentive Program
CDD	Cooling Degree Days
CIF	Canada Foundation for Innovation
CIRS	Centre for Interactive Research on Sustainability
DCV	Demand Controlled Ventilation
DDC	Direct Digital Control
DEC	District Education Centre
DHW	Domestic Hot Water
DIP	Dual In-line Package
ECM	Energy Conservation Measure
EE4	Energy Evaluation software version 4
EUI	Energy Use Intensity
EOS	Earth and Ocean Science
HDD	Heating Degree Days
HVAC	Heating, Ventilating, and Air Conditioning
IDP	Integrated Design Process
IEA	International Energy Agency
IES	Integrated Environmental Solutions
iiSBE	International Initiative for a Sustainable Built Environment
IPD	Integrated Project Development
IPMVP	International Performance Measurement and Verification Protocol
IT	Information Technology

JPCE Jim Pattison Centre of Excellence in sustainable building technologies and renewable energy

LEED	Leadership in Energy and Environmental Design
LEED NC	Leadership in Energy and Environmental Design New Construction
MNECB	Model National Energy Code for Buildings
M&V	Measurement and Verification
MWh	Megawatt hours
NSERC	Natural Sciences and Engineering Research Council
POE	Post Occupancy Evaluation
PROBE	Post-occupancy Review of Building and their Engineering
PV	Photo Voltaic
RFP	Request for proposal
UPS	Uninterruptable Power Supply
USGBC	United States Green Building Council
VE	Virtual Environment
VOC	Volatile Organic Compound

Glossary

Active chilled beam system – A type of HVAC system that uses convection of air to heat, cool and ventilate buildings. An active chilled beam system induces air from the space into the chilled beam where it is mixed with fresh incoming (or primary) air and released to the room.

Actual energy performance – The energy consumption of a building that is recorded through energy meters once the building is occupied (also see energy metering).

Air handling unit (AHU) – A part of the heating, ventilation, and air conditioning (HVAC) system, which regulates and circulates air in a building.

BOMA BEST – A Canadian green building certification program that was launched by the Building Owners and Managers Association (BOMA) Canada in 2005 (also see Green Building Certification Program).

Building commissioning – A process that verifies building systems, including the building structure, plumbing, mechanical and electrical systems, as well as fire and safety systems.

Building energy modelling – A process of creating a computer model of a building design to estimate the operational energy consumption per year. Generally, specialized software is used to generate a detailed estimate of the predicted energy consumption of the building.

Building energy rating – A rating system that evaluates the energy efficiency of a building and represents the energy performance through ranked categories.

Building handover – Process that describes the completion of the building construction and the handover to the client (i.e. owner and building managers). The handover process includes meetings following a site inspection, in which building documents and manuals are handed to the client.

Building management system (BMS) – A computer-base control system for a building that controls and monitors major electrical and mechanical systems including heating, ventilation, air conditioning and lighting.

Building occupancy – The number of people that are counted in a building room or area at a certain time. In this study occupancy is referred to as the number of occupants in a building and the hours of operation that building systems are turned on and running.

Building operation – The day-to-day process of operating building systems and facilities, including heating, ventilation, and air conditioning (HVAC), lighting, domestic hot water, and building control systems. This often also includes building maintenance such as replacement of equipment, energy conservation, and implementation of new building programs.

Building Research Establishment Environmental Assessment Methodology (BREEAM) – The worlds longest established green building rating and certification tool that was developed in the 1990 in the United Kingdom (also see Green Building Certification Program).

Closed-loop geo-exchange system – A heat pump system that uses a fluid, which is circulated through the ground in a continuous loop back to the pumps, to extract heat from or inject heat into the ground.

Compliance energy model – A building energy model that is used to compare the building design to other energy-efficient projects in a geographical location. The compliance energy model is generally done after the design and based on final design drawings to model the proposed design.

Contextual variable – In this study, a variable that is defined by the local context of the building, which can include site/soil conditions, existing infrastructure, and climate conditions on site.

Daylight sensor – A light sensor, also referred to as dimming control that adjusts artificial light levels without turning them off based on natural light levels.

Demand controlled ventilation (DCV) – A control system that automatically adjusts a ventilation system to meet occupancy demands. Common control systems are timed schedules and sensors such as motion or gas detection (e.g. CO_2) sensors.

Design-assist building model – A building energy model that uses local geographical information and climate specific requirements to assist the design of the building throughout the design process.

Design charrette – An intensive planning session, in which stakeholders collaborate on developing a design vision for a building. It allows every participant to be equally involved in the plan.

Direct digital control (DDC) – A computer controlled automated process or condition, often used for controlling building systems such as the HVAC system.

Displacement ventilation – A room-air distribution system that provides conditioned outdoor air at a low velocity through diffusers located near the floor level. Air is generally extracted from the room near the ceiling.

Energy conservation measure (ECM) – A project part or technology that helps to reduce the energy consumption of a building. The measures can have an impact on resources such as electricity and gas consumption.

Energy metering – A process in which the energy consumed by a building (i.e. electricity, natural gas, heat) is electronically recorded in real time.

Energy performance gap – The discrepancy between the predicted energy consumption of a building (at the design stage) and the actual (or metered) energy consumption after project completion.

Energy use intensity (EUI) – A metrics that expresses the energy use of a building as a function of size or other characteristics, and time. In this study the energy use intensity is calculated by dividing the total energy consumption of a building in a year (measured in kilo Watt-hours, short kWh) by the total gross floor area of the building (measured in square-meter, short m^2).

Environmental assessment – The assessment of short-term and long-term effects of a project on its environment. This process includes ways to mitigate and minimize environmental effects or compensate the impacts.

Fast-track construction – A project delivery strategy in which building construction starts before the completion of the design stage.

Four-pipe fan coil system – A water distribution system that serves climate control equipment in a building. The system has two supply pipes and two return pipes, which allow the system to provide hot water or cold water to units in the building at the same time. As such, different zones in the building can receive cold water for space cooling, or hot water for space heating, simultaneously.

Geo-exchange system – An electrically powered heating and cooling system for interior spaces that utilizes ground (or pond, well water) as heat source and heat sink. It consists of a heat pump, hydronic pump, ground heat exchanger, and distribution system.

Green building (also see high-performance building) – A building that integrates that aims to improve the building in terms of energy, water, durability, functionality and occupant productivity over the course of its lifecycle reduce the impact on the environmental, social and economic systems. In this study the terms green and high-performance buildings are used interchangeably.

Green Building Certification Program – A third-party certification program that evaluates the environmental performance and performance impacts of new and existing buildings. The following certification programs are mentioned in this study: Leadership in Energy and Environmental Design (LEED), Green Globes, Building Research Establishment Environmental Assessment Methodology (BREEAM), and Building Owners and Managers Association (BOMA) BEST.

Green Globes – An online green building rating and certification tool, developed in the 1980's in the United Kingdom (also see Green Building Certification Program).

High performance (or 'green') building – A building that integrates attributes of high performance, such as energy efficiency, durability, cost-benefit, functionality, and occupant productivity over the over the course of its lifecycle. This study refers mainly to the energy efficiency aspect of high performance buildings.

Hydronic system – A heating/cooling system that uses water or another liquid as a heat-transfer medium.

Leadership in Energy and Environmental Design (LEED) – A green building rating system and certification tool that was developed in the 1990's in the United States (also see Green Building Certification Program).

Measurement and Verification (M&V) – A process that identifies how much savings an energy conservation measure (ECM) delivered in a building.

Megawatt hour – a watt-hour is a measure of energy that is equivalent to a power consumption of one watt for one hour. A megawatt hour is equal to one million watt-hours.

Natural Ventilation – A process in which air is supplied to and removed from an interior space without the use of a fan or mechanical system. It is guarantees air flow through pressure differences between the building and its surrounding to provide ventilation.

Occupancy sensor – Here referred to as a light sensor that turns lights on automatically when motion is detected and turn lights of when no motion is detected in the area for a certain amount of time.

Open-loop well system – A heat pump system that uses domestic well water as heat source and sink. The well water is circulated through the heat pumps and returned to the ground.

Post-occupancy evaluation – A process of evaluating a building in a systematic manner to determine how successful it was delivered after it has been occupied.

Predicted energy performance – The estimated energy consumption of a building that was calculated during the design or construction process of the building. The predicted energy performance is generally calculated through a building energy model (also see building energy modelling).

Sequence of operations – The accounting of the procedure to start-up and shutdown a building system under varying conditions and operation schedules.

Stakeholder – A person, industry group or organization with an interest in a project. In this study the term is used to describe interest groups that are involved in the building project, including building owners, architects, engineers, construction managers/team, trades, commissioning agents, building/facility managers, and building inhabitants.

Sustainable building – Similar to green buildings, a sustainable building design is often understood as an approach that aims to sustain the health of social, economic and environmental systems over time.

Vacancy sensors – A light sensor that requires occupants to turn on lights manually, but turn off lights automatically if no motion is detected for a certain amount of time. Occupants can also turn off the lights manually.

Volatile organic compound (VOC) sensor – A sensor that detects CO_2 levels and numerous air pollutants that are dangerous to human health.

Work-around – A method used to overcome a problem or limitation in a (computer) program or system.

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Completing this thesis has been a long but very fulfilling journey. Numerous people have contributed to it directly or indirectly. Everybody's contribution has been essential to this work. First and foremost I am deeply grateful to my family for their love, support and inspiration. They provided a fertile ground of inspiration for this work to grow and bear fruit.

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Chapter 1: Introduction

The motivation for this study was fuelled by a previous study on the Centre for Interactive Research on Sustainability (CIRS). Fedoruk (2013) evaluated the design and operation of the multi-building energy system serving CIRS. The results revealed significant deficiencies in the performance of the multi-building system compared to its design intent (Fedoruk 2013). These findings encouraged me to better understand the extent of the building's performance gap and reasons contributing to the differences. To set this study in the larger context, two other unique buildings became objects of the study: the Jim Pattison Centre of Excellence in Sustainable Building Technology and Renewable Energy Conversation (JPCE) and the District Education Centre (DEC). Both buildings high-performance buildings were built at the same time as the CIRS building with similarly ambitious performance goals.

1.1 Energy Performance of Buildings – Problem Statement

Buildings contribute significantly to the environmental impact of energy consumption and greenhouse gas emissions. The International Energy Agency (IEA) reports that 31 percent of global energy consumption was used in the building sector in 2011 (IEA 2014). This energy consumption is responsible for 27 percent of global energy-related carbon dioxide (CO_2) emissions. The buildings in the service sector alone, including commercial and public services, covered 8 percent of global energy consumption in 2011 (IEA 2014). Over the past three decades, efforts have been made to improve the energy efficiency of buildings, which include the development and use of building environmental assessment methods to evaluate the performance of buildings (Cole 1999). In the 1990s, energy certification to reduce energy use and CO_2 emissions became prevalent on the building market (Pérez-Lombard et al. 2009; Haapio & Viitaniemi 2008). Building assessment tools and green building rating systems such as the US Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) and Green Globes have brought 'green' or high-performance building practices into the conventional construction market place in North America (Cole 2006). 'Green' or high-performance buildings are often defined as facilities that are designed in a resource-efficient manner, while minimizing impacts on the environment and community and enhancing occupant health (Zuo & Zhao 2013; Robichaud & Anantatmula 2011). Similarly, sustainable building design is often understood as an approach that aims to sustain the health of social, economic and environmental systems over time (McDonough & Braungart 2002; Reed 2007).[1]

While design assessment tools have become a widely accepted rating tool, there has been a growing concern surrounding the actual (i.e. post occupancy) performance of certified green buildings (Newsham et al. 2009; Scofield 2009; PlaNYC 2012; Scofield 2013). Discussions about the performance of LEED-certified buildings started in 2008 when the New Building Institute (NBI) published energy performance data of a large sample of commercial LEED new construction (NC) buildings that were compared to design predictions and the US national building inventory (Turner & Frankel 2008). The results of the study caused not only discussions about the actual performance of certified green buildings compared to conventional buildings, but also pointed towards a significant 'performance gap' – referred to as a discrepancy between design prediction and actual energy use of certified buildings (Turner & Frankel 2008; Diamond, R. 2011; Oates & Sullivan 2012). Turner and Frankel (2008) revealed that over half of 121 LEED-certified buildings deviated in their actual energy use intensity (EUI) by more than 25 percent from the predicted values, either exceeding or not meeting their design predictions (Turner & Frankel 2008). While buildings, on average, perform close to the predictions, 30 percent of the buildings performed significantly better and 25 percent significantly worse than predicted. Similar results have been found by a study of 18 LEED-certified buildings in the Pacific Northwest (Diamond, R. 2011). The sample of mainly office buildings revealed that the average actual consumption was close to the predictions, while individual projects deviated significantly from the design predictions (Diamond, R. 2011). More recently, a study of 19 certified-LEED buildings in Arizona indicated a significant under-performance of the entire building sample (Oates & Sullivan 2012). The sub-set of 15 medium-size buildings, mainly office and educational buildings, deviated by 74 percent from their design projections (Oates & Sullivan 2012). These U.S. studies revealed that on an individual basis, certified green buildings

[1] More recently, net-positive or regenerative design approaches have emerged in response to the inadequate 'less harm' approach of sustainable design to highlight the need that buildings add benefit and value to their context (Robinson & Cole 2015; Reed 2007).

are either significantly outperforming or under-performing their design predictions. This leaves building owners and policy makers with a high uncertainty about the actual performance that can be expected, as well as the projected energy and emission savings of individual green building projects.

While green rating systems such as LEED and Green Globes mainly provide information on the performance at the design stage, the projected performance is seldom verified by building owners (Oates & Sullivan 2012). Building performance assessment tools such as BREEAM and LEED provide certificates based on modelled performance. However, municipalities have expressed the need for more energy reporting initiatives that provide building energy performance data based on utility consumption (PlaNYC 2012). The building industry is increasingly under pressure to meet environmental targets that are expected by clients and the general public (De Wilde 2014).

This makes it important to address the performance of green building projects and investigate and document potential reasons for performance differences (Turner and Frankel 2008; Oates and Sullivan 2012). A comparison of predicted and actual performance is critical to allow for informed decision-making processes for new buildings and to achieve initial cost benefits. Thus, building performance evaluations (BPE) at the individual building level can provide an in-depth understanding of the performance gap and the lessons learned for building owners and industry. While energy efficiency is only one aspect of BPE, due to current environmental pressures and concerns about climate change, this study focuses specifically on energy aspect of the buildings performance.

1.2 Building Performance Evaluation – Research Contribution & Objectives

Energy performance studies are a significant part of building performance evaluations (BPE) (Leaman, Stevenson & Bordass 2010a). As Preiser and Vischer (2006) defined, “BPE is an innovative approach to the planning, design, construction and occupancy of buildings”. It is a way of “systematically ensuring that feedback is applied throughout the process, so that building quality is protected during planning and construction and, later, during occupancy and operations" (Preiser & Vischer 2005) (p.27). BPE was first used in the United Kingdom (UK) in the 1960s and has taken many forms over the past decades (Preiser & Schramm 2002; Preiser & Nasar 2008). There was a first wave of interest in comparing predicted and actual energy performance of buildings, when developed countries implemented programs and initiatives promoting cost-effective energy savings in new constructions in the early 1990s (Marchio & Rabl 1991; Diamond et al. 1992). Diamond et al. (1992) evaluated predicted versus actual performance of 27 new commercial buildings that were part of the Energy Edge Project, an energy initiative for cost-effective energy savings of commercial buildings in the Pacific Northwest (Diamond et al. 1992). This study used utility bills and metered energy consumption data and compared these to estimates from design-stage simulations, as well as to similar new buildings in the region. The results indicated that the 27 commercial buildings used on average 30 percent less energy than a typical commercial building in the region, but 10 percent more energy than predicted in the second year of operation. While 11 buildings required less, 16 consumed more energy than anticipated. On average, the energy consumption of the 27 buildings increased by 20 percent, from the first to the second year of operation. While for two buildings the energy consumption was probably due to increased occupancy, there was not enough information available to identify reasons for the increased consumption of the remaining projects (Diamond et al. 1992).

With the establishment of assessment tools such as BREEAM (Building Research Establishment Environmental Assessment Methodology) in the 1990s, post occupancy evaluations (POE) became a popular form of BPE. One of the milestones was the PROBE study (Post-occupancy Review of Building and their Engineering) that used a standardized POE methodology and evaluated the energy performance of 16 commercial and educational buildings in the UK between 1995 and 2002 (B. Bordass, Cohen, et al. 2001). Buildings were compared to energy benchmarks for ECON 19 'good practice' buildings that were derived from surveys of a large number of four types of office buildings in the UK. The study revealed that the majority of buildings consumed between 100 and 150 kWh/m^2, which was above predicted ECON 19 benchmarks (B. Bordass, Cohen, et al. 2001).

In the UK, the particular focus on the energy performance gap was brought forward by initiatives such as Low Carbon Building Programme, which evaluated the in-use performance of buildings compared to design models (Carbon Trust 2012). Since 2008, the online platform CarbonBuzz allows building owners and companies to report predicted and actual energy consumption data anonymously (UCL Energy Institute 2013). An evaluation of the submitted audits revealed significantly higher actual electricity consumption for office and educational buildings compared to predictions (Menezes et al. 2012; UCL Energy Institute 2013).

In the USA, similar comparisons have been possible when NBI published energy performance data for a large sample of commercial LEED NC buildings (Turner & Frankel 2008). While many subsequent studies evaluated the performance of certified green buildings compared to their conventional counterparts, only a few focused on the performance gap between design predictions and actual energy consumption of the studied buildings (Diamond, R. 2011; Oates and Sullivan 2012).

In Canada, BPE started to emerge in the early 2000s with a series of individual building performance studies in the Lower Mainland of British Columbia (EcoSmart 2007). More recently, Newsham et al. (2012) evaluated the energy performance of five certified ‘green’ office buildings in comparison to five similar conventional office buildings in Canada and the United States. Despite investigations of the energy performance, few case studies quantify the performance differences between actual and predicted consumption. Most BPE studies in Canada focused solely on actual consumption values, while neglecting energy use predictions made at the design stage. On the other side, green building certification programmes are often based on predicted energy performance values (e.g. BREEAM, LEED) with few exceptions (e.g. BOMA BEST 3.0). Nonetheless, research and industry have been pointing increasingly towards the performance gaps in green buildings (De Wilde 2014; Menezes et al. 2012; Carbon Trust 2012; Zero Carbon Hub 2013).

The comparison of predicted and actual energy performance of a building is important because it provides feedback to building owners and industry about the actual performance of projections made at the design stage to influence decision-making of future projects. “While it seems reasonable to allow for some variation in both predictions and measurements due to the realities of uncertainties (inherent in predictions) and data scatter (inherent in measurements), the evidence seems to point to the gap presently being too wide to be acceptable", as de Wilde (2014) describes (p. 40). A comparison of design targets to actual performance is of particular importance for high-performance projects that are promoted as net zero energy buildings. It allows building owners to adjust projected values for energy savings and lifecycle cost of the building to make more informed long-term decisions. This practice is commonplace in industries and professions that are related to human safety and wellbeing (e.g. automobile industry, medicine) to guarantee a successful design and product, but until now, is rarely applied to buildings. This is crucial information for the building industry when designing new buildings and for policy makers developing energy codes for buildings. Furthermore, "it would seem both natural and economical in the long run to thoroughly investigate the possibility of user-oriented 'product' evaluations in [the] complex industry of design and construction", as Preiser and Vischer (2006) describe (p.12). This study attempts to provide this information by explicitly evaluating the performance gap between the predicted and the actual performance of three certified green buildings in British Columbia.

This study further attempts to address certain reasons that contribute to the performance gaps in the three case studies. The foundation for this attempt has been an on-going discussion on reasons for the performance gaps in green buildings. Over the past twenty years, there has been a growing concern surrounding the actual performance of green and sustainable buildings. Since the 1990's, a number of studies revealed potential reasons for performance gaps in the green buildings of concern. Early studies in the UK such as the PROBE study pointed towards common problems in the building development process that affected the overall performance of buildings (B. Bordass, Leaman, et al. 2001). Over the past two decades case studies and building reports followed, discussing various aspects of the performance gap (e.g. (W. Bordass & Leaman 1997; B. Bordass et al. 2004; Knight et al. 2007; Menezes et al. 2012; De Wilde 2014). Those studies have been pointing towards causes that occur at different stages in the building development process: starting at the design and modelling stage, through to construction and commissioning, to building operation and occupancy. Based on these discussions this study attempts to evaluate key sources of performance issues, in the context of the three case-study buildings. Preiser and Vischer (2006) explain the importance of BPE case studies as follows:

> *For BPE to become integrated into the building delivery cycle of mainstream architecture and the construction industry, it is critical to integrate BPE into these disciplines and to demonstrate to practicing professionals the viability of concepts through a range of exemplary case study examples.* (Preiser & Vischer 2005) *(p.10)*

The objective of this study is to examine the energy performance of three high-performance buildings in British Columbia and identify any gaps between predicted (or modelled) and actual (or measured) performance.[2] While keeping in mind common reasons for performance gaps found in the literature, this research attempts to evaluate the factors contributing to the performance gaps found in the three case studies.

1.3 Structure and Overview of Thesis

In the light of these objectives, this study is structured in four main chapters. Chapter 2 serves as a review of the literature that discusses reasons for performance differences in green and sustainable buildings. The literature review provides the contextual overview for understanding the energy performance gap as a result of an intricate building development and operation process. The results of the review were used as the theoretical lens and framework to inform the methodological approach of the performance gap analysis in Chapter 4.

Chapter 3 assesses energy performance gaps in three LEED-certified buildings in British Columbia that have aimed to be highly energy efficient in terms of their design. An energy performance evaluation reveals differences between predicted and actual annual energy

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[2] It is important to note that energy efficiency is only one of many building performance aspects. Other aspects include health, safety, and security performance, functional and work flow performance, as well as psychological, social, cultural and aesthetic performance (Preiser & Vischer 2005).

consumption for each building. The results from the case studies provide the basis for an in-depth evaluation of reasons for energy performance gaps in green buildings.

Chapter 4 explores the reasons for identified energy performance gaps through interviews with key stakeholders that were involved in the design, construction and operation of the three case study buildings. The literature review from Chapter 2 provides information about common reasons for performance gaps and is the foundation for the expert interviews. The chapter discusses key sources of performance issues, related to modelling and design, construction and commissioning, and operation and occupancy that occurred in the studied buildings. The results of this analysis provides lessons learned for the case study buildings and offers a better understanding of key factors that contribute to energy performance gaps and need to be addressed in future building developments.

As a whole, the study provides a thorough exploration of the range of reasons that contributed to performance gaps in three high-performance buildings. In addition, a narrative of each building offers an overview of how performance shortcomings originated over the course of the buildings' lifecycle.

Chapter 2: The Energy Performance Gap – A Literature Review

As mentioned in the introduction, there is an increasing interest in understanding reasons for performance gaps in green buildings. In order to uncover the most common reasons and to guide my research investigation, I undertook a review of journal articles, case study reports, as well as industry reports discussing the energy performance gap of green buildings. The following literature review provides a contextual understanding of the energy performance gap as a result of an intricate building development process that leads to the actual operation and performance of a building. Therefore, the literature is organized according to the phases of the building lifecycle, from planning, design and modelling, over to construction and commissioning, to operation and occupancy.

2.1 Planning & Design

The building design stage involves different stakeholders including architects, engineers and building owners and/or their representatives. A common reason for performance discrepancies in high-performance buildings stems from a misalignment of performance targets between stakeholder groups at the planning stage of the project (B. Bordass, Leaman, et al. 2001; Dammann & Elle 2006; Shen et al. 2012). For example, Bordass et al. (2001) describe how "poor communication and false expectations" between designers and building owners can lead to performance issues after completion of the project:

> *[…] The occupier has not defined the level of management they regard as reasonable; and the designers have not made clear the level of support the building is likely to demand. Building user needs and operational viability are often not considered in the design of new building features. For example, technology can often be seen as the answer to a management problem while its possible downsides and the vigilance and expenditure required to look after it are not discussed in depth.* (B. Bordass, Leaman, et al. 2001) *(p.148)*

The search for optimum performance targets can then lead to overly complex building designs that require a high level of management to operate and maintain the building (Armel et al. 2013;

W. Bordass et al. 1997). Case studies revealed that automated systems and controls were difficult to use affecting the overall performance of buildings (B. Bordass, Cohen, et al. 2001; Fedoruk et al. 2015; Morant 2012; Salehi et al. 2015). The study by Dasgupta et al. (2012), on performance gaps in low carbon schools in England, revealed that performance estimations were based on the assumption that building inhabitants and operators would use the systems according to desired targets. However, occupants were often unaware of how systems were supposed to be operated, as they were not informed about the design intent of control systems (Dasgupta et al. 2012).

Problems can also arise from a lack of quantitative targets guiding the design process (B. Bordass, Cohen, et al. 2001; Butera 2013a). The PROBE study revealed that energy consumption targets were often not specified in the design criteria, leading to unexpected performance outcomes in green buildings (B. Bordass, Cohen, et al. 2001). In some cases a lack of performance targets had a direct effect on system design and sizing. Building systems were often "over-designed" compared to the predicted occupancy levels for buildings and consumed more energy than actually needed to operate the buildings (Mahdavi 2009) (p. 445). Furthermore, the design often assumes that novel technologies would function as near-to perfect systems, which can rarely be met in the overall building design (B. Bordass et al. 2004; Carbon Trust 2012; Newsham et al. 2012).

Another contributing factor to the performance gap is that the design process rarely utilizes energy models and performance assessment tools for a performance based building design (De Wilde 2014; Schlueter & Thesseling 2009; Zero Carbon Hub 2013). Where models are used, their actual application and use during the design process varies often significantly. Design-assist and compliance modelling are the two most commonly used types of energy models in North America. Design-assist energy models use local geographical information and climate specific requirements to assist the design of the building throughout the design process. Thus, the energy model is used as a tool to "compare systems and other design aspects to determine the most energy-efficient design".[3] The model is updated throughout the design process to reflect changes

[3] Information were retrieved from SSR Commissioning (October 2015): http://www.ssrcx.com.php5-13.dfw1-2.websitetestlink.com/modelling.php

and can be used to evaluate energy conservation measures (ECMs) to evaluate energy and cost savings. On the other hand, compliance models are used to compare the building design to other energy-efficient projects in a geographical location. In this case, the energy model is only done after the design and based on final design drawings to model the proposed design. Therefore, a compliance model has no influence on the actual design and only allows an evaluation of ECMs compared to building reference standards such as ASHRAE 90.1.

Although it is commonly thought that "design decisions concerning building sustainability have to be made in the early design stage", in general practice "performance analysis to support design decision-making is only used for the few buildings facing engineering challenges or explicitly focussing on sustainability", as Schlueter and Thesseling (2008) describe. In cases, where energy models are not integrated into the design process, performance criteria are seldom met or require significant modifications to meet the intended energy targets. Barry (2013) reports that "changes in the design are not followed through to revise the energy prediction; for example changes to ensure insulation, thermal mass, solar exposure, operational hours and controls" (Barry 2013) (p.7). This relates to the finding that available simulation tools for architects rarely include a performance assessment (Schlueter & Thesseling 2009). Instead, energy modelling requires expert knowledge beyond the expertise of the design team.

Finally, despite a growing interest of energy sharing networks in the industry, buildings are generally thought of as separate entities during the design, without consideration of contextual variables, such as multi-building connections and site specific conditions (Dasgupta et al. 2012; Fedoruk et al. 2015; Terim Cavka et al. 2014). Dasgupta et al.'s study (2012) revealed that available knowledge and skills in the industry are often insufficient to build energy networks with other community facilities. There is often a lack of information and knowledge regarding availability and implementation of local resources. The study points out the importance of considering immediate environment and location of the building to prevent wastage of energy (Dasgupta et al. 2012). Fedoruk et al.'s (2015) case study of the CIRS building illustrates how the lack of information of available resources can affect the performance of multi-building systems. The study revealed that project boundaries did not include existing infrastructure in the evaluation process for a successful design of a two-building system, which led to a large performance deficit of the system. A lack of consideration of site-specific contextual variables can reduce the effectiveness of energy saving technologies.

2.2 Modelling

Another cause within the design context relates to more specific issues related to the energy models and simulation tools that are generally the basis of any performance predictions of the building. A design-assist model closely follows design decisions and changes made throughout the design development process. Compliance models on the other hand are often restricted to particular requirements that follow certification guidelines (De Wilde 2014). As a consequence, compliance models such as LEED compliance models do not always account for all energy loads of a building.

A specific challenge for modelling software is the simulation of new design strategies such as natural ventilation or advanced renewable energy and water systems (Terim Cavka et al. 2014; Diamond, R. 2011; Raftery, Keane & Costa 2011; Ohba & Lun 2010). According to Ohba and Lun (2010), it is particularly difficult to simulate natural ventilation systems. Models assume uniform airflow and temperature distributions in building zones, which has a major effect on calculated heating and cooling loads for the building (Raftery, Keane & Costa 2011). Terim Cavka et al. (2014) confirmed those findings, indicating that the simulation of natural and displacement ventilation requires so called 'work-arounds' in modelling tools such as eQUEST.[4]

Furthermore, simulation tools tend to be incomplete in their representation of energy loads related to specific areas or systems in the building. Unconventional places in the building such as circulation areas and support spaces, as well as monitoring systems and loads from information technology (IT) tend to be left out in the models (Beauregard & Berkland 2011; Binks 2011; Raftery, Keane & Costa 2011; Barry 2013; Cheshire & Menezes 2013). Cheshire and Menezes (2013) found that extra energy use for lifts and escalators for catering facilities and server rooms are rarely considered in energy models. Binks' case study (2011) revealed that BMS monitoring

[4] Work-around is a method used to overcome a problem or limitation in a (computer) program or system.

servers, computer systems, and components of the control system were not part of the energy simulation, but were running constantly during building operations. As building envelopes and various energy services become more efficient these missing loads have an increasing impact on the gap between predicted and actual performance.

A particular challenge for energy models is to account for the actual usage of a building. Energy predictions seldom account for variation of building usage. Many case studies indicated that actual occupancy hours and operation sequences differed from the assumptions used in the original design (B. Bordass, Cohen, et al. 2001; W. Bordass et al. 2004; Mahdavi 2009; Beauregard & Berkland 2011; Butera 2013b; Cheshire & Menezes 2013). Wang, et al. (2012) found that changes in heating, ventilation and air conditioning (HVAC) schedules, temperature set points, and controls for plug-in equipment and lighting can alter the annual energy consumption of a building by more than 15 percent (for an 80 percent confidence level) (Wang et al. 2012). These operational uncertainties are not considered in simulation tools, which are generally based on assumptions of ideal operation (Wang et al. 2012).

Beside operation practices, occupant behaviour is not part of the current modelling practices. Quoting Wang et al. (2011), “for buildings with occupancy controls, occupancy becomes a key driving factor to accurately predict the energy consumption” (C. Wang et al. 2011). Salehi et al. (2015) found that predicted set points for a mixed-mode ventilation system were dramatically altered by occupants’ usage of operable windows. Energy simulations are seldom robust in estimating occupancy schedules, equipment use, and activities in building areas, affecting internal heating loads of buildings (Mahdavi 2009; Knight et al. 2007; Hoes et al. 2009). Measured occupancy schedules for use in building energy models are rare, particularly for academic type buildings (Davis & Nutter 2010).

Further uncertainties can stem from inaccurate weather data used in the simulations (Chan 2011; Jentsch et al. 2008). Bhandari et al.’s (2012) evaluation of impacts of different weather datasets on energy loads of three different building types revealed a possible variation of plus/minus seven percent in the annual energy consumption (Bhandari et al. 2012). Current standard weather files for building simulation are often based on typical meteorological year (TMY2) data that are generally based on 30-year historical weather data. These data “are not suited to the assessment of potential impacts of a changing climate”(Bhandari et al. 2012).

Finally, design-assist and compliance energy models are rarely verified or calibrated through as-built models, which are based on actual measurements of the energy performance after building completion (Raftery, Keane & O’Donnell 2011; De Wilde 2014). However, such a calibration process could help to “improve the quality of future design stage models by identifying common mistaken assumptions in these models and by developing best-practice modelling procedures” (Raftery, Keane & O’Donnell 2011) (p.2356).

2.3 Construction

Causes for performance gaps may also arise from the construction process of the building. Many studies point towards issues in the quality of the construction with regards to structural elements and systems (De Wilde 2014; Menezes et al. 2012; Fedoruk 2013; B. Bordass et al. 2004). Gaps in the insulation, thermal bridging or lack of airtightness can lead to energy losses, which are rarely considered in the design predictions (Menezes et al. 2012; B. Bordass et al. 2004). A case study of dwellings in the UK revealed that heat loss through fabric and air leakage were 50 to 70 percent higher than anticipated (Bell et al. 2010). Complex control systems may not be installed as anticipated, leading to changes in the overall energy consumption (Fedoruk 2013; B. Bordass et al. 2004). Fedoruk’s case study (2013) revealed that lighting circuits were not installed correctly, which led to overridden control systems. Installation issues can stem from insufficient training in how to deploy new technologies or lack of awareness of the energy performance targets for the overall system function (Zero Carbon Hub 2013; W. Bordass et al. 1997).

Further discrepancies between design and actual performance can stem from change orders during constructions (Bell et al. 2010; W. Bordass et al. 2004; De Wilde 2014). Systems that are removed from the original design often affect service and control devices such as window quality and solar control systems (B. Bordass et al. 2004). The effect of change orders is seldom considered or updated in the design predictions, but can alter the overall building performance. A low carbon housing case study by Bell et al. (2010) revealed that a change order to another window type, which were provided by another supplier, lead to a 21 percent decrease of the window performance compared to the design predictions.

2.4 Commissioning

The construction process ties in closely with building commissioning, which describes the process of verifying building systems, including structure, plumbing, mechanical and electrical systems, as well as fire and safety systems. Commissioning has evolved from focussing mainly on the review of the mechanical systems in the building (i.e. the HVAC system) to overseeing the entire building system, a requirement of LEED NC 2009 buildings (which applies to the three case-study buildings of this research). LEED certification requires a review of the major building systems including HVAC, lighting, domestic hot water, and renewable energy systems. However, many authors point towards incomplete and inadequate commissioning of advanced building systems that are seldom assessed according to the design intent (Fedoruk 2013; Zero Carbon Hub 2013; Morant 2012; B. Bordass et al. 2004). Despite the assumption that commissioning is a "standard practice", according to Mills (2011) "buildings are *rarely* commissioned for energy savings" (p.146). As a result, energy saving devices such as heat recovery systems and building control systems are often working poorly despite general commissioning (Zero Carbon Hub 2013; B. Bordass et al. 2004).

A general issue is that commissioning processes tend to vary in scope and focus. While the commissioning process encompasses a large numbers of steps, including documentation and training, in reality these steps are seldom all followed through (Mills 2011; Jump et al. 2007). Mills' review of commissioning experiences of 643 non-residential buildings, revealed that commissioning is often squeezed in at the end of the construction process, just before the hand-over stage of the project, when there is little opportunity to address identified design or performance issues (Mills 2011).

> *For new construction [the commissioning process] dictates involving the commissioning agent at the very outset of the design and planning process and keeping them on board well through start-up and into the warranty period. This is often not the case in practice, i.e., in only about one quarter of our projects was*

commissioning begun during the design phase, and in only one third of the cases did it include construction observation. (Mills 2011) (p.167)

While the commissioning process is intended for entire building systems, often sub-systems are only reviewed individually rather than as part of entire system or network design (Fedoruk et al. 2015; Mills 2011). According to Mills, in many case studies commissioning only focused on the HVAC systems, leaving out sub-systems such as service water heating, plug loads and envelopes. In other cases, the lack of clear guidance from manufacturers led to insufficient commissioning of new technologies (Zero Carbon Hub 2013). As a consequence, improvised commissioning approaches are often used and based on *ad hoc* checklists rather than on design documents.

Further performance issues can stem from insufficient communication within the commissioning team (Mills 2011). While a commissioning agent generally leads the commissioning process, this process requires the collaborative work of participating engineers, contractors, trades, and operation managers. A lack of careful communication and coordination among stakeholders, as well as insufficient knowledge of the commissioning practice can have a significant impact on the performance of building systems.

2.5 Handover

While efforts have been made to improve handover processes to owners and building operators, for example by applying 'Soft Landings' strategies, there is generally a lack of verification after project completion (De Wilde 2014). Soft Landings refer to a process that retains designers and constructors involved in the performance of buildings after completion of the project with the intent to provide more rigorous quality insurance. However, this process is far from being a standard practice yet (Zero Carbon Hub 2013; Carbon Trust 2012; Morant 2012). The same is the case for measurement and verification (M&V) guidelines, such as the International Performance Measurement and Verification Protocol (IPMVP) and ASHRAE guideline 14, that provide independent methods to verify savings estimations and produce reliable results that are replicable (Jump et al. 2007). Despite the availability of these established guidelines, they are rarely applied during commissioning or re-commissioning of a project. Services from the construction industry generally stop at the hand over stage, while verification and feedback processes are missing particularly from commissioning and operation back to the building design (Fedoruk et al. 2015; B. Bordass et al. 2004; B. Bordass, Leaman, et al. 2001).

> *Consequently, large differences between energy performance expectations and outcomes can occur virtually unnoticed, while designers continue to repeat flawed prescriptions. Designers may also fail to realize when they have a success on their hands, which they should be replicating: instead they may attempt to gild the lily and create 'solutions' which are more complicated than necessary. (B. Bordass et al. 2004) (p.4)*

2.6 Operation

Once the building is occupied, the operational side of the building can also contribute to performance discrepancies. Changes in the sequence of operation and maintenance can significantly alter the energy performance of the building (Newsham et al. 2012; Cheshire & Menezes 2013; B. Bordass et al. 2004). Equipment and systems tend to be left on after general operation hours or even permanently, to prevent complaints from building inhabitants or to by-pass control systems. Wang et al. (2012) revealed that operation sequences and HVAC set points changed the annual energy consumption dramatically, particularly for buildings with unconventional heating and cooling systems than those with conventional ones.

As high-performance buildings can be relatively complex to operate, they require a high degree of management and technical understanding to achieve optimal performance, which is not always available for the building (Cheshire & Menezes 2013; W. Bordass & Leaman 1997). Adequate training of building managers and occupants is required, in order to operate and interact with the system according to the design intent. If no sufficient training is provided and the management is overextended, "the symptoms of under-performance are very likely to come to the surface as occupant dissatisfaction and/or energy wastage" (B. Bordass, Leaman, et al. 2001).

2.7 Occupancy

Another significant factor contributing to the energy performance gap is the occupancy and use of the building. Recent research has revealed that occupancy and occupant behaviour can significantly affect the energy performance of buildings (Mahdavi 2009; Herkel et al. 2008). Occupant control over buildings' systems such as windows, temperature set points, and lighting can significantly change the energy use in a high-performance building. Salehi et al.'s case study (2015) revealed that a changed use of operable windows from the original design intent (i.e. left open windows overnight or during the heating period) changed the ventilation mode of the building significantly. According to simulations by Hoes et al. (2009) occupant behaviour particularly affects heating and cooling loads of buildings. Changes in occupancy numbers as well as "occupants' energy use characteristics" can have a similar impact on a building's performance, affecting the loads for cooling and ventilation of the building (Hoes et al. 2009; Liao & Barooah 2010; Davis & Nutter 2010; Azar & Menassa 2012). Despite increased modelling efforts, the effects of occupancy patterns on the energy consumption of a building are rarely considered in the predictions, leading to significant energy performance gaps (Erickson et al. 2009; Davis & Nutter 2010).

2.8 Methodological Approach

Given the range of reasons that can contribute to the performance gap in high-performance buildings, the goal was to discern important factors in the building lifecycle that affect the performance of individual buildings and across a range of building examples. The first step to answer this question was to evaluate whether performance gaps were apparent in the case-study buildings chosen for this study. This would allow further evaluation of contributing factors that caused differences in the energy performance of the buildings. This approach led to the following research questions:

- What is the extent of the discrepancy between predicted (i.e. modelled) and actual (i.e. measured) energy performance in the three case-study buildings?
- What factors contribute to performance differences between predicted and actual energy consumption in each building?

- Is there a connection between the performance-gap reasons identified in the literature and the case-study building?
- What lessons can be derived from the case studies to help prevent performance gaps in future building projects?

In order to answer these questions a sequential mixed-method approach was chosen in order to evaluate the performance of each building first, and explore reasons for performance gaps after. In the first part, energy performance evaluations of the three case-study buildings provided information about the discrepancies between predicted and actual energy performance for each project. Energy models were used to analyze the predicted energy consumption. The actual performance was based on measured energy consumption data of the first two to three years of operation.

In a second step, common reasons for performance gaps derived from the literature were evaluated in the context of performance gaps identified in the three buildings. Interviews with key stakeholders such as designers, consultants and building managers provided information about potential sources of performance issues occurring in the studied buildings. Based on these findings, lessons learned were derived from the analysis, focusing on overarching reasons for performance gaps across projects and aiming to inform building owners and stakeholders in the building industry alike.

Chapter 3: Energy Performance Evaluation of Three Sustainable Buildings in British Columbia

The three certified ‘green’ buildings were chosen with the interest of evaluating the building-specific high-performance goals as well as the context-specific building uses. They were constructed during the same time period and were all completed in August 2011 (Table 2-1). The projects are considered medium-size buildings, including two academic buildings and one office building, with net floor areas ranging between 5,500 m^2 and 11,420 m^2, and construction costs ranging between \$2,500 and \$5,610 per square meter (reflecting somewhat different uses and implementation of technologies).

Table 3-1: Overview of General Building Information of Case Studies

Building	Location	Type	ASHRAE Climate Zone	Net floor area (m^2)	Construction Cost (CA\$/m^2)
District Education Centre (DEC)	Surrey	Office Building	5C: Cool-Marine (CDD ~90, HDD ~2680) [5]	11,420	\$2,500
Jim Pattison Centre of Excellence (JPCE)	Penticton	Academic Building	5A: Cool-Humid (CDD ~240, HDD ~3340) [6]	6,780	\$4,150
Centre for Interactive Research on Sustainability (CIRS)	Vancouver	Academic Building	5C: Cool-Marine (CDD ~60, HDD ~2820)	5,500	\$5,610

[5] Degree-days for Surrey (DEC) were retrieved from The Weather Network, http://legacyweb.theweathernetwork.com/statistics/degreedays/cl1101708/cabc0284/metric, Feb 17, 2016. Degree-days from Canadian Climate Normals were not available for Surrey.

[6] Degree-days for Penticton (JPCE) and Vancouver International Airport (CIRS) were retrieve from Canadian Climate Normals between 1981 and 2010: http://climate.weather.gc.ca/climate_normals/index_e.html, Jan 20, 2015.

The buildings are situated in the same temperature-oriented climate zone, as defined by the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE), covering two different moisture regimes within British Columbia (BC) (ASHRAE 2013). The particular interest in these buildings arose from their unique vision and goals that influenced their design and development. Since there are more than 250 LEED NC buildings in BC, these buildings cannot be considered a representative sample, but were selected as suitable case studies with willing participants.[7]

3.1.1 The Surrey District Education Centre (DEC)

The idea for the District Education Centre (DEC) was conceived almost two decades before the design process began in 2007. The vision of the building was to reunite Surrey School District's administration from seven different locations into a first-class facility that provided a professional working environment for staff and a learning space for students, in an open and welcoming sustainable environment, celebrating education and environmental responsibility. The administrative office building for the Surrey School District is located in a mainly residential neighbourhood in the City of Surrey. The four-storey building has a large atrium in the centre that gives access to a cafeteria, a boardroom, as well as training rooms, offices, and meeting rooms. The basement provides space for further offices, fitness rooms, and showers, as well as a large computer sever room for the Surrey School District. The building hosts an online learning school, as well as a First Nation lounge, which attract visitors and students. The project was entirely funded by the Surrey School District that has been saving for a new building for the Board of Education over the past twenty years.

3.1.2 The Jim Pattison Centre of Excellence in Sustainable Building Technology and Renewable Energy Conversation (JPCE)

The JPCE is an innovative academic building at Okanagan College in Penticton that aims to be highly adapted to its site, climate, and context. The two-storey building features classrooms,

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[7] The number of certified LEED NC buildings in British Columbia were retrieved from Canadian Green Building Council (July 2015): http://leed.cagbc.org/Leed/projectprofile_en.aspx

trade shops, office and meeting rooms, computer labs, as well as a gymnasium, fitness room, and a cafeteria. The main intention was to provide space for courses on sustainable building technologies and research on alternative and renewable energy sources. Thus, the novel design characteristics of the building itself were intended and set-up to be used as a teaching tool for trades students in particular. At the same time, the building aimed to reach a net zero energy goal using renewable energy sources. The main source of funding was the Knowledge Infrastructure Program, which is a two-year stimulus plan that aimed to revitalize facilities at universities and colleges as part of Canada's Economic Action Plan. Based on this financial agreement, the building was successfully completed within the two-year timeline, in August 2011.

3.1.3 The Centre of Interactive Research on Sustainability (CIRS)

Located on the University of British Columbia campus, the Centre of Interactive Research on Sustainability (CIRS) is a multidisciplinary education and research facility. The vision of the building was to provide space for researchers from diverse organizations and disciplines exploring sustainable concepts. CIRS was striving to achieve net-positive goals in terms of energy, embodied carbon emissions, operational carbon emissions and water.[8] The four-storey building connects two office wings through an atrium that provides access to a café, a theatre and a 450-seat auditorium on the first floor, as well as offices and meeting rooms on the remaining floors. The building promotes a solar aquatic room for an on-site wastewater treatment plant and a basement with storage rooms, showers, service rooms and computer server rooms. The building had multiple funding sources including Canada Foundation for Innovation (CIF), BC Hydro, and Sustainable Development Technology Canada. The building was conceived in 2002 with the intent to be "at the forefront of sustainable building performance" (Fedoruk 2013). It underwent many redesigns at different locations in the seven years before construction began in 2009.

[8] Three net-positive goals for human performance (health, productivity and subjective wellbeing) were also defined. See cirs.ubc.ca/sites/cirs.ubc.ca/files/pageUploads/LEED_CIRS percent20-narrative_PerkinsWill.pdf (accessed January 2015).

3.2 Methods

The energy performance evaluation applied for this study investigates how a building is operating in terms of energy consumption, compared to design predictions and benchmarks. This research compares actual building performance with predicted performance at the design stage, and reference values for a typical building of similar use in the region. For a comprehensive understanding of the major energy systems, the system design of each building was examined through analysis of design documents, system manuals, and energy modelling reports.

The actual energy consumption was evaluated by collecting metered energy data if available, or utility bills for each building over a minimum of two years of operation. The most consistent available energy data for two subsequent years of operation were used, starting at least six months after the start of operation. Based on this information, the energy use intensity (EUI) in kWh/m^2/year was calculated and weather-normalized by using heating degree-days (HDD) and cooling degree-days (CDD).[9] Where available, sub-metered energy data were collected for individual building systems including: lighting, plug load, heating, ventilating, air conditioning (HVAC), and domestic hot water (DHW). Sub-metered data were obtained either from the data interface or from energy reports. The predicted performance was examined through analysis of design-support energy models that were provided by the energy consultant or building owner. For all three projects, a version of the energy model was chosen that was closest to the actual design of the building based on recommendations of the energy consultant. The reference energy use of a typical academic or office building in British Columbia was based on the Comprehensive Energy Use Database published by Natural Resources Canada.[10]

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[9] The energy consumption data were collected by the author of this thesis, as part of a project initiated by iiSBE Canada, carried out by researchers from the University of British Columbia, the University of Manitoba and Ryerson University, and supported by Stantec and the Natural Sciences and Engineering Research Council (NSERC). The project investigates how actual performance of buildings compares to predicted performance, and reports the lessons to industry. More information is available on the iiSBE Canada web site at: http://iisbecanada.ca

[10] Information were retrieved January 2015 and based on values for 2012: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/trends_egen_ca.cfm

3.3 A Comparison of the Energy Systems

A variety of new and original design characteristics and technologies were applied in the case-study buildings. All projects used similar energy saving strategies that are reflected in the major building systems. For lighting, increased natural lighting strategies were implemented in the design of all three buildings through narrow floor plates, large window fronts, and high ceilings. Advanced lighting control systems such as occupancy sensors and daylight sensors were implemented consistently in office areas and classrooms. Heat losses in the buildings are reduced by the implementation of high or improved roof and wall insulation, as well as high performance glazing.

All projects applied a mixed-mode ventilation system, using operable windows and ventilation chimneys (or an atrium) for natural ventilation and air handling units sensible to heat recovery for the mechanical ventilation system. The DEC building used an active chilled beam system for ventilation, heating and cooling that distribute tempered air using water pipes as a heat exchanger. The JPCE uses a displacement ventilation system to provide tempered air through exhausts in the ceiling to all spaces. The CIRS building implemented the same system using an under-floor air distribution system for offices and the auditorium. All three buildings are equipped with CO_2 sensors and temperature sensors that regulate the ventilation mode in the building zones.

For common areas, all buildings applied radiant floor heating, but used different heat distribution systems for offices and classrooms. The JPCE building has radiant floor heating for all its spaces, except for the gymnasium, where radiant heating is integrated in the composite wood and concrete walls. CIRS uses radiant baseboard heating for offices, and mechanical heating and cooling (i.e. tempered ventilated air) for the auditorium. The active chilled beams in the DEC building provide heating and cooling to all office areas. The system is set up as a four-pipe fan coil system, which allows to heat and cool different building zones simultaneously.

In each building, the distribution system is connected to water-to-water heat pumps, which themselves are connected to different heat sources. The primary heat source for the JPCE building is an open-loop geo-exchange field that draws groundwater from drilled wells for heat extraction. The cooler groundwater is used directly through a heat exchanger, without mechanical cooling, provided to the space through the radiant slab. The field has a relative capacity of 260 kW. Since the heat pumps are only used for heating, the imbalance of heat flow to the ground is reduced by solar thermal hot water heating as a supplement for space heating. Furthermore, the heated ground water that is used for cooling is reintroduced to the ground.

Table 3-2: Overview of Main Energy Systems of the Case Study Buildings

Systems	DEC	JPCE	CIRS
Lighting (electric)	Mainly energy saving fluorescent luminaires	Mainly LED luminaires	Mainly energy saving fluorescent luminaires
Controls Lighting	Occupancy sensors (copy rooms, restrooms, service & storage rooms); Vacancy sensors (offices, meeting rooms); DDC controlled lighting in remaining areas; Daylight sensors.	Occupancy sensors[11] (classrooms, trade shops, restrooms); Vacancy sensors[12] (offices, meeting rooms); DDC controlled lighting in remaining areas; Daylight sensors[13]	Occupancy sensors (offices, restrooms); Light switches (meeting rooms, copy rooms, service & storage rooms); DDC controlled lighting in remaining areas; Daylight sensors.
Ventilation (mechanical)	Central mixed air handling system, sensible to heat recovery	Dedicated outdoor air system with reverse-flow heat recovery (two air handling unit coils, with heat recovery system)	Two air handling units with mixing dampers and heat recovery system
Ventilation (natural)	Operable windows, tickle vents, and exhaust chimneys in the atrium	Operable windows, tickle vents, and solar/wind assisted natural ventilation chimneys	Operable windows with cross-ventilation, tickle vents, and exhaust vents in the atrium

[11] Occupancy sensors turn lights on automatically when motion is detected and turn lights of when no motion is detected in the area for a certain amount of time.

[12] Vacancy sensors require occupants to turn on lights manually, but turn off lights automatically if no motion is detected for a certain amount of time. Occupants can also turn off the lights manually.

[13] Daylight sensors are here referred to as dimming controls that adjust artificial light levels without turning them off based on natural light levels.

System	DEC	JPCE	CIRS
Heating & Cooling (distribution)	Active chilled beam system (convective tempered air system for heating/cooling) in all spaces.	Water-borne radiant in-slab system (for heating and cooling) in all spaces	Waterborne radiant in-slab system (for heating) in atrium; baseboard heating in office area; displacement ventilation (tempered ventilated air system for heating/cooling) in auditorium
Heating & Cooling (heat sources)	1. Ground source geo-exchange field (COP_H=5.0, COP_C=4.0) 2. Condensing hot water boilers	1. Open-loop ground water (260kW) heat pumps (COP_H=3.8, COP_C=5.5); (cooling through groundwater cooled water + air); 2. Heat recovery coils 3. Solar hot water	1. Heat recovery coils connected to neighbouring building's lab exhaust 2. Heat-recovery coils (AHU + washroom exhaust) 3. Ground source geo-exchange field (67kW) (ground source heat pump COP_H=3.9, COP_C=4.9)
Controls HVAC	Occupancy sensors (motion); Occupies space CO_2 sensors; Outdoor CO_2 sensors; Temperature sensors; Thermostats (set-point adjustments of +/- 2°C from 21°C); Partially DDC controlled (based on schedules).	Occupancy sensors (motion); Occupied space CO_2 sensors; Outdoor CO_2 sensors; Temperature sensors (indoor/ambient); Weather sensors (wind speed); Minimal DDC controlled (based on schedules).	VOC sensors[14]; Temperature sensors (indoor/ambient); Window status sensors; Partially DDC controlled (based on schedules).
Domestic Hot water	Solar hot water preheat; natural gas boiler	Solar hot water preheat; electrical gas boiler	Solar hot water preheat; heat pump heat supply; electrical gas boiler (back-up system)
PV Capacity	--	259kW	25kW

[14] VOC or volatile organic compound sensors not only detect CO_2 levels but numerous air pollutants that are dangerous to human health.

The CIRS building uses the lab exhaust of the adjacent Earth and Ocean Science (EOS) building as its primary heat source through heat-recovery coils. The system was designed to make use of the waste-heat from the lab exhaust and to return the excess heat to the EOS building to preheat the makeup air for the adjacent building. This thermal energy transfer system requires additional compressor work, pumping and fan electricity. CIRS's secondary heat source is excess heat from the building's own exhaust air (coming from air handling units, washrooms and mechanical service rooms), that is fed back into the hot-water loop system. The tertiary heat source is a small ground source geo-exchange field that has a relative capacity of 67 kW. The geo-exchange field was sized according to the buildings cooling requirements, as primary cooling source to balance heat injection and extraction over the year. Since the building is located in a mild climate cooling is only provided for the theatre, electrical rooms, and the café. The heat-transfer system with the EOS building is designed as a backup cooling system. The heating system is backed up through an electric boiler.

The DEC building has a large[15] geo-exchange field as its primary heating and cooling source. The field is connected to a cold-water loop and a hot water loop in the building that can both extract and inject heat simultaneously. Control valves regulate the connection between the geo-exchange field and each of the loops. This system allows to heat and cool different building zones simultaneously. The back-up heating system consists of condensing natural gas boilers to provide sufficient heat capacity during peak heating demands.

All three buildings are equipped with a solar hot water system to preheat the water for domestic use. The JPCE building pre-heats water by vacuum tube solar panels and flat plate solar panels that are supplemented by electric gas boilers. CIRS supplements the solar pre-heated water by heat from the heat pumps and electrical boilers as a back-up system. The DEC building uses a condensing natural gas boiler to meet the domestic hot water demand.

[15] Information on the rated capacity could not be made available for the study.

While DEC's only renewable energy system is the solar hot water supply, JPCE and CIRS both implemented photovoltaic cells to reduce the net electricity demand in the building. The JPCE building generates large amounts of electricity by a 259-kilowatt solar photovoltaic (PV) array. The PV array is a grid-tied system, which allows the building to export electricity to adjacent buildings on the Okanagan campus, when the supply exceeds the building's electricity demands. CIRS integrated a total of 25-kilowatt PV panels as exterior window shades and shades on the glass roof of the atrium.

In addition to the typical building functions, the CIRS building was designed with its own rainwater harvesting system and wastewater reclamation system. The wastewater treatment system was intended to collect, treat and disinfect the wastewater from the building and distribute it within the building for non-potable water needs such as toilet flushing and irrigation. The system is based on a solar aquatic process, which includes plants and bioreactors that are situated in a greenhouse environment. The wastewater treatment plant requires mainly electricity for running the pumps and lighting the greenhouse.

For the design prediction each project applied a different energy modelling software. The DEC building was modelled in the Energy Evaluation software version 4 (EE4) of the Commercial Building Incentive Program (CBIP). The JPCE building used the Integrated Environmental Solutions (IES) Virtual Environment (VE) software, and the CIRS building used the eQUEST® software.

3.4 Energy Performance Results – An Overview

As high-performance projects, all three buildings were designed to consume significantly less than functionally equivalent conventional buildings in the region. The following analysis aims to review the buildings' performance in the context of the design predictions and conventional counterparts. Figure 3-1 shows the predicted (i.e. modelled) and actual (i.e. measured) energy use intensity (EUI) of the three buildings, in comparison to a reference (i.e. similar conventional buildings in British Columbia). The EUI is based on the total building energy demand, including electrical, gas, and renewable energy sources, but excluding recovered thermal energy. A comparison between these EUIs has to be done with caution, since the data are of different nature. The reference buildings are based on average energy use data for academic and office type buildings, which include buildings of different age, functionality and usage. Reference EUI is based on actual energy consumed in academic or office buildings in BC, using a course climate index and reflecting real occupancy patterns.[16] Predicted EUIs are based on energy models that use design predictions and reference standards such as ASHRAE to simulate the final building and predict occupancy numbers. Actual EUIs are based on two years of actual energy consumption for occupancy levels that differed from typical reference standards, as will be further discussed in Chapter 4 (Section 4.5.4).

With these caveats in mind, Figure 3-1 indicates that predicted EUIs were significantly lower than references values for similar type buildings in BC.

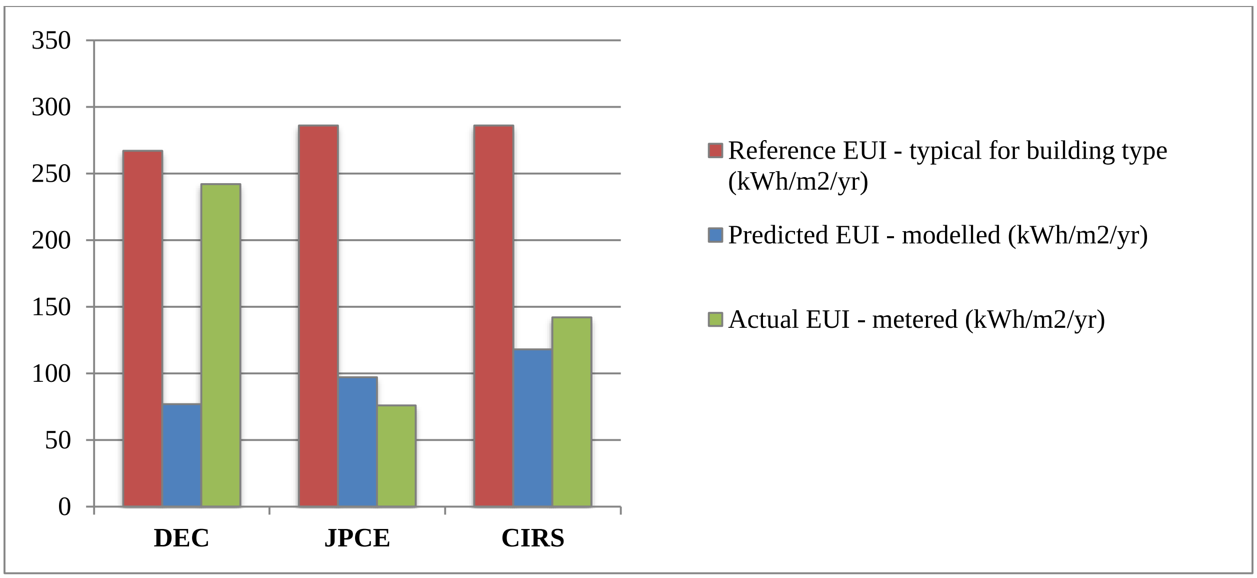

Figure 3-1: Comparison of building energy use intensity (EUI) predicted, actual, and reference.[17]

[16] Information were retrieved from the Comprehensive Energy Use Database of Natural Resources Canada (January, 10, 2015) and are based on values for 2012: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/trends_egen_ca.cfm

[17] Note: Reference EUI is based on actual energy consumed in academic or office buildings in BC reflecting real occupancy patterns (information were retrieved from the Comprehensive Energy Use Database of Natural Resources Canada (January 2015) and are based on values for 2012: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/trends_egen_ca.cfm). Predicted EUI is based on an energy model of the building that uses design predictions to represent the final building and that is typically based on ASRHAE

While the actual EUI of all buildings stayed below reference benchmarks, the actual consumption varied significantly compared to the design predictions. The DEC building required significantly more energy than anticipated in the energy model, while the JPCE building and the CIRS building consumed close to the predicted EUIs.

The DEC building had a much higher annual energy consumption compared to the predictions and consumed almost as much as reference office buildings in BC. Interestingly, DEC was predicted to require the least amount of energy, but had the highest actual energy consumption among the three buildings. The building consumed on average 242 kWh/m^2/year, compared to the predicted 77 kWh/m^2/year. The energy consumption was still lower than for an average office building in BC.

JPCE was the only building that required less energy than predicted at the design stage: The actual building had an average annual consumption of 76 kWh/m^2, compared to predicted 97 kWh/m^2. On average, academic buildings in BC required 286 kWh/m^2/year, more than twice as much as the amount consumed by the JPCE building. The CIRS building consumed 20 percent more energy than predicted, with an average annual energy consumption 143 kWh/m^2. The actual EUI is still significantly lower compared to the average academic building.

While this high-level of analysis shows that there is a performance gap in all three case studies, a more detailed analysis of the energy consumption will help to better understand the significant variation of the performance differences across buildings. In the following sections, the predicted and actual energy use intensity of each building is evaluated in terms of the monthly energy consumption and energy breakdown by end-usage if available.

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occupancy standards (Energy models often use occupancy benchmarks based on ASHRAE standards that were found to be higher than typically realized in buildings (Duarte et al. 2013)). Actual EUI reflects measured energy consumption at occupancy levels that are not the same as ASHRAE benchmarks (Actual occupancy numbers were evaluated for this study and will be discussed in Section 4.5.4)

3.4.1 District Education Centre

The energy system of the DEC building was expected to rely mainly on imported electricity. The design intent was to use natural gas only used for the domestic hot water system, which is preheated by the solar thermal system, and for the back-up heating system in case of emergency.

As mentioned earlier, the building's actual energy consumption was significantly higher than predicted in the design-assisting energy model (Figure 3-2). In 2012/13 the building required more than twice of the predicted amount of electricity and more than eight times the predicted amount of natural gas.

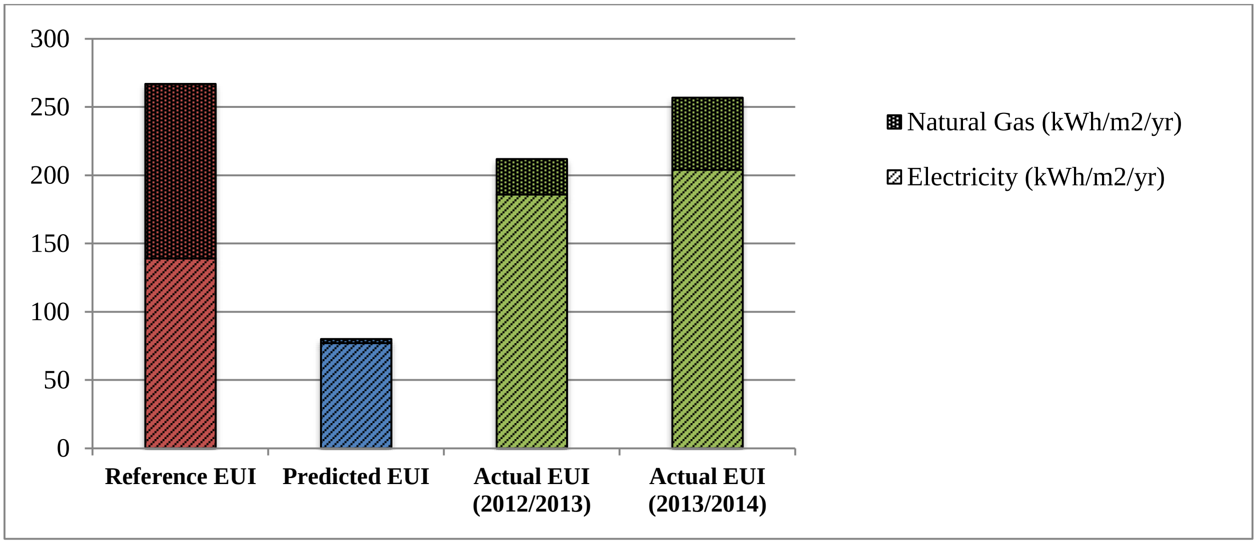

Figure 3-2: DEC: Energy use intensity by energy sources – natural gas and electricity: reference, predicted vs. actual.[18]

The electricity consumption increased only slightly in 2013/14, while the natural gas consumption doubled from the previous year values. This steep increase in natural gas is surprising since the natural gas should have been mainly used for DHW heating.

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[18] Note: Reference EUI is based on actual energy consumed in office buildings in BC, including activities, such as real estate, rental and leasing; finance and insurance; professional, scientific and technical services; public administration; and others (information were retrieved from the Comprehensive Energy Use Database of Natural Resources Canada (January 2015) and are based on values for 2012, http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/trends_egen_ca.cfm).
The survey takes into account the influence of weather on the energy demand of the buildings. The following natural gas conversion factor were used to calculate the energy content of 1m^3 natural gas in Giga joule: 0.0373 https://www.nrcan.gc.ca/energy/natural-gas/5641#measured).

The monthly comparison in Figure 3-3 shows that the building consumed significantly more electricity than predicted in the model throughout the year. The natural gas consumption was particularly higher than predicted during the heating season, from October to March (Figure 3-4). While the building is supposed to use natural gas only for the heating domestic hot water (DHW) heating, it is also the energy source for the backup heating system of the building (i.e. gas boilers). The energy model calculated only natural gas consumption for the DHW heating, but did not consider eventual use of natural gas for the backup heating system.

Although the building is using an intricate energy system requiring advanced management of building operations, energy meters for sub-systems were not installed due to budget constraints. Since no sub-metering system was available, higher consumption values for end-uses, such as lighting, plug load, HVAC, and DHW could not be evaluated through metered data and require further evaluation.

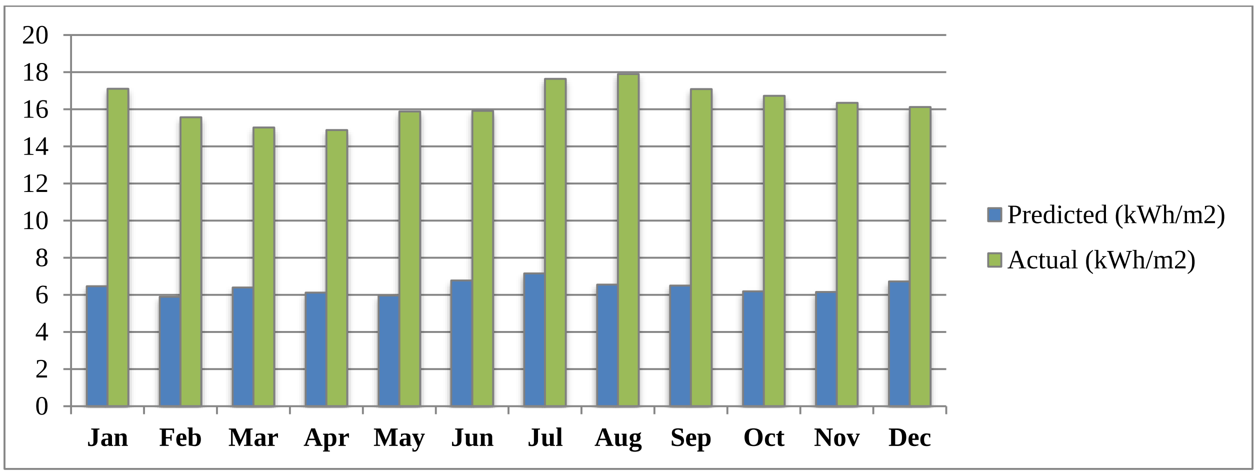

Figure 3-3: DEC: Monthly electricity consumption of the building: predicted vs. actual (between 2012 and 2014)[19]

[19] The values for the predicted energy consumption accounted for all building systems and functions, including the server room.

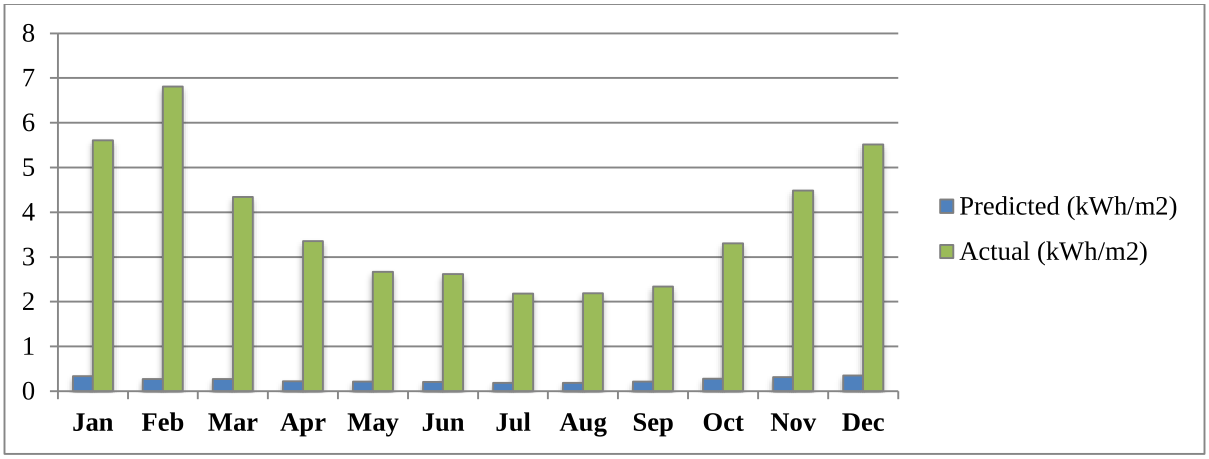

Figure 3-4: DEC: Monthly natural gas consumption of the building: predicted vs. actual (between 2012 and 2014)

3.4.2 Jim Pattison Centre of Excellence

While a typical academic building in BC covers half of its energy through natural gas, the JPCE building was designed to rely entirely on electricity. A design-assist energy model predicted a total annual energy demand (or EUI) of 97 kWh/m^2 for the building.[20] Figure 3-5 shows the EUI by energy sources for the reference building, the design predictions, and the actual consumption from 2012 to 2014. The actual energy consumption of the building was more than 20 percent lower than predicted in the first two years of operation (with 76 kWh/m^2/year and 74 kWh/m^2/year respectively).

According to the initial net-zero design intent, the required electricity should be generated to a large extent by the PV array, and supplemented with electricity imported from the grid.

[20] The design-assisting energy model was updated after completion of the building for LEED certification purposes, which lead to a higher total energy consumption of the building. According to the energy consultant the LEED version of the model is the more accurate model that should be used for comparison with actual energy consumption data.

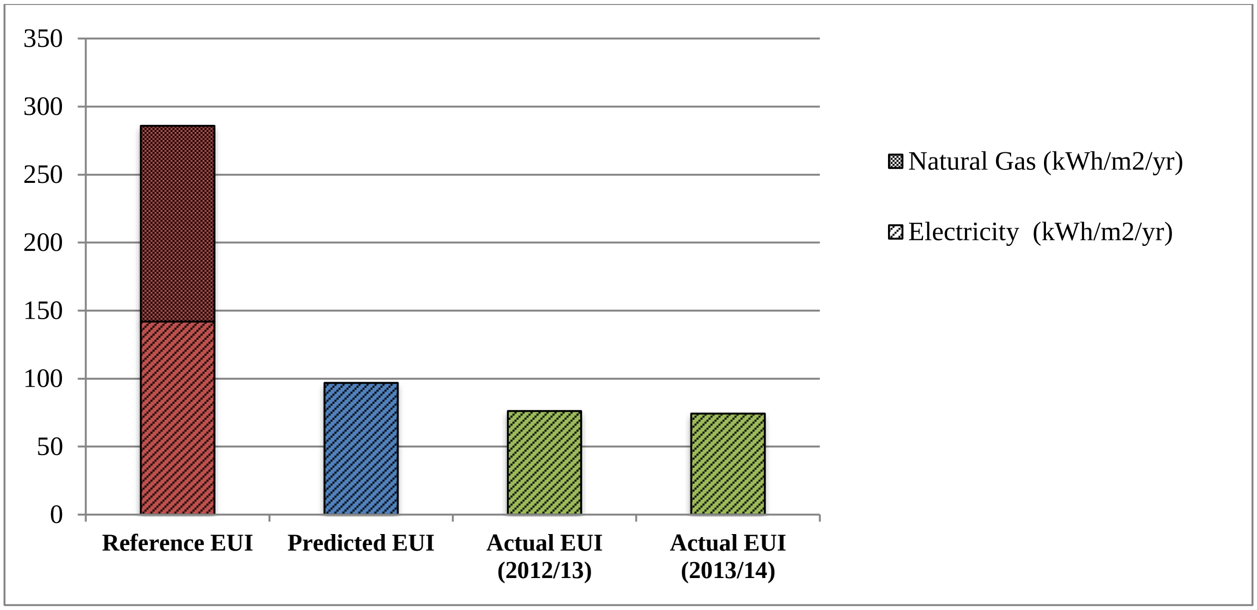

Figure 3-5: JPCE: Energy use intensity by energy sources – natural gas, electricity (imported from the grid as well as generated by PV panels): reference, predicted, and actual

A spreadsheet, submitted with the LEED certification documents, indicated that the PV system would generate 293 MWh/year to cover part of the building's energy demand. However, as a comparison with the energy model revealed, the capacity of the PV array was not high enough to meet the predicted energy consumption of the building. Only 80 percent of the predicted energy load could be covered with the designed PV array.

In the first two years of operation (from 2012 to 2014), the PV panels generated 229 MWh/year, 22 percent less than predicted. Furthermore, only half of the PV-generated electricity could be used directly in the building. The remaining surplus electricity was exported to adjacent buildings on the campus. The total amount of PV-generated electricity (i.e. 229 MWh/year) was equivalent to 58 percent of the building's total annual energy demand, not enough to meet the initial net-zero energy target.

Nonetheless, monthly-metered energy data revealed that the building consumed, on average, less energy than predicted in the energy model throughout the year (Figure 3-6). The building required particularly less electricity between September and April, which is surprising since the academic building was supposed to be used intensively during this time of the year, as most classes run between September and April.

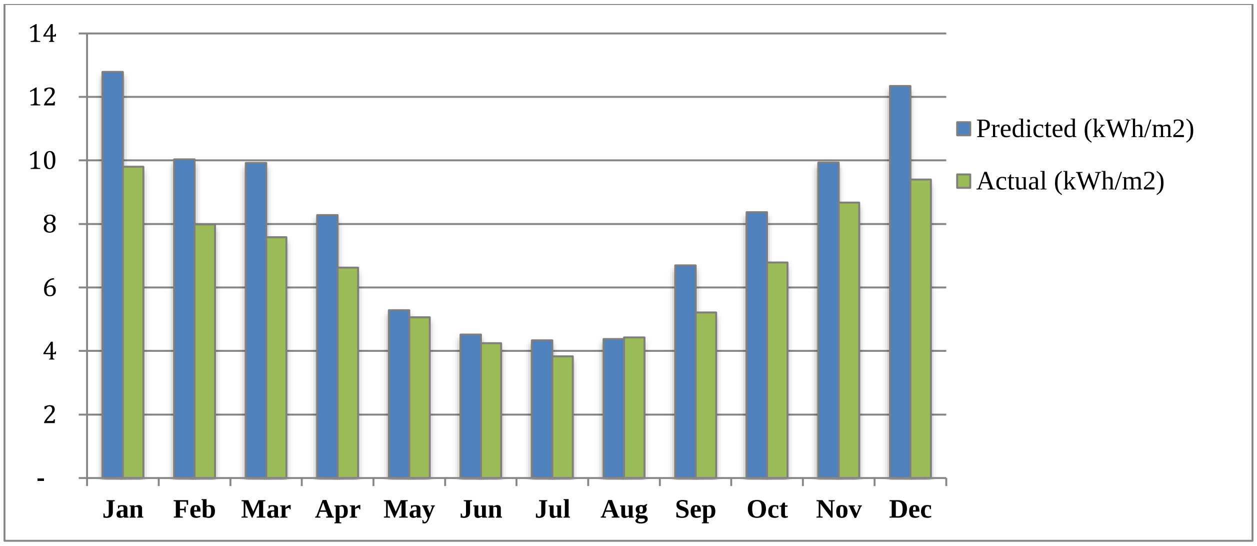

Figure 3-6: JPCE: Average monthly energy use intensity: predicted vs. actual (between 2012 and 2015)

The building is equipped with energy meters for major building systems that allow a detailed evaluation of the energy consumption by end-use: lighting, plug load, heating, ventilation and air conditioning (HVAC), and domestic hot water (DHW). However, metered data have only been logged since May 2014, and thus, performance data for individual building system were only available for the third year of operation. Figure 3-7 compares the actual consumption in 2014/15 with the predictions of the annual electricity breakdown by end-uses. The metered data show that the energy consumption for lighting and plug load was significantly lower than predicted (32 percent and 38 percent respectively), while the HVAC system as well as the DHW system required slightly more energy than predicted. The energy consumption for the HVAC system was close to the design prediction (with a 7 percent higher energy use than predicted), while the DHW system required 22 percent more electricity than anticipated in the energy model. The monthly energy results were varying for each building system and performance differences did not occur during a particular time of the year.

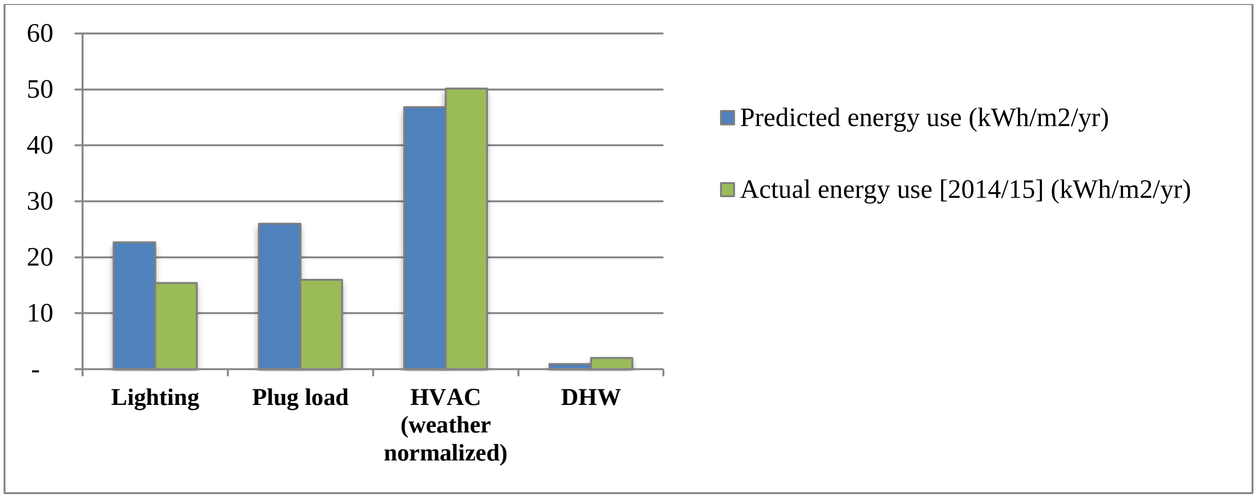

Figure 3-7: JPCE: Electricity breakdown by building end-uses: predicted vs. actual

3.4.3 Centre for Interactive Research on Sustainability

The CIRS building is a multi-purpose academic building and was designed to rely on electricity and thermal waste heat from an adjoining building. Electricity was imported from the grid and supplemented by solar panels, while thermal heat was recovered from the adjacent EOS building and supplemented by a small geo-exchange field. The design-assisting energy model predicted an annual energy consumption of 118 kWh/m^2 from which 7 kWh/m^2 would be provided by on-site renewable energy (i.e. 4 kWh/m^2 from PV panels and 3 kWh/m^2 from solar hot water). The operational data of the building showed that the actual electricity consumption of the building was 20 percent higher than anticipated, with a consumption of 141 kWh/m^2 in 2012/13 (144 kWh/m^2 in 2013/14) (Figure 3-8).

In 2013/14, the PV panels generated 3.8 kWh/m^2, close to the predicted 4 kWh/m^2. The amount of generated hot water could not be evaluated, since the hot water panels were not equipped with energy meters. Although the PV panels were sub-metered, accurate data were only available for 2013/14.

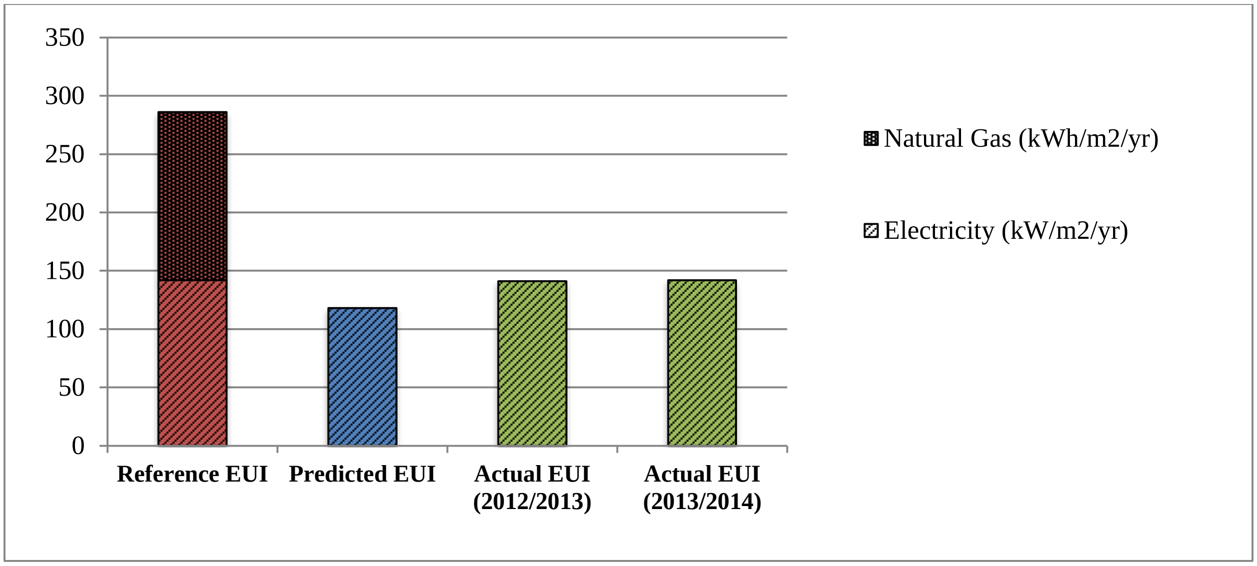

Figure 3-8: CIRS: Energy use intensity by energy sources – natural gas and electricity: reference, predicted vs. actual

While the overall energy consumption of the system was close to the predictions, major components of the heating and cooling system did not perform as expected in the design. The energy model predicted that the CIRS building would harvest 906 MWh/year of thermal energy from the exhaust of the adjacent EOS building and transfer 622 MWh/year of its own heat back to EOS. The graph below shows that CIRS harvested only 30 percent of the predicted annual 906 MWh/year of thermal energy in the first two years of operation (Terim Cavka 2013; Terim Cavka 2014; Fedoruk 2013). In 2012/13, CIRS sent back 18 percent of the predicted 622 MWh. Of those 112 MWh the EOS system used only 22 percent (i.e. 25 MWh) (Figure 3-9). In 2013/14, CIRS sent only 60 MWh to the EOS building, but EOS accepted more than 90 percent of the transferred heat. Therefore, the net-positive energy target was not reached in the first two years of operation.

A previous research study revealed that CIRS transferred more heat to the EOS building than it was able to harvest during the heating seasons in the first year of operation (Fedoruk et al. 2015; Fedoruk 2013).

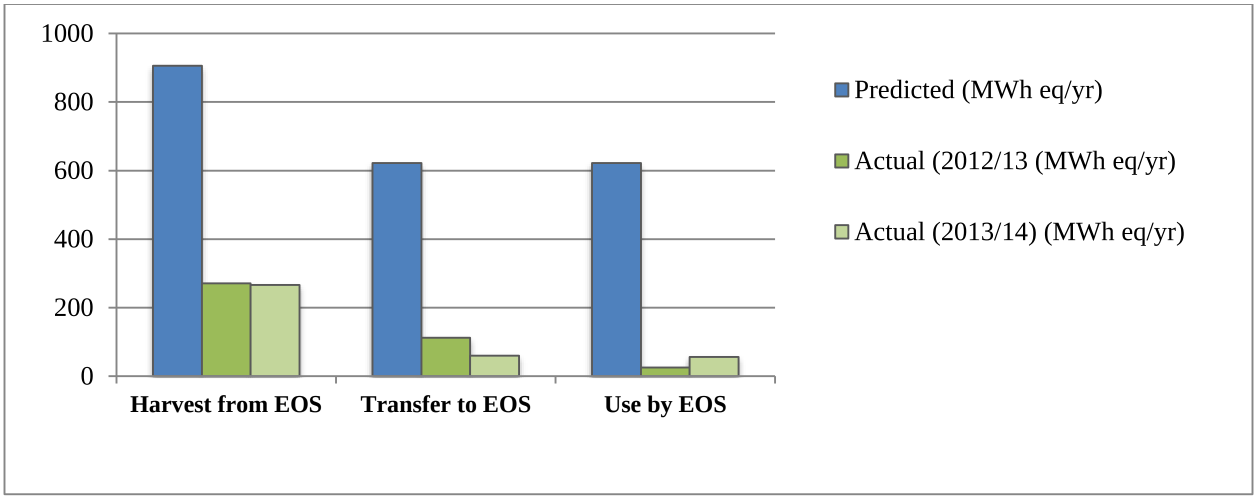

Figure 3-9: CIRS: metered results from heat-exchange with EOS building (heat harvested from the adjacent EOS building, heat transferred to EOS, and heat used by EOS building): predicted vs. actual[21]

Thus, instead of providing heat to CIRS, the EOS building was actually cooling CIRS during the heating season. The study revealed that the make-up air (MUA) unit on the rooftop of the adjacent EOS building did not work as intended in the design (Fedoruk et al. 2015; Fedoruk 2013). The exhaust temperature of the EOS building was 4°C lower than assumed in the design, and thus, less heat could be harvested from the adjacent building. Furthermore, the design of the transfer system that is connected to the air handling unit of the EOS building did not allow for the intended heat transfer from the CIRS building to the EOS building, since the existing EOS air handling was operating differently than anticipated in the design (Fedoruk et al. 2015).

It was also revealed that the installed smart meters did not record the heat transfer correctly between the two buildings (Fedoruk 2013). Harvested heat by CIRS and transferred heat to EOS were recorded simultaneously by non-directional smart meters that did not allow for an evaluation of the direction of the heat flow. As a consequence, the recorded results were incomplete in representing the actual heat transfer between the buildings (Fedoruk 2013).

Similar shortcomings occurred for the remaining building systems. Over 30 electrical sub-meters were intended to allow a detailed evaluation of the energy consumption of the system, but as

[21] The actual consumption data were obtained from Belgin Terim Cavka and Laura Fedoruk who collected the metered data in previous studies(Terim Cavka 2013; Terim Cavka 2014; Fedoruk 2013).

electricity meters were grouped together in several motor control center panels, it was cumbersome and not always possible to obtain a detailed energy breakdown by end-uses (Salehi et al. 2015). Only lighting loads and plug loads were metered separately, while mechanical systems were grouped together on several electricity panels. The panels for the mechanical systems included the electricity load for heating, cooling, pumping, fans, domestic hot water (DHW), as well as the emergency systems, power transformers and the uninterruptable power supply (UPS) system (Terim Cavka et al. 2014).

Figure 3-10 shows the results of the electricity breakdown for plug load, lighting, and the mechanical system for two years of operation, based on data from annual energy reports of the building (Terim Cavka 2013; Terim Cavka 2014).

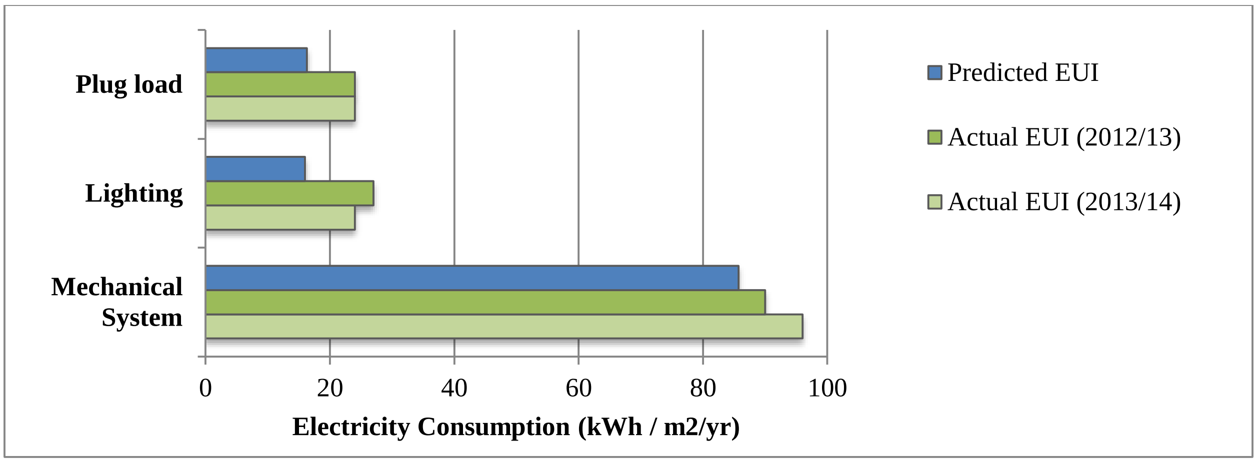

Figure 3-10: CIRS: energy use intensity by end use (plug load, lighting, mechanical system): predicted vs. actual

The plug load was predicted to make up 14 percent (or 16 kWh/m^2/year) of the total electricity consumption. In the first two years of operation, the building required on average 24 kWh/m^2/year, 50 percent more than predicted. The actual lighting load was also significantly higher than the predicted 16 kWh/m^2/year. The lighting load was 69 percent higher in the first year and 50 percent higher in the second year of operation. The mechanical system required most of the buildings energy consumption. The actual electricity consumption of the mechanical system was only 10 percent higher than the predicted 86 kWh/m^2/year. During that time, the CIRS building harvested and transferred significantly less heat to the adjacent EOS building than predicted. Since the building was working in part load, the heat pumps, power transformers, and the UPS system operated at lower efficiency, and thus, required more electricity to operate (Salehi et al. 2015). Together, transformers and the UPS system were responsible for 10 percent of the mechanical load (Terim Cavka 2013; Terim Cavka 2014). Furthermore, the rainwater reclamation plant and wastewater treatment plant of the building did not function since the building opened. Although the wastewater treatment plant did not process any water, 9 percent of the total annual EUI (or on average 13 kWh/m^2/year) were required in order to maintain the system (Terim Cavka 2013; Terim Cavka 2014).

3.5 Discussion of the Performance Gap

The previous evaluation revealed performance gaps, between predicted and actual energy consumption, for all three case-study buildings. The energy performance gap varied significantly in size and compared to the design predictions. While both academic buildings, JPCE and CIRS, performed close to the predicted energy use intensity, the office building, DEC, under-performed the design predictions significantly.

The DEC building showed the largest performance gap among the buildings that increased from the first year to the second year of operation. While the electricity consumption was consistently higher during the two-year time period, monthly consumption data displayed a sudden increase in the use of natural gas in the second year of operation. The increased natural gas consumption can be an indicator for changes in the system operation or failure of system components. Since the building was not equipped with a sub-metering system, an alternative approach of analysis is required to provide performance information about the current usage and functionality of the systems, as well as about the occupancy of the building. Since extensive commissioning of entire building systems was not performed, additional information needs be acquired from stakeholders that were involved in the implementation or operation process of the building.

The JPCE building was the only building that required less energy than predicted in the energy model. Sub-metered data revealed that the building required significantly less energy for lighting and plug load, and slightly more for HVAC and DHW systems than predicted in the design. Performance gaps in the electricity consumption for the lighting, equipment (i.e. plugs), and

DHW could indicate changes in the occupancy of the building. As the lighting system was regulated through occupant controls, the lower energy consumption for lighting could be an indicator for lower-than predicted occupancy levels. The same applies to the lower-than-predicted plug load that is mainly related to equipment use by occupants. However, the DHW load, which is mainly related to water use for kitchen and showers, was higher than predicted. Thus, the actual consumption values did not consistently indicate a lower-than-predicted occupancy of the building. In order to understand these findings, an evaluation of potential reasons for performance differences, including occupancy, is needed.

The breakdown of the CIRS building revealed significantly higher electricity consumption for lighting and plug loads, and a slightly higher consumption for the mechanical system than anticipated in the energy model. Although the mechanical system load was close to the predictions, mechanical systems did not operate as intended in the design. The waste-heat transfer system, as well as the wastewater treatment plant did not operate as expected in the design, changing the overall operation of the mechanical system (Fedoruk et al. 2015; Salehi et al. 2015). Thus, power transformers and the uninterruptable power supply system consumed additional energy, as they were working under lower efficiency levels (Salehi et al. 2015). A previous study of the waste-heat transfer system found potential reasons for the performance gap being related to

- insufficient consideration of system boundaries at the design stage;
- commissioning of individual components rather than of the entire systems during construction and commissioning;
- changes of operation sequences from the design intent after project completion;
- lack of appropriate information for building operators; as well as
- misaligned incentives and lack of feedback processes at the institutional level (Fedoruk et al. 2015).

An as-built model revealed that the LEED model of the building did not account for the energy required to operate the water treatment centre and for the occupant behaviour in calculating energy requirements for the HVAC systems (Salehi et al. 2015). These results indicate that discrepancies in the buildings' energy performance are potentially related to various causes stemming from the design, modelling, construction, commissioning, and operation of the building. These stages of the building lifecycle need to be assessed to identify potential reasons for performance gaps.

The three case-study buildings have shown that detailed energy performance data are not readily available, even for high-performance buildings. The DEC building had only monthly energy bills available for its overall electricity and natural gas consumption. The lack of sub-metering is a common phenomenon for office buildings and commercial buildings, which limits not only building performance evaluations but also the operational viability of a building (PlaNYC 2012; Karell 2015).

Although the other two buildings were equipped with sub-metering systems, consistent performance data were not readily available. Data were not logged consistently for the first years of operation or were not recorded at the sub-system level. For example, the JPCE building had 400 sub-metering points installed, but data for only 15 of them were logged in the first two years of operation. For the CIRS building, electrical meters were not segregated by end uses as intended in the design, which complicated a detailed performance evaluation. Previous studies of CIRS revealed that BMS-monitored data required calculations and queries for more detailed performance evaluations and were not consistently reliable (Fedoruk et al. 2015; Salehi et al. 2015). Other research studies found similar deficiencies in the monitoring systems due to a lack of careful implementation of control strategies (Lowry 2002). According to Armel (2013), predicted energy targets would be difficult to meet, if advanced metering systems were installed 'without careful consideration of the human element' (Armel et al. 2013). Consistent performance data are required to allow for a detailed energy performance evaluation of buildings. The variability in quality and quantity of actual performance data that was found in the three case studies highlights the importance for improved guidelines that guarantee the documentation of energy performance data in buildings. One approach could be to implement mandatory energy benchmarking initiatives, which can help to increase availability of consistent energy performance data (PlaNYC 2012).

As the energy performance data varied significantly for the three buildings, reasons for performance gaps could not be evaluated through performance evaluations of individual building systems. The energy use of sub-systems indicated that reasons for performance gaps may be of technical nature, but could be also related to dimensions such as operational practices and occupancy of the buildings. As the results have shown, a range of factors has to be considered when analysing the energy performance of buildings. Previous studies of the CIRS building revealed that institutional barriers, misaligned incentives, and lack of information caused performance differences in the building (Salehi et al. 2015; Fedoruk et al. 2015). Reasons may not only be related to the design or building operation, but could also stem from other stages of the building lifecycle such as construction and commissioning. This calls for an alternative approach of analysis that allows for an in-depth evaluation of reasons that contributed to performance differences over the building lifecycle.

Chapter 4: Exploring Reasons for Identified Energy Performance Gaps

As the previous chapter revealed, performance gaps occurred in all three case-study buildings, reflecting a significant range of energy performance differences compared to design predictions. In response to these findings, this chapter explores reasons for the identified energy performance gaps through interviews with key stakeholders that were involved in the design, construction and operation of the three case-study buildings. While these experts are often not considered in building performance or post-occupancy evaluations, they are increasingly recognized as integral to the performance of green buildings. Their involvement in the development and operation process has been central to the final performance of the three studied buildings, which will be discussed in the following pages.

4.1 Methods

As the literature suggests, there are a number of reasons that can contribute to performance differences of sustainable buildings, which can arose from different stages in the building lifecycle. As reasons are frequently discussed in terms of these stages, it has been found useful to organize the literature accordingly. The literature review in Chapter 2 provided information about common reasons for performance gaps and was used as a foundation for the expert interviews that will be discussed in this chapter. The most common reasons found in published and grey literature were synthesized in a number of key causes that contributed to performance gaps in green buildings.

This comprehensive list of reasons (discussed in detail below) was then used to develop interview questions with key stakeholders, who were involved in the development and operation of the three case-study buildings: architects, engineers, and energy consultants, as well as construction managers, commissioning agents, and building managers. Experts were grouped into designers (D), consultants (C), and building managers (M), in order to emphasize their main role and protect their identity. A total number of 19 expert interviews and two interviews with owner representatives (O) were conducted, each approximately an hour long.

The semi-structured interviews included questions about development and operation procedures, as well as technical questions about energy performance strategies applied in the case studies. Open-ended questions on successes, challenges, and surprises that occurred at different stages in the building lifecycle prompted discussion of identified performance gaps.

Hypotheses from the literature guided a deductive content analysis of the interviews, which were coded using the qualitative data analysis software NVivo. Emerging themes and categories were added to the analysis by following an inductive approach. The results from the interview analysis were complemented by observations from guided building walkthroughs and visits of electrical and mechanical rooms, as well as building documents. Where available, the energy modelling reports and commissioning reports were acquired from consultants, for further analysis of reasons for performance gaps during the building design and commissioning process of the buildings.

4.2 Potential Reasons for Performance Gaps – An Overview

As discussed in the literature review in Chapter 2, there are multiple reasons that can contribute to energy performance gaps in the buildings. Based on the literature review the most common reasons for performance gaps in green buildings are summarized in the following table.

Table 4-1: Common Reasons for Performance Gaps Found in 'Green' Buildings.

Category	Performance gap reason	Examples & References
Planning & Design	There is a lack of quantitative targets to guide the design process.	➢ Energy consumption targets are not specified in briefing and design criteria. ➢ Environmental systems are overdesigned compared to actual occupancy. (Newsham et al. 2012; Mahdavi 2009; Morant 2012; Newsham et al. 2009; B. Bordass, Cohen, et al. 2001; B. Bordass et al. 2004; Carbon Trust 2012; W. Bordass et al. 1997)
	Buildings are thought of as separate entities without consideration of contextual variables (e.g. building connections, system networks).	➢ Poor boundary definition of new system networks. ➢ Energy exchange systems are not evaluated in the context of existing infrastructure. (Fedoruk et al. 2015; Fedoruk 2013; Terim Cavka et al. 2014; Dasgupta et al. 2012)
	Building users needs and operational viability are not considered in the design of new building systems.	➢ Technology is used as an answer for management problems without considering the level of support of building users and operators required running the systems. ➢ Poor usability of automated systems such as lighting for occupants and operators. (Salehi et al. 2015; Morant 2012; Fedoruk et al. 2015; Dasgupta et al. 2012; Armel et al. 2013; Shen et al. 2012; Blumsack & Fernandez 2012; B. Bordass, Leaman, et al. 2001; W. Bordass et al. 1997)
	Energy models and other design tools assessing the performance are typically not used in the design process beyond certification and permits.	➢ Simulation tools are not used for performance analysis to support design-decision making. ➢ Changes in the design are rarely followed through in the energy model (e.g. changes to insulation, operation hours or controls). (De Wilde 2014; Schlueter & Thesseling 2009; Zero Carbon Hub 2013; Barry 2013)

Category	Performance gap reason	Examples & References
Modelling	Energy models do not accurately capture the energy consumption of a building due to: a. the simplification of complex energy-saving and energy supply systems;	➢ Simulation tools are limited to simulate novel design features such as radiant floor heat, natural & displacement ventilation, and solar thermal systems. (Terim Cavka et al. 2014; Raftery, Keane & Costa 2011; Ohba & Lun 2010; L. Wang et al. 2012)
	b. the incomplete representation of building energy loads;	➢ Energy models do not account for places such as circulation areas, support spaces, or for building services such as IT loads and monitoring systems. (Beauregard & Berkland 2011; Raftery, Keane & Costa 2011; Barry 2013; Cheshire & Menezes 2013; Binks 2011; Diamond, R. 2011; B. Bordass et al. 2004)
	c. limitations in accounting for variation of building usage; and	➢ Occupancy hours do not include additional after-hours and variable usage. ➢ Operation hours and set points are unknown for unconventional HVAC systems and different building types. (L. Wang et al. 2012; Cheshire & Menezes 2013; Davis & Nutter 2010; Mahdavi 2009; Knight et al. 2007; Hoes et al. 2009; Salehi et al. 2015; Butera 2013a; B. Bordass, Cohen, et al. 2001; B. Bordass et al. 2004; Liao & Barooah 2010; Azar & Menassa 2012; Korjenic & Bednar 2012)
	d. lack of consideration of accuracy of weather data and climate change.	➢ Local weather conditions are estimated by averaged yearly weather data from the past decades. ➢ Limited availability of geospatial sampling locations of approved weather data and of climate change weather files. (Bhandari et al. 2012; Chan 2011; Jentsch et al. 2008; Cheshire & Menezes 2013)

Category	Performance gap reason	Examples & References
Construction	Building parts and systems are not installed according to the design intent.	➢ Installation changes to service & control systems alter the building performance. ➢ Unexpected performance of new systems due to lack of training. (De Wilde 2014; Menezes et al. 2012; Fedoruk 2013; B. Bordass et al. 2004; Bell et al. 2010; Zero Carbon Hub 2013)
	Change orders and value engineering during construction can compromise sustainability features.	➢ Cost cuts after the design stage often affect novel design strategies (e.g. PV control devices, unprecedented insulation). ➢ Changes in contractual design reduce quality and functionality of equipment. (Bell et al. 2010; B. Bordass et al. 2004; De Wilde 2014)
Commissioning	Commissioning of new building systems is rarely done in accordance with the design intent.	➢ Malfunctioning energy-saving devices such as heat recovery and control systems are not detected during commissioning. ➢ Poor setting, calibration, and programming of automatic control systems. (Fedoruk 2013; Zero Carbon Hub 2013; Morant 2012; B. Bordass et al. 2004; Mills 2011)
	The commissioning process is incomplete or inadequate for novel building systems.	➢ The numerous commissioning steps are rarely all exercised during commissioning. ➢ Lack of knowledge of appropriate commissioning of new building systems. (Mills 2011; Jump et al. 2007; NCBC 2008; Fedoruk et al. 2015)
Handover	There is a lack of verification during and after project completion compromises the building performance.	➢ Low-level chronic problems receive little or no attention after project completion. ➢ Mistakes during design are repeated due to a lack of feedback from industry and client after project completion. (De Wilde 2014; Zero Carbon Hub 2013; Carbon Trust 2012; Morant 2012; Fedoruk et al. 2015; B. Bordass et al. 2004; B. Bordass, Cohen, et al. 2001)

Category	Performance gap reason	Examples & References
Operation	Sequences of operations and maintenance are changed from original design intent.	➢ Equipment and systems are left on permanently during nights and weekends to prevent user complaints. ➢ Building systems are shut off due to operation issues or insufficient training and expertise of building managers. (Newsham et al. 2012; Cheshire & Menezes 2013; L. Wang et al. 2012; B. Bordass et al. 2004; B. Bordass, Cohen, et al. 2001)
Occupancy	Building systems (e.g. ventilation system) are not used as expected by building occupants.	➢ Operable windows have been left open during heating season changing the heating and ventilation mode of the building. ➢ Controllable lights are left on and additional equipment (e.g. space heaters, fans and plug-in lights) is used. (Fabi et al. 2012; Herkel et al. 2008; Mahdavi 2009; C. Wang et al. 2011; Liao & Barooah 2010; Hoes et al. 2009; Davis & Nutter 2010; Azar & Menassa 2012; Brown et al. 2009)

4.3 Evaluation of the Building Development Process

As discussed in Chapter 3, performance gaps occurred in all three case studies and varied significantly across projects. While sub-metered energy consumption data provided useful information about the performance of individual systems, the data did not indicate what caused performance gaps in the three buildings. For the CIRS building, previous research studies indicated that reasons for the identified performance gaps originated from shortcomings such as misaligned incentives during the development of the building (Fedoruk et al. 2015; Salehi et al. 2015). The literature review confirmed these findings, indicating that reasons for the identified performance gaps can stem from various stages of the building development and operation process. In the following discussion, I evaluate potential reasons in the context of the identified performance gaps in the three case-study buildings. The literature is hereby used as a guide for the analysis of interviews with designers, consultants, and building managers from all three building projects. As such, I discuss reasons for performance gaps for each stage of the development and operation process: from planning/design and modelling, through construction, commissioning and handover, to building operation, and occupancy.

4.4 Planning & Design

The planning and design stage sets the foundation for the performance of the building by making key decisions on the purpose, function, and form of the building. For all three case-study buildings, ambitious energy performance targets were set at the planning stage. The way, however, these goals were integrated and realized during the design process, differed significantly from each other, indicating potential reasons for energy performance gaps in the buildings.

4.4.1 Energy Goals & Quantitative Targets

Setting clear goals for performance is one of the key elements of the integrated design process (IDP) and is generally established at the outset of the project (Lewis 2004). All three studied buildings developed a set of energy performance goals.

The DEC project team aimed for an annual energy use intensity of 100 kWh/m^2, with a primary focus on innovative design features for the HVAC system and passive design strategies for lighting and ventilation. The JPCE building and the CIRS building set equally specific, but even more ambitious energy performance targets, aiming for a net-zero and net-positive energy performance, respectively. The JPCE project team planned to achieve an energy performance below 100 kWh/m^2 through the use of renewable energy sources, a high-performance envelope, passive design strategies, and modern technologies. The CIRS building set even more ambitious energy targets, aiming for an overall net-positive energy performance, as well as net-positive embodied and operational carbon emissions. CIRS main strategies were to make use of available and renewable energy sources, passive design strategies, and highly energy-efficient building materials and technologies.

In addition to the energy goals, the projects had other sustainability goals such as a reduced water consumption and storm water management. While the DEC building mainly focused on a reduced water consumption and a reliable storm water management strategy, the JPCE project aimed for net-zero water consumption, and CIRS targeted to become net-positive in water usage by designing on-site water treatment plants. All three projects specified targets in terms of certification by green building rating tools. The DEC building aimed to achieve LEED Platinum certification and to consider aspects of Living Building Challenge (LBC), without seeking certification. The JPCE aimed to achieve both, LEED Gold and LBC certification. The CIRS building set out to meet LEED Platinum and LBC certification.

While often perceived as a constraint, one of the main goals for each project was to stay within a certain budget, as members of the development team reported. For development team of the DEC building, the budget was the over-riding constraint, which an owner representative recalled as part of the vision statement of the building: "to maximize energy efficiency and social environmental responsibility within budget" (O1, personal communication, May 21, 2014). The same applied to the JPCE building, which had a fixed budget from program offered by the government. Despite these constraints, the budget was always considered in the context of performance and efficiency targets, as members of the development team described. According to a consultant, "lifecycle cost was an enormous driver for us to continually make decisions"

(C5, personal communication, Feb 06, 2015). As a result, low life cycle costs became one of the major goals in the design process, in particular with regards to long-term savings in building operation and maintenance. The CIRS building had similar goals to build the project at market price.

Beside the quantitative targets, the projects had guiding principles describing the design and function of the building. The main focus of the DEC building was to design an open, welcoming, and transparent building, bringing together the Board of the Surrey School District from seven different locations into one building. According to one of the designers, this was a major cultural shift for inhabitants to move from private offices to a large open plan office design in the DEC building. The vision of Board representatives was to celebrate education and natural elements such as daylight, fresh air, and natural materials in the building.

For the JPCE project, the major goal was to create a building that could be used as a teaching tool for green building technologies for the college students and would connect the campus to the surrounding community. Similarly to JPCE, the CIRS building was intended to function as a living lab for innovation in green technologies, in which the building would become part of a process of research and teaching. Furthermore, the building strived to be net-positive in terms of inhabitants' health, productivity, and subjective wellbeing. As we will see in the subsequent section, the energy performance targets, together with further quantitative and qualitative project goals had a significant impact on the subsequent design and decision-making process for each project.

4.4.2 Alignment of Targets in the Integrated Design Process

One of the essentials in the integrated design process is the commitment to the intended performance goals to ensure their implementation in the final design of the building (Lewis 2004).

Energy goals and targets were promoted and supported by different stakeholder groups represented in the design process, as members of each project team reported. It was either the design team or building owners, who showed the most commitment to the initial performance targets.

For the DEC building, the initiative for a high-performance design came from the design team, which promoted new technologies, such as a chilled beam system and a geo-exchange system. Building owner representatives, the Board of Surrey District Education, were engaged in the design process and supported most of these goals throughout the project. While representatives of building management were initially in favour of a more traditional system design that they were already familiar with, managers eventually supported the proposed innovative design strategy. As a representative of the design team described, the design process as very helpful to integrate novel design features supporting the performance targets of the building:

> So by having the IDP we were able to model early and we were able to actually shift the school district away from the systems they knew to a new system. And there was huge resistance there, because they were saying, "Well, we have all the school buildings that have this system. We don't want to have a different one." But when they saw the advantages and how much better the air quality would be they were convinced to go with the chilled beams and the geothermal. (D1, personal communication, Dec 11, 2014)

On the other hand, some of the consultants highlighted the challenges that were faced in choosing the viable design option during IDP. One of the consultants raised concerns about two of the proposed design strategies with regards to their operational viability, the chilled beams and the geo-exchange system:

> I've been arguing because, well the ground source-system isn't new, but at the time chilled beams were new, and I think they equated the application of the system to being innovative. But I argued then and I still argue now that that was not the best solution for this building. So in terms of the integrative design process, I think that's where it failed, and I think it's resulted in a number of subsequent failures in terms of being able to operate the building; because it is a very complex and very unstable building from an HVAC perspective. (C1, personal communication, Jan 14, 2015)

While alternatives were considered in IDP, the final decision was made in favour of both novel building systems, which were implemented in the final design. One of the reasons for choosing the chilled beam system was that the project did not have the financial capacity to integrate a raised floor system. While this novel technology from Europe was intended to improve the energy performance, the operational requirements were not further considered at the design stage. In general, consultants, such as the energy consultant and construction manager, were the stakeholders provided most of the feedback on the design in terms of operational viability, while contractors for building construction were not part of the design process. Although the commissioning agent was initially involved in the design process, his main engagement only started during the construction process of the building.

In contrast to the DEC building, the energy efficient design for the JPCE and CIRS building were primarily promoted by owner representatives (instead of designers), who were involved in the design process. For the JPCE, a driving force in the integrated design process was a supportive owner, who was dedicated to integrate the most operational viable and cost effective sustainable strategies in the building design. With his incentive and dedication to look for the most viable solutions in terms of energy performance and life cycle costs, the owner representative had a major influence on the design team, consultants, and building managers, as a consultant described:

> […] He never seemed to settle. Like it was always, he was just [saying] "No there has to be an even better way"; like, "That's a great solution, but you guys came to it too quickly!" Like if everyone [was saying] "Ok, we've solved it, move on", he was [saying] "No, let's pull it back and let's beat it up a couple of times more, and see if we can improve upon it." And we did that with everything. It just became that culture. And he was the driver of it, but then it started becoming that culture of, 'maybe this is too easy, we'll park it because it was too easy; let's keep thinking and see if we can improve upon it'. (C5, personal communication, Feb 06, 2015)

The support and driving initiative from the building owner representative led to a design process, which fostered open communication and close collaboration among stakeholders. As a result, IDP was perceived as a successful approach for constructive communication among stakeholders that led to collaboration beyond the usual "siloed" design approach:

> The integrated design approach really helps people to collaborate, and to collaborate openly and honestly. We had several… several open out screaming matches during the design phase. Several, because there were a lot of strong opinions in the room, and the beauty of that was, we were all comfortable enough to speak our minds and give our strong opinions. And we were all comfortable enough not to… No one ever left the room in a mood or just got up and left and never came back. No one ever did that. It was always done with respect. And it was always done with the intent of making it an incredible design. And I think it worked. It paid off. (C5, personal communication, Feb 06, 2015)

This supportive environment together with the two-year timeframe for building design and construction led to a streamlined design process, in which stakeholders provided feedback to all areas of the building design, beyond their specific discipline. A design team representative described the benefits of this process as "collaborative decision making" and "creative problem solving", when decisions needed to be made quickly with the support of all stakeholder groups during the fast-track[22] development process (D2, personal communication, May 26, 2014). Members of the design team, consultants, and building managers all emphasised the benefits of the collaborative decision-making approach in order to achieve energy goals and performance targets for the building.

The CIRS project team, followed a similar design approach, which was mainly driven by the targets that owner representatives had set for the building. CIRS, however, had a unique situation, as several partnering institutions were initially involved as owners of the project. Multiple institutions were involved in the planning process of the building that was designed for several different sites and locations, and contributed to the vision of the project. However, due to a lack of sufficient funding and a shared inter-institutional agreement for the financial and legal requirements, the first building design never moved in to the design development stage. During that time, alternative options for funding and collaborations were considered, since the two main investigating institution were not able to come to a final agreement, as an owner representative described. The decision for the final project was made when UBC agreed to support the project, on the condition that it would be built on the UBC Campus and that all funding sources would be in place. Once this decision was made, UBC became the owner of the project with the responsibility for the financial and legal requirements. During this time, owner representatives, who had been involved since the early beginning of the project, were curial to the process as they ensured that the original vision was carried through the changes of location and project-partners. Despite their effort to retain the same design team on the final project, one of the companies had become part of a larger company and several individuals on the design team had changed position and location.

Nonetheless, most members of the design team could be retained on the project and helped to translate the project vision into the final design for the building. The original 24 sustainability targets were adapted to the new context and the goals were translated into a list of 10 guiding principles closely related to goals as described above. These guidelines provided a clear

[22] Fast-track construction is a project delivery strategy in which building construction starts before the completion of the design stage.

conceptual direction and working tool to the design team for the development of the building. The unexpectedly prolonged planning and design process required continuous commitment from the owner representatives, members of the design team, and strategic funding partners. Similar to the JPCE project, several owner representatives took a key role in ensuring the realization of the initial performance goals throughout major project changes, as one of the owner representatives described:

> Like it was not something that a lot of people thought was going to ever be built. So it just required constant hammering and that took a significant number of years and effort, mainly from Charles[23] and me. So it just took a lot of effort and we had to keep hammering and keep meeting and keep aggregating, and keep showing positive results and keep the momentum going. (O2, personal communication, Mar 21, 2015)

After several years of planning and design of the CIRS building, the final design process took another eight months, during which the entire project team had be engaged. Designers, consultants, building managers, and technology suppliers were involved in this final design process. While all parties provided valuable feedback on how systems could be integrated within the larger system, one of the designers described the challenge to find a common ground among all stakeholders during those meetings:

> Of course, there were challenges with everything, the challenges were bigger, you know. The meetings usually had like 30, 40 people and not everybody has the same agenda in my opinion. Everybody has their own agenda. […] So, everyone is different. Some of the suppliers that were involved and engaged, I think their main goal was to try to have their product to be a part of the showcase of the project. In terms of partnership, how they contributed, definitely they contributed to the design stage on how, you know, how their product or their technology would be applied. (D6, personal communication, Dec 19, 2014)

Along with the benefit of integrating all stakeholder groups in the design process, comes the challenge to reach consent among multiple expert groups. Each group brings expert knowledge from multiple professions and disciplines to the table that have traditionally not been involved in the building design process. As such, the IDP approach itself does not seem to be enough to guarantee a successful realization of performance goals, as one of the owner representative of CIRS described:

[23] Names have been changed to protect the identity of the people, who were involved in the project.

> I think the benefits of integrated design are sometimes overblown. I think people think too much of integrated design process when in reality, it's not that complicated, and it is not really providing tremendous benefit. I think there's huge benefits but not to the degree of expectations of people. People think that… that because you are now sitting at a table, automatically all the constraints are going to go away. And automatically all the issues of the project are going to go away. And guess what, no. The budget is still there. You have a project manager or program developer that is going to trump any decisions you make because the budget is dictating that. You have code and issues that are not going to go away because you are in an integrated design process. (O2, personal communication, Mar 21, 2015)

While the IDP can support the implementation of sustainable design goals, it is the team that matters eventually. According to the same representative, a key component to the process is teamwork of main designers and project manager and their collaborative experiences on previous projects. Design team members of the JPCE project gave the similar feedback, pointing out the importance of assembling a team of designers and consultants that has worked successfully together on previous project. One of the consultants summarized benefits of this approach for the development of the JPCE building:

> And yet when we do integrated design, I think it should be like an RFP [request for proposal] that goes out for an integrative design team. Come with your team. It should be that you actually have the ability to assemble your team. You know, the bones of your team, the superstructure of your team, to actually say, "Here's our team. We believe our team is the best and we are going to tell you why it's the best. Here's examples where as a team we have done this, this, this […] very successfully. Here it is; we've got a track record as a team." Rather than assembling individual silos and saying, "Now work well as a team. Oh and by the way you are going to do it lean, you are going to do an integrated delivery process, you are going to do a 'Living Building Challenge'. Have any of you guys done it?" "No…" Like I think for the Penticton project, the College did a really good job of assembling good bones of the team […] (C5, personal communication, Feb 06, 2015)

This approach may not be always possible to achieve and the teams for the three studied buildings were mainly not assembled based on previous collaborative experiences. How that affects the actual performance of each building will become clearer in the following sections.

4.4.3 Consideration of Contextual Variables

As the literature indicates, buildings are often thought of as separate entities without consideration of contextual variables, such as energy sharing networks. Among the three buildings, the DEC building was the only building that did not plan to integrate a multi-building system in the design. Although it was not originally planned, the energy system of the DEC building became the platform for an energy sharing system. After project completion, during the first year of building operation, the geo-exchange field of the building, the main energy source for heating and cooling of the building, was connected to an adjacent, 1,662 square-meter size, modular building, which was serving the Surrey School District as a learning centre. The connection provided cooling to the adjacent centre, and allowed the building to be operated during summer months. As one of the owner representatives described, the system network was installed at the ‘second phase’ of the project, at the same time when a potable building, which had served the Surrey School District for several decades, was demolished and extra parking and landscaping was added to the DEC building site. A different team of consultants and contractors installed the network, as an independent project after completion of the DEC building. A design team or energy consultant was not involved in this additional project. According to one of the owner representatives, the decision for creating an energy network with the adjacent building was made based on the fact that the geo-exchange system was designed for a higher capacity than the predicted demand of the building. The implication of the changed usage of the geo-exchange field was not further evaluated in an energy model prior to the installation of the connection. Most representatives from the design team (i.e. designers and consultants) of the original project were not aware of the installation of the energy network with the adjacent building after building completion. The experts, who had designed, analysed and tested the geo-exchange system, were not involved in the second phase of the project. Hence, there was no active knowledge transfer about the system design and set-up to the development team of the connection to the adjacent building during the second phase. These system changes affected the performance at a later stage of the building lifecycle, which will be discuss further in this chapter.

In contrast to the DEC building, the JPCE and the CIRS building both integrated some form of a multi-building system. As both projects were part of a larger campus, the design of system networks became a more obvious possibility. For the JPCE building, an electricity network was developed to reach the net-zero energy goal for the project. At the beginning of the project, the design team of the JPCE building decided to use a large PV array as the main energy source for the building. One of the designers described, the challenge in reaching the net-zero energy target within the specific context of the building. The PV array would produce more electricity during the summer when the demand would be generally lower (due to the summer break at the college), but it would produce less when the demand of the building would be high, during the rest of the year. The initial idea was to send electricity back to the grid when surplus energy was available during the summer, and to import electricity during the rest of the year in order to meet the net-zero energy target. However, a 'buy-back' solution with the local utility was legally not possible at the time. Hence, the development team decided to supply other buildings on the campus with the surplus energy, and to import electricity from the grid when required. Following this strategy the required electrical connection was set up and none of the interviewees for the project reported further challenges in designing or implementing the system network. However, other challenges hindered the project to meet the original design goal. During the design process, it turned out that limited roof space and budget constraints did not allow for an installation of a larger PV array that was needed to meet the net-zero energy goal. As a result, a PV array with a generation capacity of 259 kW was designed, instead of a PV system with a 400 kW-capacity. According to a designer, the project team decided to implement the first part of the original PV array, until metered performance results would show how much additional capacity was required to reach the original design intent after project completion. While this allowed the project team to consider additional funding sources to implement the half-million system, the original design goal could not be met. Despite the intent to implement the second half of the PV array in a second project phase, the system extension has not yet been realized, four years after project completion.

Compared to the JPCE, the CIRS building adopted a more intricate energy network system in order to meet the aspired net-positive energy target. The goal was to reduce the campus energy use through a waste heat-transfer system with the adjacent laboratory building. The system was designed to use the waste-heat from the lab exhaust of the adjacent EOS building for the new building and return excess heat back to EOS, to preheat the makeup air of the existing building. The transfer system was intended to help save more energy for heating of the EOS building, than energy required for operating the CIRS building. However, as described in the previous chapter, the existing system at the EOS building, which was part of the waste heat-transfer system, did not work as anticipated in the design. Interviews with members of the design team revealed challenges in the design and realization of the multi-building systems contributed to the performance issues at later stages of the buildings lifecycle.

The decision for the waste heat-transfer system was made early at the design stage. One of the consultants described how certain assumptions were made with the agreement of all consultants in order to model the system network at the schematic design stage. While these early assumption should have been verified as the design progressed, it turned out to be challenging to get access to detailed information about the actual system on the rooftop of the EOS building. The make-up air unit on the rooftop of the EOS building, where the heat-transfer system was going to be connected to, was considered a risk area with limited access. As designers described, site visits had to be coordinated with several authorities at UBC, including the Health & Safety department, and were limited to a certain amount of time in order to keep the building operational. One of the consultants recalled that only preliminary information about the system was made available to designers during the design stage. Detailed information on airflow rates and temperature set points were only made available once the project had moved into the construction phase. None of the interviewees mentioned that other information sources such as the energy model for the EOS building were used for the design of the system. Once the accurate data were made available, the decision for the design of the energy network had been already finalized. The challenges that arose from the lack of sufficient information, gathered during the design stage, will be discussed as we move forward in the analysis.

4.4.4 User-friendly Design & Operational Viability

Similarly to the alignment of energy targets, the implementation of these strategies in the final design is crucial for successful building operation. A component, which is often underestimated in the implementation process, is a user-friendly design to ensure a successful operation and building use by inhabitants and operators. The operational viability of building systems is hereby of particular importance for the overall building performance.

4.4.4.1 Novel HVAC Systems

While green buildings tend to use increasingly passive design strategies, the HVAC system often remains the main energy consuming systems (see Chapter 3). As such, the design strategy and operational viability of the HVAC system still plays a major role in the building performance discussion. While all three buildings chose a low-temperature heating system, which uses water as the medium to distribute heat throughout the building, the implementation strategies in the overall building systems differed for each project.

As mentioned earlier, the design team of the DEC building decided to use an active chilled beam system for heating, ventilation and air conditioning of the entire building, using a large geothermal field as main energy source. The system was designed as a four-pipe fan coil system, which allowed to heat and cool different zones in the building simultaneously. According one of the consultants, this combination of systems was very complex and unstable design for an HVAC system. The chilled beam system was new to the entire project team, as the European technology has only recently been introduced to the North American market. In combination with the set-up as a four-pipe fan coil system and the connection to the geo-exchange system, the chilled beam system would challenging to operate and maintain. As a building manager describes, the chilled beam system needs to be operated carefully to make effective use of the energy provided by the slow-responding, low-temperature geo-exchange system. As the system is difficult to conceptually understand, it would require expert knowledge to maintain and operate, which was not available for the project. According to the owner representative this high level of required expertise to operate and maintain for these systems was not expected at the design stage (O1, personal communication, May 21, 2014).

Managers faced similar challenges with the geo-exchange system, which did not work as anticipated in the design. The system was designed to be the main energy source for heating and cooling, supported by a heat recovery system and backed up with gas boilers for heating. While a backup heating system was provided, there was no additional emergency cooling system installed for the operation of the cooling equipment of the café and the server room, which led to major performance issues during building operation. According to the building manager, the lack of a back-up cooling system not only affected the conditioning of the office areas, but particularly the computer-sever room in the building and cooling equipment for food in the café. Two air conditioning units that use chilled water from the geo-exchange system provided cooling to the server room. While one of them was connected to an emergency power system to provide mechanical cooling in case the building was under emergency power, no alternative cooling source was provided. The lack of consideration of a sufficient back-up cooling system for the computer-server room could be due to the fact that the server room was added in the early construction phase of the building. As a design representative described, the project underwent a major functional change in the building design, in order to integrate a second building that was planned by the owner. Consultations with the surrounding community of the project revealed that less parking would be required than originally anticipated and that the parkade that was designed for the basement of the building would not be required. Instead, the space was made available to integrate another planned building within the DEC project. The parkade in the basement was changed into a server room, offices, and storage space. While a cooling system for the server room was developed and connected to the geo-exchange system, as primary cooling source, no backup-cooling source was installed. Furthermore, the heat generated from the server room was not recovered and connected to the heating system of the building. During operation, it turned out that the server room would have been required a backup-cooling source in several instances when the geo-exchange system failed. This design changes led to unanticipated challenges in the performance of the building after completion of the project, which will be discussed in more detail in Section 4.9.1.

In contrast to the DEC building, the JPCE and the CIRS building both chose a radiant heating and cooling system. The JPCE combined a radiant in-slab heating and cooling system with an open-loop geo-exchange system as primary energy source. While the design of the in-slab distribution system was fairly simple in terms of operational viability, the open-loop well system required unanticipated maintenance efforts. The open-loop geo-exchange system, which used domestic well water as energy source and sink, was chosen over a closed loop system, in order to be able to use the well water for irrigation purposes and toilet flushing in the building. However, the implications for the performance of the system design were not carefully considered during the design stage. As it turned out, high sediment content in the water caused problems of corrosion and mineral deposition in the system, which affected the overall system performance. As such, the six well pumps need to be exchanged every couple of years, which was not anticipated during the design of the system.

While the DEC building was lacking a back-up cooling system, the JPCE did not have a back-up heating system for the geo-exchange system. According to one of the managers, the geo-exchange system could not provide enough heat in the first year of operation, during an unusually cold winter. As it turned out, the pressure in the water-distribution system was lower than anticipated in the design. As a consequence, an electric boiler was installed by building operations to ensure sufficient heating capacity and to mitigate the risk for freezing in the water system, particularly in the in-wall heating system in the gymnasium.

In contrast to the previous two building cases, the CIRS project used multiple strategies for ventilation, heating, and cooling of the building, which require a high degree of operational sophistication. As the building was designed to function as a research lab, a building management specialist was anticipated for the project. Despite the more intricate heat distribution system (a combination of tempered air system, baseboard and in-slab heating), the main challenge should be the operation of the waste-heat transfer system, the main energy source and sink of the building. As discussed in the previous section, the waste-heat transfer system did not work as anticipated in the design. The malfunctioning system had less an effect on the operational viability than on the overall performance of the building. According to one of the building managers, the heat recovery system and the small geo-exchange field (the secondary heat sources and sinks) provided enough energy to heat and cool the building most of the time. This was mainly due to the sophisticated heat recovery system that provided heat from the auditorium to the rest of the building. As the building manager described, the heat that was produced by people using the large auditorium was recovered to heat other parts of the building through a series of heat pumps. As such, the backup electric boiler was rarely required since the building started operating. However, as a previous study revealed, internal system loads were higher than anticipated (Salehi et al. 2015). Power transformers consumed more energy, as they were working at lower efficiency than predicted.

4.4.4.2 Complex Building Control & Monitoring Systems

Besides the system design, an emerging challenge was the design of control and monitoring systems, which are operational viable and user-friendly. With increased automation and complexity of systems, controls and monitoring strategies come more sophisticated building systems, such as HVAC and lighting systems. Based on the design goals, each project took a different approach in integrating control and monitoring systems, ranging from simple to very intricate design solutions. While all three buildings used a direct digital control (DDC) system to control the mechanical and electrical systems in the building, the amount of control points varied significantly among projects.

The DEC project designed a fairly complex mechanical system with a sophisticated control system. At the same time, the DEC building was the only project that provided occupants with a manual control interface for temperature set points for particular building zones. While this could be perceived as an advantage in terms of user-friendly design, this control strategy interfered with the intended performance of the HVAC system. According to a consultant, the chilled beam system was very sensitive to temperature set points, but also slow in its response to changes due to its low-temperature water supply. If not operated as intended, the system would be prone to dramatic performance changes, as one of the consultant described:

> […] this building is very, very complex when you get to the plant level. And that extends somewhat to the chilled beam system. And if it is not operated precisely, you can end up with some serious unintended consequences. […] The system should still be relatively stable to externalities relative to [the] environment, but it is very, very vulnerable to operational externalities, specifically not operating the system the way it was intended. It's not an inherently stable system. (C1, personal communication, Jan 14, 2015)

This intricate system design led to operational challenges and performance issues after project completion. Despite the sophisticated control system, shortcomings in the design or installation could not easily be addressed after project completion, as the building was lacking a monitoring system. As monitoring had not been a priority during design, sub-meters for building systems were taken out of the original design in order to stay within the budget. Surprisingly, only the backup system was equipped with sub-meters, as one of the building managers reported. The lack of a consistent sub-metering system made it almost impossible to operate the mechanical system as per design intent due to its inherent complexity. For example, building operators could not check system efficiency and functionality, and, consequently, issues often remained unresolved.

In contrast to the DEC building, the JPCE and CIRS project both integrated an extensive control and monitoring system in the buildings. Both projects had the design goal to create a building, which would function as a teaching tool, which required an extensive monitoring system. While both buildings followed this goal, they chose very different implementation strategies.

The JPEC followed the principle of a simple design in terms of its control strategies by providing building inhabitants and operators with simple and straightforward user-interfaces. One of the consultants describes the idea of the design process as follows:

> The whole project was on KISS principle, 'keep it simple, stupid'. If the user can't use it and the maintenance guys cannot maintain it, it's going to be removed and replaced with traditional methods. So, the window system cannot be a fancy motorized controller with touch screen and all fancy panels. Make it simple, so we said red light/green light [system]. It can't get any simpler than that. That's the entire premise around every process and every concept. The entire mechanical system which we then designed with electrical, the entire electrical system, everything that has been designed in here, very simple, very straightforward, you know. A non-technical person can use it, work it and fix it. That was our guiding principle all the way through. (D5, personal communication, Dec 19, 2014)

As described by the consultant, the design team focused on low maintenance cost, which often implied easily accessible building systems, as well as mechanical and electrical interfaces that could be used as teaching tools for students from building trades programs.

Together with the simple system design, the project integrated an extensive control and monitoring system, with approximately 500 metering points in the building. Nevertheless, control and monitoring points were not always placed in positions that were useful for building operation and maintenance and metering was missing in some essential places. For example, the large PV array was metered only as an entire system, but not at the level of individual panels, which made it difficult to identify faulty technology, as one of the building managers described. On the other hand, the building was equipped with a large amount of control points, which were rarely used for the operation of the building.

Compared to the JPCE building, the mechanical system of the CIRS building was less straightforward to operate. Despite feedback and input from representatives for building operation and maintenance during the design stage, the system design was intricate and required expert knowledge for its operation. However, building systems were not always easily accessible. For example, the mechanical room was not big enough for the amount of equipment required for the building. As a building manager described, this made it very difficult to maintain building systems:

> Everything is packed in there, tighter than it should be. It makes it a lot more difficult to work with and trouble shoot, if something does fail. [For example,] it may not be something that can be fixed in a couple of hours, like something you have easy access to. You may have to put in a significant amount of work to gain access to the piece of equipment you need to work on. (M5, personal communication, Feb 06, 2015)

The complexity of the design added to a more difficult maintenance of building systems. In addition, the CIRS building was equipped with a very sophisticated control and monitoring system, with more than 2,500 monitoring points. The intent for the system was to allow researchers to study the building and enable occupancy engagement, following the idea of a living laboratory. However, the design team was debating about the usefulness of a system that had more measurement points than control points as a design representative described. The discussion was left partly unresolved, and resulted in a system with more monitoring than control points. In contrast to the DEC building, the CIRS building did not lack sufficient monitoring points, but enough control points for sub-systems such as the lighting system. One of the main performance issues for the lighting system was the lack of sufficient control system over lights in several building areas.

4.4.4.3 The Challenge of Lighting Controls

The operational viability of the lighting control system was a major challenge in all three building projects. Across the projects lighting control points were not designed in a versatile way, but often grouped together by building zones on one electric circuit. This set-up did not allow operators to control lights independently for certain building areas, leading to increased energy consumption.

In both, the DEC and the CIRS building, emergency lights that were connected with the general lighting system, so that lights could not be turn off in areas which received sufficient daylighting. This design approach is still common practice, although it is not a code requirement, as one of the owner representatives explained:

> What happens is engineers, electrical engineers, what they do is they take the path of least resistance. So if there's a requirement, like OK you should provide for adequate lighting levels in all emergency exiting paths for the building, they read that as we should have a failsafe system that's on all the time. I'm never

> going to have anyone coming back to me saying, "Oh you did not put in a system that was not going to fail during an emergency." So what they read into that is the lights have to be on all the time. But that's not what the code says. The code says adequate illumination levels should be provided in all emergency exiting paths and stairwells and whatnot. […] So during the day, you have a means of turning those lights off. You can do it. There's nothing preventing you to do that. (O2, personal communication, Mar 21, 2015)

In both buildings, in corridors and common areas emergency lights were constantly on. As an owner representative of the CIRS building reported, the control strategy could only be changed in certain areas, as part of a re-commissioning process two years after completion of the project. In other zones, lighting controls could not be changed, as several lights were tied together in one electric circuit. In these zones lighting controls could not be changed individually to provide different light levels, without doing a major retrofit to rewire the entire zone. Similar issues were reported from the DEC building, where emergency lights required entire corridors to be constantly lit due to potential liability issues.

Similar issues have been found with exterior lights, such as parking lot lights, for the DEC and the JPCE building. Both buildings have no zoning for the exterior lighting system that includes parking lot lights. A manager of the JPCE building described the consequences of insufficient zoning for the lighting control system as follows:

> […] When you come here in the middle of the night or in the wintertime, it's lit up very much like a shopping mall. Not inside, exterior lights and there's plenty of lights, by every beam there are lights. What we've found through the operations, everything is basically done on one control so when it's dark out all the lights come on in the exterior. […] But the thing is, it is all architectural lights that are not… doesn't necessarily have to be energized. (M2, personal communication, May 26, 2014)

A manager at the DEC building reported similar difficulties in controlling parking lot lights or exchanging the lights.

Similar control issues occurred with the inhabitant interface of the lighting system in all three buildings. In the JPCE and the CIRS building managers reported a lack of control over occupancy sensors and daylight sensors. In both buildings occupancy sensors and daylight sensors were used in combination for certain building areas. Occupancy sensors were overriding override daylight sensors, which meant that lights turned on as soon as any motion was detected in a certain area. Once the lights were turned on, daylight harvesting controls only reduced the intensity of the electric lights by dimming them, but lights did not turn off when daylight conditions would allow for it. A manager at the JPCE building described the common challenge that comes with the these daylight harvesting technologies:

> We know, 'daylight harvesting control of the lights', but we're finding that in a lot of places the lights could be simply turned off. […] What we're seeing is, often people say 'well why is that light [on], there is so much sunlight in here, why is it on?' Because the light does not turn off. So to us, in my new projects, I say if we're by a window and there is a high level of light, I would prefer just to have on/off control. Simplify it and I wouldn't have dimming ballast that costs a lot of money to deal with. (M2, personal communication, May 26, 2014)

As the manager further described, in certain areas daylight sensors did turn lights off, while in other areas they did not. As a result, the overall design followed a good intention, but was not well executed at the more detailed system level for building zones.

One of the design challenges was the availability of suitable technologies for the desired control strategies. At the time of the CIRS project, LED lights were not yet readily available for different types of lighting systems. As a consequence, additional costs often outweighed long-term benefits of more energy efficient lighting solutions. The CIRS project tried to solve this challenge, by introducing a hybrid system of sensors and relays. The relays were supposed to give inhabitants the control over individual lights through a computer interface. Unfortunately, issues in the installing of the interface compromised this design strategy that was still not available three years after project completion. A manager described how inhabitants complained about the lack of control over sensors that either turned on during the day when not required, or turned off during the evening when lights turned off if people did not move enough to trigger the motion sensors. As a consequence, some inhabitants taped over sensors and brought additional desk lights in order to be able to control the lights for their personal needs, which in turn changed the energy consumption of the lighting system from the predictions.

Instead of a computer based lighting control-interface, the JPCE and DEC building used more common technologies that allowed occupants to control lights manually in office areas. Both projects implemented vacancy sensors, which require occupants to turn on lights manually. These sensors turn lights off automatically, if no motion is detected for a certain amount of time. Occupants can also turn off light manually when desired. In the DEC building, occupants had mixed reaction to the implemented control strategy. While some inhabitants were satisfied with the control over the system, others complaint about the inefficiency of the control system for open-plan offices that could only be regulated by a single light switch. This underlined the issues of adequate zoning for lighting and control systems, which were observed in all three projects.

The inconsistencies in the design of control strategies are possibly related to shortcomings in the design process. According to a consultant, the design of the controls systems is often allocated to a specialized contractor, who is generally not involved in the design process of the system. As a result, the original design intend was often not communicated to the contractor, which was possibly due to the conventional approach used in the design and development process of buildings, as a consultant described:

> Actually, the contactor generally doesn't get the design intent document. Just because… I don't know. I suppose that's an industry problem. In that the way that things have always been done is just: you spec it, you sell it, you procure it, you start it up, and you walk away. You know. And that's… nowhere in there is anyone… the controls contractor or the vendor isn't paid to go… isn't paid for their time to go back and check the original design documents. (C7, Dec 19, 2014)

The lack of an accurate translation of the design intent to the actual system design, then, affects the construction, installation, and verification process of the control system. If the intent for the operation of the overall system is not properly communicated to the contractor, design flaws remain undetected until the building starts operating. Stakeholders from all three projects reported similar issues, concerning the design strategy of the control system.

4.4.5 Application of Energy Models

As the discussion of control strategies has shown, verification of design strategies through energy models and design tools is key for a successful performance of the building. While energy models are becoming a common tool to evaluate high-performance energy targets, their use and application in the design process often varies from project to project. This was also the case for the three buildings considered here. All three buildings used design-assist models during the design process, a generic model that was used at the schematic design stage and refined when the design further developed. While all projects used a similar modelling approach, the energy models were used and integrated differently in the design process.

The DEC building started with a generic model to inform design decisions, particularly on daylighting and passive ventilation strategies, as one of the main goals was to create an open, welcoming, and transparent building. The energy model became an important part of the design process, as designers and consultants described. The modelling was an iterative process, in which designers and energy consultants provided feedback to each other. One of the main discussion points was the decision for the mechanical system of the building. The design team proposed to design a mechanical system with chilled beams and geo-exchange field. While concerns were raised about the system, only high-level information was available at the early design stage. When more specific system information became available and the major systems were eventually modelled, the model revealed that the chilled beam system was not the most energy efficient solution compared to a standard four-pipe fan coil system. Beyond the energy performance, the energy model indicated potential challenges with the chilled beam system, as one of the consultants described:

> It [the chilled beam system] introduced a number of compromises in terms of indoor air quality, temperature control, and everything else, which they [building managers] are finding out now. […] Unless the system is designed and operated exactly the way it is laid out, it is very sensitive. It is not a robust system. It is very fragile in terms of its performance. (C1, [personal communication, Jan 14, 2015)

Despite the results from the energy model the design team decided to pursue with the original idea, as it was promoted a very innovative technology. In the subsequent design stages, the energy model was used to optimally integrate the chosen system in the overall design of the building.

Different to the DEC project, the JPCE team started with a compliance model in order to compare the design with a baseline building. As the project moved into the schematic design stage, the design team realized that the model was not able to simulate the specific energy demand for the building. Based on the suggestion of one of the designers, the team switched consultants in order to use more suitable modelling software. The IES VE software was able to assist the development of energy efficient design strategies, such passive ventilation systems. This design-assist model became an essential part in the design process, as one of the consultants described:

> This model was sort of, like a living model, right, because it started out as one thing and slowly evolved into the final energy model. So you know, in those steps there were some assumptions we had to make, because not all the design constraints and parameters were set. So once you make some of those assumptions, as we get further on and come back to revisit some of those assumptions and revise them and update them. […] So there is lot of back and forth. I mean it was good that we were updating the model, but sometimes like that presented a challenge because sometimes something wouldn't get updated and all of a sudden there is [a change] all throughout [the model]. And then it took a lot of time to pinpoint where did we miss updating something right.

As described here, one of the main challenges for design-assist modelling is to keep the model updated, as the design changed throughout the process. According to the consultant, the energy model often pointed in the 'right direction', assisting the design team in making the decisions on the overall design. The detailed energy modelling often followed the design once decisions were made.

The CIRS project faced the same challenge of keeping the model updated throughout the design process. As a consultant described, it was particularly challenging to understand important decision-making points, which changed the design, and to ensure that these changes were captured in the model. Another difficulty was that the CIRS project used several models throughout the project. Right at the beginning of the project, preliminary models were used to set energy performance targets and to assist four design charrette meetings. These preliminary (or partial) models helped in developing passive design strategies during the schematic design phase. The actual design-assist model was developed based on these preliminary models. Parallel to the design-assist model a schematic compliance model was done, based on the requirement from one of the funding partners. The schematic compliance model, referred to as 'post-tender' model, focused particularly on energy conservation measures (ECMs). ECMs were compared to standards from general building practices in order to evaluate energy savings and cost savings of proposed design strategies. At this stage, the energy model had probably the most influence on design decisions, as one of the consultant recalled:

> And then the schematic energy model, where we got a preliminary sense of LEED points as well as looking at those 18 ECMs, energy conservation measures, and tied it with costing. That was a big part of advising design as well. So that modelling that is happening at the schematic design stage is really powerful in driving the strategies. (C3, personal communication, Mar 03, 2015)

Both, design-assist and compliance model needed to be updated throughout the following design stages. Once major design decisions were made, the model was mainly used for verification purposes to check whether the design was still on track with the energy performance targets.

At this stage, the particular challenge was to obtain detailed information from the design team and from consultants, as many parties were involved in the design process. Particularly for the waste-heat transfer system, details about the system design were only made available at the end of the design process. The decision for the heat-transfer system was already made before the schematic design (at a design charrette meeting) based on preliminary site information. Detailed information about the existing infrastructure at the adjacent EOS building was only available when the CIRS building moved into the construction documentation stage, as one of the consultants described. Until then, the design was based on preliminary modelling results of the waste-heat transfer system. Detailed information (such as temperature set points) was only integrated in the energy model when the project moved into the construction phase. At that stage, the design of the system was already confirmed and was not altered any more, which led to unexpected performance issues after project completion.

Although all three buildings used a design-assist model, the models were often only following major design decisions instead of informing them. While this approach is generally more common for compliance modelling, the actual compliance models for LEED certification were only done during or after the construction phase of the project.[24] For the DEC and JPCE project, the design-assist model was utilized to create a LEED compliance model for the project, based on construction documents. According to consultants the compliance model for both projects should reflect the final design of the project most accurately.

In the case of the CIRS project, the compliance models were incomplete in representing the energy performance of the building. According to a consultant, process loads could not be accounted for in both compliance models. The LEED and post-tender model did not allow to

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[24] The compliance model generally does not inform the design, but provides feedback on how the building performed compared to baseline buildings in the same geographical region.

inclusion of the heat exchange system with the adjacent building, as the related energy loads were considered process loads and thus, could not be included in the energy use intensity of the building. The compliance models did not represent the actual design of the CIRS building, although they were used to compare the project with a baseline building in the same geographical location. Despite the incomplete performance representation, the compliance models were the only models readily available to owners, designers and the public. The final version of the design-assist model was not publicly available, but had to be obtained by researchers after project completion.

4.5 Energy Modelling

Taking the case of compliance modelling for the CIRS building, the energy model itself can be the cause for performance differences between predicted and actual design of a building. In the following section, I will discuss the limitation of the energy simulation tools, which were used for the three case-study buildings.

4.5.1 Integration of Intricate Energy-saving Systems

As new building technologies emerge, software companies need to adapt the tools for the new modelling requirements. Thus, modelling tools vary in their capacity of simulating novel building design strategies. All three projects faced this challenge with the software that was used for the energy model.

As pointed out by the literature, one of the current challenges of modelling tools is to simulate passive design strategies, such as daylighting and natural ventilation systems. Except for the modelling software used for the DEC building, daylighting strategies could not be modelled within the energy model, but required external calculations. The results from these external calculations were then translated into energy loads that could be integrated in the energy model. A similarly challenge was to model the natural ventilation system in all three projects. Both, the JPCE and the CIRS project had to use work-arounds[25] within the simulation software to model

[25] A work-around is a method used to overcome a problem or limitation in a (computer) program or system.

the passive ventilation systems in conjunction with radiant slab heating. One of the consultants for the JPCE building described, how in-slab heating and stratification of the air at different heights were represented as separate 'rooms' within the modelling software:

> […] Lets go back to this, the shops. We have an occupied zone, where everyone needs to be thermally in comfort and ventilated and all that stuff, then we had above it, an unoccupied zone. So, above that, we let the air stratify and get hotter than it needs to be, in the summer months. In the winter months, we weren't concerned about what temperatures were about there, as long as people below are satisfied thermally. So, the thing about that is, now you can at least sort of look at it as those levels, just worried about the occupied zone and not above it. But that's also making the assumption that there is this imaginary line in the room between those two spaces. So, you still get an interaction between those two zones, but it is not 100 percent reflective. […] To model your radiant slabs that is actually again another separate room that we defined as just concrete that is separately heated and cooled. This shop, here, is actually 3 separate rooms. The slab is its own room that heats and cools, like a radiant slab. Then, you have your occupied zone above that and then you have your third room, as stratified zones. So we actually use 3 rooms for one room. (C2, personal communication, Dec 18, 2014)

Although new versions of the modelling tool now incorporated natural ventilation systems, it was not yet common practice among consultants at the time of this study. The DEC building faced a similar issue in modelling the chilled beam system, a combined ventilation, heating, and cooling system. According to a consultant, they had never modelled a chilled beam system before. In addition, the system had to be modelled by developing an external code, which was then added to the energy model.

The same approach had to be taken for modelling the geo-exchange system of the DEC building, for which external calculations were added to the model. The modelling tools that were used for JPCE and CIRS building, allowed work-arounds within the model, to simulate the ground-source heat pump system. In all three cases, however, the model assumed that the heating or cooling source in the geo-exchange system would be constant over time, which is in reality often not the case.

Similar to the chilled beam system in the DEC building, the waste-heat transfer system in the CIRS project could only be simulated externally to the model. The external calculations were then added as hourly spreadsheets to the energy model. The same was the case for the photovoltaic (PV) array of the JPCE building, which was not part of the energy model. The capacity of the PV array was calculated by another consultant and not verified with the energy model.

Despite the required external calculations and work-arounds, consultants of all three projects were confident that the final energy model represented the systems, which could be integrated, fairly well. However, none of the consultant commented on the prediction errors in the used models.

4.5.2 Consideration of Additional Building Energy Loads

While the previous section discussed systems, which could be integrated in the energy model, this section looks at the loads that were not considered in the energy models.

According to consultants, the energy model for DEC represented the building design as issued for the construction documents. The design-assist model was updated accordingly and then submitted as the LEED compliance model according to the LEED requirements. After the construction stage, building drawings were reviewed again to reflect changes made during construction and the final as-build conditions as closely as possible. However, parking lot lights were not part of the energy model, as everything outside the building footprint, including the building exterior is not included in compliance modelling. The same applied to the JPCE building, for which exterior lights and parking lot lights were not included in the modelled energy consumption of the building. While not considered in the energy model and thus the predicted energy load, exterior lights were part of the monitored consumption data.

Similarly, process loads were not accounted for in the final compliance model of the CIRS building. As mentioned in the previous section, both compliance models for the project did not include the process loads related to the waste-heat transfer system or the water treatment plants. To reflect the actual design of the building, the design-assist model was updated after project completion by the consultant, to include the process loads. Nonetheless, the overall energy-sharing concept was not reflected in the model, but only considered the energy consumption and production on the building site. The similar applied for the renewable energy system of the JPCE building, with the difference that the PV array of the JPCE building was never added to the energy model. The results from the compliance model were only once compared with the modelling results for the PV array in a spreadsheet calculation for the LEED submission documents. At the time, the energy modelling practice did not reflect energy-sharing systems appropriately, which were required to meet net zero or net positive energy performance targets.

4.5.3 Consideration of Varying Building Usage

The modelled energy loads are not only affected by building systems and implemented technologies, but also by the anticipated usage of these systems. This is generally reflected in the energy load, which is either based on the building area or on occupancy numbers. While all three projects based the energy load mainly on space area, the amount of attention to operation schedules and occupancy numbers was different for each project.

The interviews revealed that consultants had different perspectives on the importance of occupancy numbers. A consultant for the DEC building argued that the number of occupants would have only "a marginal impact on the energy use of the building, unless there is DCV [demand controlled ventilation], since their metabolic heat and humidity contribution is not significant in the big picture" (C1, personal communication, Dec 2, 2014). According to the consultant, only in classrooms and assembly areas, occupancy numbers could have an effect on the energy consumption depending on the HVAC system. For the DEC building, the consultant argued that the operation hours of the HVAC and lighting system were far more important than occupant density. Despite the fact that the DEC building had a few classrooms with a DCV system (here CO_2 sensors), the operation hours for the mechanical system seemed more important to the consultant. A building manager provided more details on the importance of occupancy in the building. The manager explained that CO_2 sensors would help to reduce the fan power required to distribute air in the building. However, the mechanical ventilation system would still operate, unless the air-handling units (AHU) were turned off. AHUs would turn off when entire zones in the building were unoccupied. According to the manager, the HVAC system was designed to be controllable for eight separate zones through the building management system (BMS). This control strategy was supposed to allow scheduling operation hours according to occupancy numbers for separate areas in the building to reduce the energy consumption. Therefore, both actual occupancy numbers and operation hours would play a role in energy performance of the DEC building.

Consultants for the JPCE and CIRS argued that the number of occupants played an important role in the modelled energy predictions, as the heat gain through occupants would affect ventilation and temperature set points. Similar to the DEC building, the ventilation system is controlled through CO_2 sensors and the building management system (BMS) in both buildings. Building managers of the two projects reported how the control through CO_2 sensors and occupancy sensors led to a noticeable reduction in energy consumption for the building. In the JPCE building, where CO_2 sensors control the mechanical ventilation in classrooms and trade shops, and fresh air is only delivered as required, the fan power of AHUs was reduced when the building was less occupied. In the CIRS building, where the heat generated by occupants in the auditorium is re-circulated back to the heat-recovery system to provide heat for other parts of the building, the energy consumption was reduced when the auditorium was occupied during winter months, as a building manager reported.

Depending on the system design of each building, occupancy numbers and operation hours were treated with different amounts of attention in the energy model. The energy model for the DEC building used reference standards to predict occupancy numbers and operation hours, since no detailed information were provided by the project owners. Number of occupants were determined for each space using ASHRAE Standard 90.1 2004. Operation hours were based on schedules provided by Model National Energy Code for Buildings (MNECB).

For the JPCE building ASHRAE standards for different space types were used as a baseline. Occupancy numbers and operation schedules were then adjusted according to the typical academic school year of the college, with reduced numbers and hours during the summer months when fewer classes would be scheduled in the building. But similar to the DEC project, building owners did not provide more detailed information about occupancy numbers or operation hours.

A similar approach was used for the CIRS building. According to a consultant, a daily schedules were adjusted according to class schedules for winter and summer terms of the academic year. One of the consultants described the difficulty of predicting occupancy schedules for the academic building:

> I'm not a big fan of the ASHRAE schedules. They are sometimes good as a starting point for, you now, if you have a very standards office building eight to five. But it is very important to spend time on creating appropriate schedules. So we definitely did that. […] We kind of looked at the offices and the first floor a little bit different, and then the auditorium. How many classes per day and length, for winter occupancy as well. So it was considered. And in hindsight maybe we could have spent more time, really reviewing the schedules in detail with UBC… but we kind of did due diligence at the time. (C3, personal communication, Mar 03, 2015).

Although occupancy schedules were adjusted, detailed schedules from existing buildings on the university campus were not used for the energy model. As the consultant pointed out, this information is critical, but its importance is often underestimated by building owners.

As indicated by consultants and previous studies, occupancy numbers and operation schedules can have a significant impact on the predicted energy performance, and thus on the energy performance gap of each building (Koike et al. 2005). In the following section, occupancy schedules, which were used in the energy model, were compared with actual occupancy numbers for each building.

4.5.4 Excursus: Understanding the Occupancy

While it is difficult to estimate the impact of building occupancy[26] on the overall energy consumption of the building without re-calibrating the energy model (which is a research study on its own), occupancy is a valid indicator whether the building is being used as anticipated in the design or not. The following section provides a better understanding of the differences between predicted and actual occupancy levels in the buildings.

Predicted number of occupants and operation hours were retrieved from the energy models, provided by consultants with permission of the building owner. For each building, actual numbers of occupants and operation hours were calculated based on records from human resources, class schedules and class enrolment numbers, which were provided by building owners and managers. Typical operation hours were defined as hours, during which the building

[26] In this study occupancy is referred to as the number of occupants in a building and the hours of operation that building systems are turned on and running.

was occupied by more than one percent of its maximum capacity. Typical daily occupancy numbers were defined as number of occupants during typical operation hours of the building.

The comparison of predicted versus actual occupancy numbers revealed that all three buildings were significantly lower occupied than predicted during operation hours. While the DEC and the CIRS building were both 55 percent occupied, the JPCE building was only 25 percent occupied compared to predictions in the energy model (Figure 4-1). In terms of operation hours, only the DEC building was occupied for the anticipated number of hours per week. The JPCE building operated only 75 percent of the predicted number of hours and the CIRS building only 69 percent compared to the predictions.

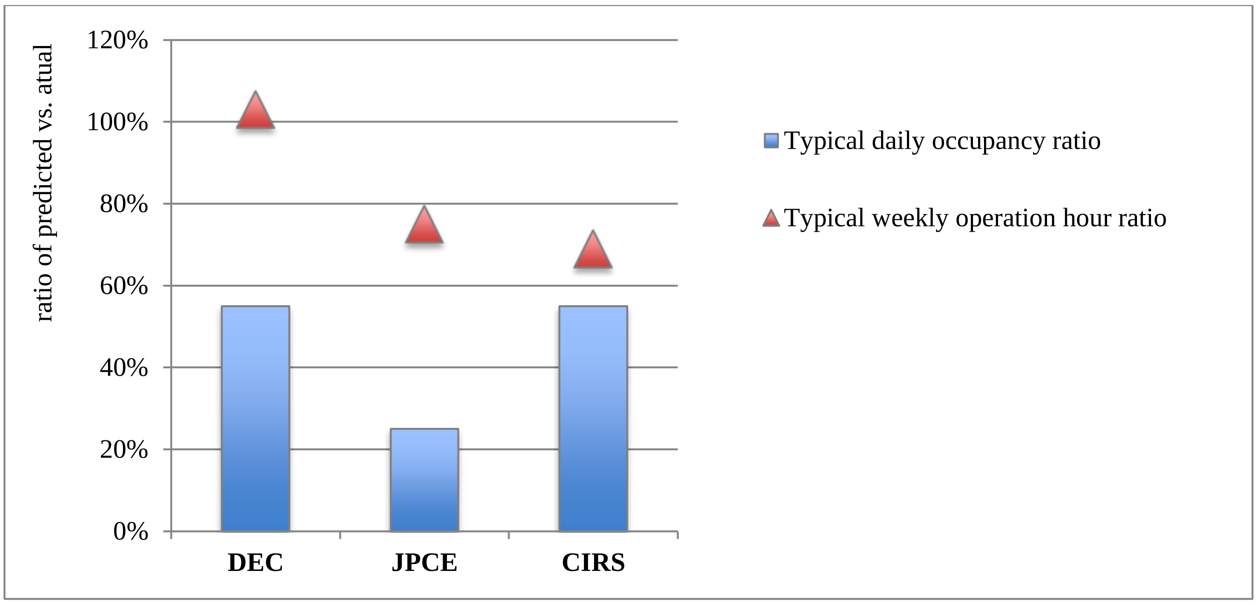

Figure 4-1: Comparison of occupancy use intensity (ratio of predicted vs. actual) for typical daily occupancy and typical weekly operation hours

These significant differences in occupancy numbers and in most cases operation hours can be better understood by comparing values by room type and building function, as well as seasonal operation schedules for each project.

Although the DEC building functions mainly as an office building with fairly stable occupancy numbers throughout the year, there was a significant gap between predicted and actual occupancy numbers for the building. The energy model estimated an average daily occupancy of 524 people and average weekly operation hours of 80 hours. Figure 4-2 shows that the actual building was occupied 45 percent less than anticipated, with an average daily occupancy of 290 people. Weekly operation hours were three percent higher than predicted. While the difference in operation hours was minimal, the gap between predicted and actual occupancy numbers was significant, despite the fact that the building was supposed to be fully occupied according to owner representatives.

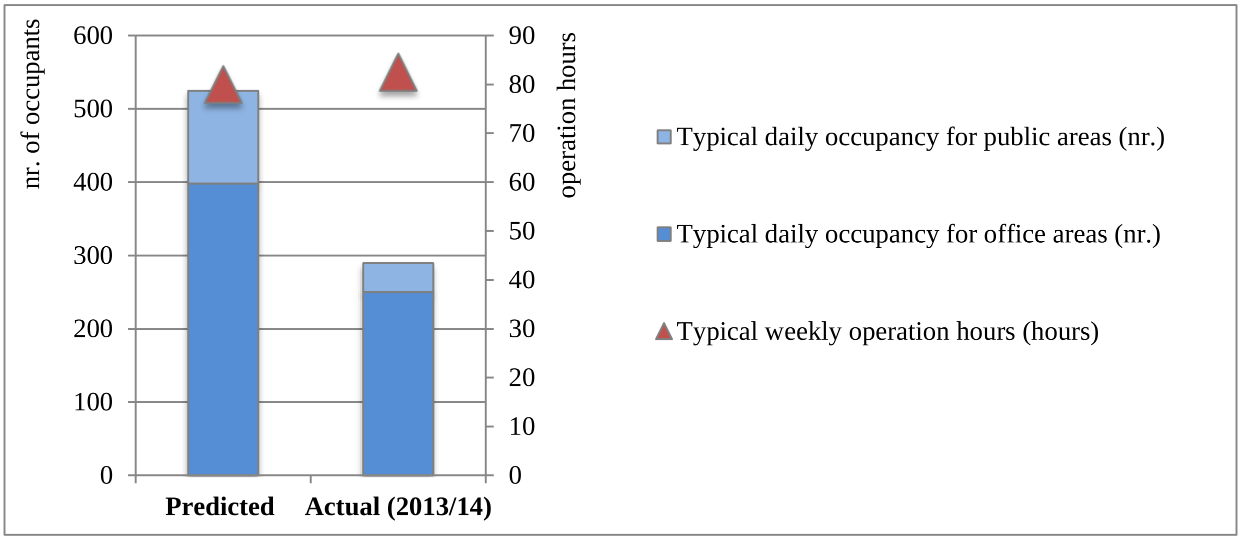

Figure 4-2: DEC: Typical daily occupancy and typical weekly operation hours: predicted vs. actual

A more detailed analysis revealed that a major reason for this gap was due to very high numbers of occupants used in the energy model. As mentioned in the previous section, the energy model of the DEC building estimated occupancy numbers based on reference standards provided by ASHRAE Standard 90.1 2004 and MNECB. These reference standards provide occupancy densities per square meter for various room types. As these occupancy densities were applied to the floor area of the DEC building, the resulting number reflected the maximum possible occupancy of the building, assuming that all building areas would be equally occupied during general operation hours, including meeting rooms, lounges, and common areas. This resulted in an estimated peak load of 878 occupants during general operation hours. In reality, building areas, such as meeting rooms, were often not permanently occupied, even when the building was fully occupied. According to records of full time employees and visitors the building reached peak loads of 660 occupants in 2013/14, which is still 25 percent below the estimated peak load in the energy model.

In contrast to the DEC building, JPCE is mainly used for teaching purposes and recreation, with classrooms, trade shops, a gymnasium, and office areas. The predicted occupancy numbers from the energy model were based on software-internal templates for room type usages. The predicted values were adjusted for the summer months, May to August, when significantly fewer courses would be offered at the college. During this time, the model anticipated a quarter of occupants in classrooms, trade shops, and office areas compared to occupancy levels during the rest of the year. These estimations resulted in an average occupancy number of 537 people including staff, students, and community members using the sports facilities throughout the year. The actual occupancy was 75 percent lower than predicted during general operation hours. Figure 4-3 shows the typical daily occupancy for different building areas, as well as the typical weekly operation hours. Despite peak loads of almost 500 occupants, the daily occupancy was 92 people on average. Classrooms and trade shops, as well as the gymnasium were particularly less occupied, with below 20 percent occupancy compared to the modelled predictions.

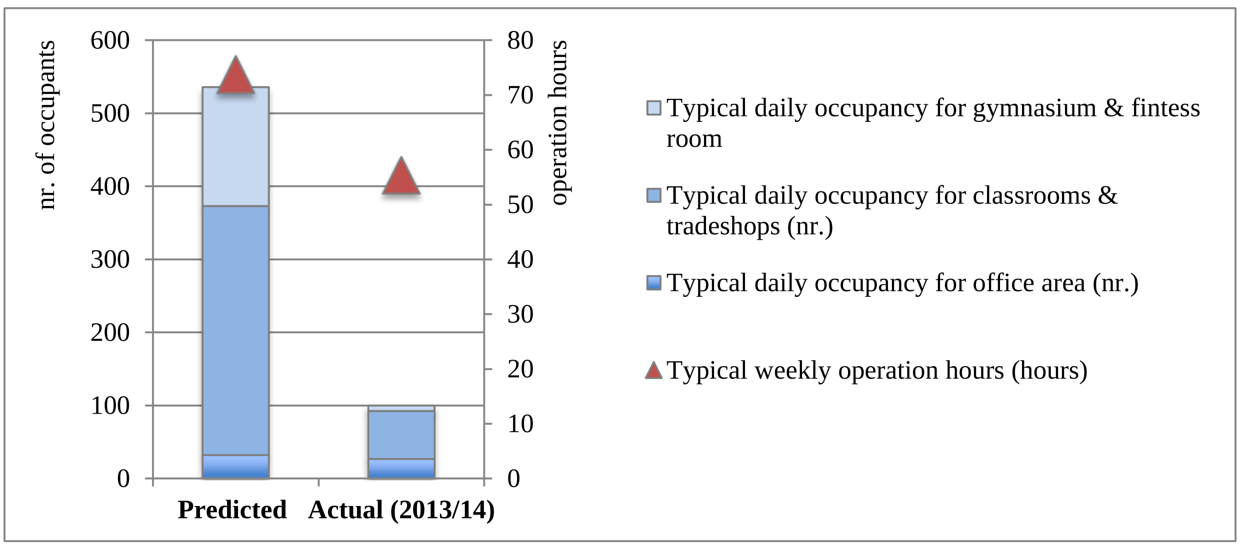

Figure 4-3: JPCE: Typical daily occupancy and typical weekly operation hours: predicted vs. actual

Despite seasonal adjustments of predicted occupancy schedules, the actual number of occupants was significantly lower than anticipated for the classrooms. Office areas, however, were occupied at a constant level throughout the year. The gymnasium was significantly less occupied than anticipated in the energy model. The energy model had anticipated that the gymnasium would be used 105 hours a week, including weekends. In reality, the gymnasium was mainly unoccupied during the week, and almost never used during weekends, since the community did not use the facility as originally anticipated. According to a consultant, it was anticipated that the gymnasium would not only be used by members of the college, but by the neighbourhood as a community facility. After three years of operation, numbers have been gradually increasing, as one of the owner representatives reported. While the gymnasium was operating only half of the predicted times, classrooms and trade shops were used slightly longer than predicted. Overall, this resulted in 20 percent shorter weekly operation hours of the building than predicted. A detailed comparison of predicted occupancy levels and operation hours is provided in the Appendix.

As a mixed-use building, CIRS was intended to be used by researchers, university staff, industry partners, and university students. Predicted occupancy numbers and operation schedules were based on reference standards and then slightly adjusted in the energy model, according to typical holidays and class schedules of a university. Based these predictions, the energy model estimated an average daily occupancy of 330 people in the building and on average 68 hours of operation per week. However, actual numbers from records of human resources and course enrolments revealed that the building was occupied and operated less than predicted (Figure 4-4).

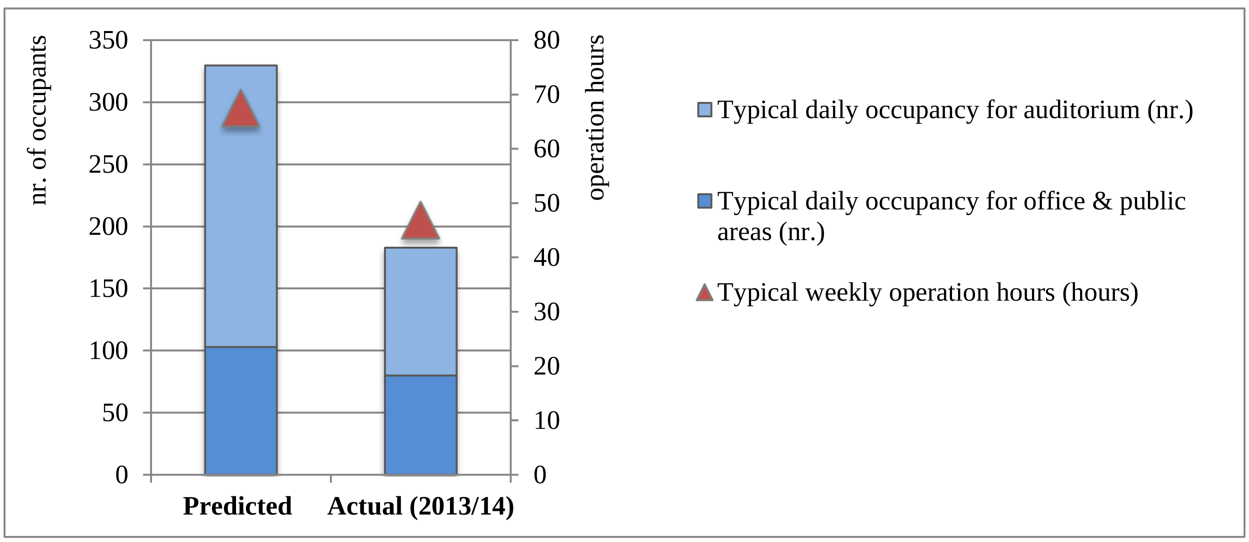

Figure 4-4: CIRS: Typical daily occupancy and typical weekly operation hours: predicted vs. actual

In 2013/14, the CIRS building was on average occupied by 183 people per day and operated for 47 hours per week.[27] The 45 percent lower occupancy compared to the design prediction was mainly due to lower student numbers in classes hold in the auditorium, particularly during summer months when the building hosted fewer classes (see Appendix). In the summer months, from May to August, occupancy numbers for the auditorium were 73 percent lower than predicted. During the rest of the year, the occupancy was 52 percent lower than predicted. It should be noted that visitors and students using common areas, such as the atrium and the café, were not included in the calculations. However, a significant number of students studying in the building were observed during fall and winter of 2013/14, indicating that the actual occupancy numbers are potentially slightly higher than the available numbers from records.

The overall operation hours were 31 percent shorter than predicted, while the operation hours of the auditorium were much closer to the design prediction. During fall and winter, the auditorium was occupied for 58 hours, close to the predicted 60 hours per week. In the summer however, the auditorium was only used for 40 hours per week. The operating hours of the office areas and common areas were 40 percent shorter than predicted, which corresponded more to a classic 45-hour workweek.

These shorter operation hours and lower occupancy levels than predicted in the energy model increases the performance gap. On a per occupant basis the discrepancy between predicted and actual energy consumption would be even more significant.

4.5.5 Consideration of Occupant Behaviour

While occupancy schedules are an essential part of energy models, occupant behaviour was not modelled in standard simulation tools. Energy models assumed an ideal usage of systems according to environmental conditions. In all three cases, the energy model made similar assumptions about the use of lighting controls and operable windows.

[27] Actual occupancy numbers do not account for visitor numbers or attendees of occasional events held in the building.

For instance, for the JPCE project it was assumed that occupancy sensors would reduce the lighting load by five percent, using the recommendations of ASHRAE Standard 90.1. According to a consultant this simplified approach is recommended by LEED and used, because another approach would require a much more detailed investigation with further assumptions. While the lighting control system was simulated as a reduced load, the use of operable windows was represented as fresh air supply, providing air at ambient temperatures. This approach is based on the assumption that occupants would open windows only at certain ambient temperatures in accordance to the heating and cooling system. In the JPCE building, this assumption was to a certain degree justified, since a window control signalling system was installed at operable windows in order to indicate to building users whether the ambient air temperature would allow to open the windows or not, without interfering with the heating and cooling system. The same assumptions were made for the DEC and the CIRS building, although the buildings were not equipped with a window control signalling system.

While the CIRS building was designed with a ventilation system, which is responsive to the operation status of windows (i.e. opened or closed) in individual building zones, the model assumed that windows would be only operated when ambient temperatures would be higher than heating set points. However, as a previous study revealed, windows were used with ambient temperatures lower than heating set points (Salehi et al. 2015). These irregular use-patterns of operable windows were not considered in the energy predictions. While left-open windows during the heating season led to significant heat losses, the actual heating load was lower than anticipated in the model. This was due to the responsive heating system that would turn off when windows were open. The same study showed that actual cooling set points were lower than anticipated in the energy model, leading to an under-predicted cooling load for the building. The same applied to the plug load that was under-predicted in the energy model (Salehi et al. 2015). The predicted plug load was based on the reference standard ASHRAE 90.1 2004 for a typical office building. As the reference standard does not reflect the specific use of the building, energy required for the equipment used in the building was not adequately represented. This explains the higher-than predicted energy consumption for the plug load that we found in the data for the first two years of operation in the building (see Section 3.4.3 in Chapter 3).

4.5.6 Accuracy of Weather Data

The annual energy consumption of a building does not only depend on occupancy behaviour, but also changes according to local weather patterns. Energy models make use of local weather data to estimate required energy loads for the building. One of the most commonly referred sources for weather data is the Canadian Weather for Energy Calculations (CWEC), which provides 30-year average weather data for specific locations in Canada. As CWEC data are retrieved from large weather stations across Canada, weather data are not always available for specific locations.

For all three projects, consultants tried to use available CWEC data from the closest weather station to the building site. While all buildings sites had a CWEC weather station within an area of 26 kilometers, the geographical locations of the weather stations not always match the buildings site perfectly. The DEC building had to use the CWEC weather data from Vancouver International Airport, as no CWEC data were available for Surrey. The weather station is 25.4 kilometers away from the DEC building. Different to CIRS, the DEC building is located inland, further east from the weather station. According to one of the consultants, this difference in location would only be visible in the average cloud coverage during the winter season, as Surrey is further away from the Pacific Ocean. Despite these potential differences, the consultant did not expect to see differences in the results of the energy model, as the difference of cloud coverage would not be significant. However, these estimations were not based on actual calculations or modelling results. While no CWEC data were available for the City of Surrey, 30-year averaged weather data from online sources showed that the number of cooling degree-days differs significantly for Surrey compared to Vancouver International Airport. Records of cooling degree-days for Surrey[28] were almost 40 percent higher than data for Vancouver International Airport, based on data from Canadian Climate Normals.[29] The significant difference in cooling

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[28] Degree-days for Surrey (DEC) were retrieved from The Weather Network, http://legacyweb.theweathernetwork.com/statistics/degreedays/cl1101708/cabc0284/metric, Feb 17, 2016. Degree-days from Canadian Climate Normals were not available for Surrey.

[29] Degree-days for Vancouver International Airport (CIRS) and for Penticton (JPCE) were retrieve from Canadian Climate Normals between 1981 and 2010: http://climate.weather.gc.ca/climate_normals/index_e.html, Jan 20, 2015.

degree-days could have an effect on the energy modelling results with respect to the cooling load for the building as previous studies have shown (e.g. Bhandari et al. 2012). Heating degree-days for Surrey were five percent lower than for Vancouver International Airport, so would have less impact on the predicted heating load for the building.

For the JPCE building weather data from Summerland could be used, which is 7.4 kilometers away from the building location in Penticton and, as Penticton, located at Okanagan Lake. According to one of the consultants, the conditions from the weather station should well reflect the location of the building site. CIRS was in a similar position, with the closest CWEC weather station at Vancouver International Airport, which is 9.2 kilometers away. Despite the distance, the geographical location of the station was similar to the location at the CIRS building, both within two kilometers from the Pacific coastline. A previous research study evaluated the different effects on the energy model when using CWEC weather data compared to real-time weather data from a local weather station at the adjacent EOS building for the (Salehi et al. 2015). The results revealed that the difference between CWEC weather data and measured weather data did not significantly contribute to the energy performance gap of the CIRS building.

Although consultants from all three projects did not consider weather data to have a significant affect on the performance gap, the case of the DEC building indicated that inaccurate weather data could have affected the modelled energy performance results. While the applied CWEC data in the energy models were also used to normalize the actual performance data for the three case-study buildings, inaccurate weather data could have led to changed cooling and heating patterns than anticipated. Furthermore, a changing climate could have had an impact on the long-term performance results of the building (Bhandari et al. 2012). Such changes in the climate was not considered in the energy models, as all three projects used CWEC weather files, which are based on 30-year historical weather data.

4.6 Construction

While the energy model have an impact on the performance predictions of a building, the implementation of design strategies during construction can affect the actual energy performance outcomes. The following section will discuss performance issues stemming from change orders or unfamiliar installation practices, as well as issues related to construction and implementation procedures.

4.6.1 The Impact of Change Orders

The construction process for all three projects involved new installation strategies, as all buildings integrated novel design features. Both, the DEC and the JPCE building changed the design of the exhaust chimneys for the natural ventilation system, during constructions. The project team of the DEC building realized that the originally design of the exhaust chimneys in the atrium were not compatible with the building structure. As a designer recalled, the design team had to find an alternative design solution on site in order to address the problem without reducing the performance of the passive ventilation system. While the DEC building only had to modify the design of the exhaust chimney, the solar exhaust chimneys of the JPCE building had not been part of the original design. As a consultant described, initial height restrictions did not allow the implementation of high exhaust chimneys. During construction, the chimneys were added to the design, although the team was not sure whether the developed strategy would be fully functional under the height restrictions. But with the help of the energy model, the system design was finalized and implemented. Double-glazed units were added to further improve the airflow.

Beside these major design changes, consultants did not recall significant change orders or no-cost changes during construction.

4.6.2 Systems Installations & Equipment

While consultants recalled only few change orders, they reported on many challenges from implementing unprecedented building and control systems. In some cases common construction practices needed to be changed in order to reach the design goals. One example was the installation of the large wood structure of the CIRS building, which required the construction team to develop new installation techniques. One of the main challenges in building the structure was to keep the wood dry during winter, the main structural construction phase. As a designer described, it was key to keeping the structural wood dry to avoid stored moisture within the building. This was particularly important, as design of the high-performance envelope would leave little chance for moisture to evaporate later. As the project schedule was delayed, it was necessary to build the structure during a season with high precipitation. According to a consultant, it was a very unusual practice for the construction team to try to keep the structure dry and required additional work to dry out the structure after its completion. During construction, de-humidifiers were used to dry the lumber. As concerns were raised about potential moisture in the wooden roof of the auditorium, the original design was changed to a cross ventilated system to allow the structure to dry out. After the fact, consultants were quite confident that structure could be dried sufficiently to meet the design targets.

In other cases the new design strategies require changes to common installation practices. For example, the installation of a rain screen at the CIRS building required an unusual assemblage of wall materials to achieve a high insulation value. According to one of the consultants, it was still fairly unusual to install the vapour barrier and insulation on the outside of the wall assemblage at the time of the project. A clear communication of the benefits of this new design strategy was crucial to avoid faulty installations, as one of the designers described. The benefits of new installation strategies were initially not communicated to contractors, who were not aware of the effect of an altered material assemblage. There was little technical awareness about how the order, in which wall materials were installed, could change the effective insulation value of the entire wall assemblage. The intent of the design needed to be explicitly communicated to the construction team, by providing more technical information to justify a changed practice to the usual installation process.

Similar to the rain screen, new construction practices were required for the installation of control systems in all three buildings. A consultant of the CIRS building described the challenge in coordinating the installing window sensors, which required several trades to work closely together during constructions:

> So, is it a challenge? Yeah, it was a major challenge. Did I think it was going to be a headache? Yes. But everybody on the job that I worked with, we did it as a team effort. The job was a success, because there is no 'I-in' a team. […] The glazing contractor would pull the wires, or he would wait till the windows went in. We'd have to have the electricians make sure, he had taped the wires. There was sequencing of putting in all the types of glasses and putting in windows. You had to sequence it, wiring in the wall, sequencing it with the electricians and sequencing it with the controls [contractors]. But the sub trades all work together and it was a success, because they did work together and we all knew what we had to do. And it went good. So, we had a program, performance meetings, and we made sure, we had sequencing procedures in place to put this stuff in, so we didn't miss it. (C6, personal communication, Jan 13, 2015)

The construction teams faced similar challenges installing the lighting control system that require coordination of several consultants. Furthermore, the design of lighting controls conflicted with other system or the room layout in several instances. A designer of the JPCE building remembered that the location of lights conflicted with sprinklers of the fire control system, and changes had to be coordinated and accommodated on site. Similar applied to the CIRS buildings, were changes in the layout of offices from the first set of drawings required changes in the location for lighting controls that needed to be confirmed by designers. The complexity of the design and installation process of control interfaces led to malfunctioning systems in the DEC and the CIRS building, which were only discovered after project completion. In the DEC building several light controls were not wired according to the design intent, leading to malfunctioning switches and non-responsive lights that could not be controlled through the DDC system.

4.6.3 Contractual Design & Implementation

Different from the above-described cases, some of the control issues only occurred after project completion. One example was the solar hot water system in the JPCE building, which did not engage with the building management system (BMS) and the domestic hot water system. This issue was discovered during commissioning, but was only resolved after project completion. As pointed out earlier, a potential reason for the imprecise installation of control systems could stem from an improper translation of the design intent to the control system design. The improper design was carried through the construction process until the system was tested or even operated.

Implementation issues also occurred when the construction team was unfamiliar how to install and integrate unprecedented technologies in the overall system design. In several cases, novel design features had never been installed by the company before and required additional training or expert knowledge. For the construction team of the DEC building the curtain wall system was fairly new, as the company had specialized in school buildings, which rarely used such wall systems. As a result, specialized sub-contractors had to be hired, which were challenging to find and delayed the construction process. Another unfamiliar system for the construction team was the active chilled beam system. While consultants thought the system had been integrated correctly, it turned out that some of the chilled beams were not installed as intended in the design. Chilled beam units of the wrong size were installed in several spaces, leaving a gap between the units and the air supply. This led to a squealing noise when the beams were operated at maximum airflow, as a building manager reported later. Although the issue was discovered during commissioning when unusual noise occurred during the demonstration session of the system, the actual problem was only resolved after project completion. A similar installation issue occurred in the connection of the geo-exchange field to the hydronic system of the building. According to owner representatives and building managers, balancing valves in the geothermal field were installed backwards, leading to wrong water pressures in the hydronic system. In contrast to the chilled beam system, this issue was not discovered during commissioning and only after the building was already in operation.

In other cases, technology providers were directly contracted to install novel systems, to avoid potential installation issues during construction. For instance, in the JPCE and the CIRS building the photovoltaic system was designed and installed by the technology supplier. These design approaches required a close collaboration between technology providers and the construction team to guarantee a successful integration of the technology. For example, the construction team of CIRS had changed manufacturers for the PV panels, as the original manufacturer did not provided information that was required for a successful collaboration. Similar challenges occurred in the implementation process of the wastewater treatment plant in CIRS. The system was procured using a ‘design-build’ approach instead of a more conventional ‘design-bid-build’ delivery process. Under this approach, a single contractor was responsible for the system design and construction. Despite this single-pointed responsibility for the system delivery, the wastewater treatment system had to be integrated in the overall system. While consultants did not recall particular challenges in incorporating the technology, a building manager recalled communication issues between designers and the contractor, while several issues occurred in integrating the technology to other building systems. For example, the drainage of the green roof was mistakenly connected to the water cistern and not to the rainwater treatment system.

A delayed regulatory approval process further contributed to the implementation challenges of the water treatment plant. According to the owner representative, the treatment plant was on a different time schedule than the building project. This led to several issues in the implementation process of the treatment plant, which in turn affected the energy performance of the building. For example, a wrong type of glazing was installed for the greenhouse, which was not suitable for the plants of the aquatic system. Due to lack of sufficient communication, the same low-e coated triple glass windows, which were installed in the entrance area of the main building, were used for the adjacent greenhouse. However, the low-e coated glass did not transmit the required light spectrum for the plants of the aquatic system to carry out photosynthesis. This issue was only discovered after project completion when the plants in the aquifer started to die. In response, special electric lights had to be installed and kept turned on in order to keep the plants alive.

Further examples showed that close collaboration among stakeholders, including designers, contractors and sub-contractors, were key during the construction phase to ensure a successful implementation of design strategies. Similar to the water treatment plant, the construction of the waste-heat transfer system for the CIRS building with the adjacent EOS building required a lot of coordination. Each site visit required a permission of the Health and Safety department of the university, which then had to be coordinated with designers and contractors involved in the installation process.

In other cases, a lack of clear contractual requirements impeded the implementation of innovative design strategies. As previously mentioned, the computer-based control interface of the CIRS building was not implemented before project completion. According to an owner representative, the computer-based control interphase was part of the controls strategy assigned to one of the contractors, but was not developed on time. Thus, the contractor handed the responsible for implementing the technology back to the owners after project completion.

Similar issues were observed for all three projects, where owners and building managers reported a general lack of responsibility for systems functionality after the official handover stage of the project. As a building manager at JPCE described, it was very challenging to inquire consultants and contractors to review systems, once they were installed: “you really have to now convince someone to come back to double check their work at no cost, and verify that they are right” (M4, personal communication Feb 06, 2015). For example, the water distribution for the heating system in the JPCE building was not well balanced, leading to heating issues in the winter. Although this was potentially due to a wrong implementation of the system, only one contractor was willing to help resolving the problem after project completion. The CIRS project faced a similar challenge when the water treatment system was not completed on time with the remaining project. A building manager described the challenge to keep contractors on the project once the building was occupied:

> The completion date on the water systems was not the end of September 2011. That was put off. They knew they weren't coming in. It’s hard to get contractors to come back in eight months later, six months later. If you need the electrical person or the controls it’s hard to do that because they don’t want jobs to go on indefinitely. I think that ‘helped’ to exacerbate the problem. So that, the communication and ensuring that everybody was on the same page, was part of the issue with the water treatment systems. […] I think we’ve seen it in other buildings as well, I think partial occupancy… I believe was a bad idea for that particular reason. Generally they’re not as bad as the water treatment systems were here, as far as the time lag, but any time you’ve got systems complete but other systems that are delayed or not going to be complete for one or two or three months after occupancy, you're going to start running into some of these concerns because you can’t expect an electrical contractor to come back three months from now to do… to make up something, work that they weren’t able to complete earlier, or mechanical or whichever. (M5, personal communication, Nov 13, 2014)

These issues indicate that contractors’ responsibilities were not always clearly defined in terms of project delivery and verification. A lack of clearly defined responsibilities can be particularly challenging if several stakeholders are involved. Furthermore, contractors may be less willing to agree to terms, which require them to come back after project completion.

4.7 Commissioning

While contractors are generally responsible for a correct implementation of design strategies, the commissioning agent’s responsibility is to verify the correct installation of systems and to test equipment, ensuring that the building is ready for service. The following sections will discuss the challenges in commissioning energy-saving systems, as well as issues stemming from the applied commissioning process in each building case.

4.7.1 Novel Design Features

Across the three projects, most challenges in commissioning the building were related to the implementation of the HVAC system and the building control strategies. As mentioned in the previous section, some of the implementation issues were not discovered during the commissioning process. Particularly in the DEC building, the installation of individual components of the HVAC system was not well commissioned. For example, backwards installed balancing valves remained uncovered during the commissioning process.

While such significant installation issues in the HVAC system were otherwise rare, balancing issues of the hydronic system occurred in two of the three projects. As one of the consultants described, the commissioning of novel HVAC systems, which combine multiple sub-systems, is generally a challenge for the commissioning team:

> The operation of the building mechanical systems becomes more complicated with many more sub-systems, which integrate into the main hydronic system and ducted HVAC systems. There are many more control points to be programmed and commissioned which takes longer to complete. Major pieces of equipment such as chillers, boilers, and heat pumps now have their own PC boards, which allow standalone control. The information and control from equipment is networked to the BMS through a BACnet[30] protocol, which can make equipment start-up difficult where frequent tech support is required. There is always a learning curve with new technology for the engineers selecting the equipment, and for the installation and operation of the equipment. (C8, personal communication, Feb 18, 2015)

All three projects used a hydronic distribution system for heating and cooling of the building. Both, the DEC and JPCE building encountered significant water pressure issues in the hydronic system, which were not discovered during the initial commissioning process. In the DEC building, the water pressure in the hot water distribution system was three to four times higher than in the original design. Despite heating problems and occupant complaints about overheating or undercooling of the system, the actual issue was only discovered when an independent commissioning agent was hired to address overall performance issues of the heating and cooling

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[30] BACnet is a protocol that allows the communication of **b**uilding **a**utomation and **c**ontrol **net**works and is based on common reference standards such as ASHRAE.

issue, four years after project completion. The high pressure in the system led to cavitation of heating valves over time, which had to be replaced for the entire system with more than 500 heating valves. This re-commissioning process was outside of the original project scope.

The opposite issue was found in the JPCE building, where building managers realized that the required heating loads could not be met by the systems in the first winter after project completion. As it turned out, flows of the hydronic distribution system were 40 percent lower than intended in the design. Although measured during the initial commissioning process, consultants or contractors did not address the issue before project completion. Building operations only found out about out-of-spec pressures when they started checking the commissioning report after heating issues had occurred. As this had happened during the warranty period, consultants were called back to re-commission the system. However, the consultants disagreed on what actually caused the pressure discrepancy in the system, as there were several potential flaws in the system, which could have cause the problem, as a building manager recalled:

> Was something restricting the flow, was the pipe size done wrong, was the pipe not cleaned out? There are a number of different possible sources, and each different potential player in the construction site could have been the main cause of the problem. But you never know which one, so everybody starts off by saying, "well it's not mine, it must be somebody else's." And everybody says the same thing. […] It could be any of that, and so you really have to now convince someone to come back and double check their work at no cost, and verify that they are right. (M4, personal communication, Feb 06, 2015)

According to the different consultant, the problem could stem from obstructions of flow meters, wrong sizing of pipes, or insufficiently closing valves. Although the commissioning authority provided final recommendations for system changes during the re-commissioning process, the main consultant disagreed with the recommended changes. With the agreement of the project owner, the consultant sought a second opinion by another commissioning agent, who had worked for the consultant before. The problem was eventually resolved after the second review, but only outside of the original scope of the project. According to the building owner, one of the challenges was that individual systems were not sufficiently third-party commissioned. While a contractor hired through the main consultant was responsible for the commissioning process, an independent commissioning agent should have signed off the service of the systems. In the case of the JPCE building, the independent commissioning agent was contracted by the consultant and thus, was working for the consultant and the building owner simultaneously. This contractual situation could lead to conflicts of final responsibility of system functionality, as a building manager described:

> On our new project we have hired an independent commissioning agent, as we think that some of the issues would be between... If the mechanical picks up the commissioning person and then that commissioning person goes back to the mechanical consultant there's politics to play in there that you have to be cautious with. So what we've done is by hiring the commissioning people ourselves. If he was doing any testing or what not, it would come back to us. (M2, personal communication, May 26, 2014)

According to the manager, the double function of the commissioning agent inhibited clear communication among the groups involved so that information was insufficiently communicated to the building owner.

Similar communication issues occurred during commissioning of the DEC building. As the commissioning report revealed, several deficiencies, which were documented in the final report, did not reach building owner representatives in order to be addressed in a timely manner. Instead, some of the deficiencies were only discovered and addressed months after official project completion. For instance, several lighting controls did not work as intended in the design. Two lights were accidentally interconnected, while other lights did not respond to the command through the DDC system. These identified deficiencies were supposed to be addressed by the electrical contractor after the completion of the commissioning process. However, there were no documents, which confirmed that the deficiencies had been addressed by the consultants. The same applies to other deficiencies mentioned in the final commissioning report that were left outstanding after the handover stage of the building.

While some of the lighting deficiencies were identified, interviews and a re-commissioning report revealed that many deficiencies in the lighting and control system were not identified during first commissioning, and required a re-commissioning process of the entire system six month after project completion. There were numerous problems with the lighting system, which required the re-commissioning of the system. The commissioning agent together with designers, consultants, contractors, and building managers conducted multiple tests of the control and lighting systems. The results of the control system revealed that several control strategies of the building were conflicting with each other. For example, in several rooms, wall mounted (line voltage) switches with built in occupancy sensors conflicted with DDC controlled occupancy sensors. The testing team came to the agreement to remove the DDC occupancy sensors from the lighting controls program to remove the conflict between the control systems, as a building manager recalled. In other cases, the installed switches with built-in occupancy sensors were malfunctioning and difficult to use. Based on recommendations from the designer, the switches had to be replaced in several locations. According to the re-commissioning report, a list of further deficiencies was identified that were related to wiring issues, sticky relays, and configuration issues of light control switches with internal occupancy sensors. These issues had to be corrected by responsible consultants and contractors after project completion.

Although the identified deficiencies were eventually resolved, the building manager had expected that these issues would have been addressed before project completion. According to the building manager, one of the reasons for the faulty systems was a lack of sufficient supervision of the implementation of controls strategies that were originally proposed by designers and consultants. On the other side, one of the consultants explained that it was challenging to integrate the novel control system, in which lighting controls were tied together with the HVAC and the security system. According to the consultant, this system was new to the construction, commissioning and operation team and thus, it was difficult to educate stakeholders about the new design approach. This seems to be a common challenge with unprecedented design features, as the consultant described:

> So there's challenge there with the education of everyone from the construction team all the way through the occupants and end users. I think for its time, this building was very, very high tech. Like a lot of the stuff they did here we are seeing fairly regularly now, like another three or four years later. […] I think that's always going to be a challenge with cutting edge technologies, is the vendors. And way back here at the beginning of that three year process, everyone from the vendors and the engineers are on the cusp, and then everyone else has to sort of catch up. So I think there's a challenge there. (C7, Personal Communication, Dec 19, 2014)

The CIRS building encountered a similar deficiency with the lighting control system. In several areas of the building lighting controls with occupancy sensors were not working as intended in the design. Similar to the DEC building, there were conflicts between wall-mounted occupancy controls and the DDC system. In other instances, lights could not be controlled as intended, as several lights had been installed on one circuit. These installation issues could either stem from incorrect implementation of design strategies, or as mentioned earlier, from incorrect translation of design documents to the control strategies, or even inadequate zoning strategies in the design. The common issues in the lighting control system might have been related to the fact that commissioning of the entire electrical system was not required for LEED certification. According to a consultant, commissioning agents specialized in the electrical systems were not common practice at the time of the project. Therefore, the electrical contactor, who installed the systems, also commissioned the electrical systems.

As it turned out, commissioning of intricate control systems was a particular challenge in all three projects. For instance, the operation and control of the HVAC system in the DEC building has been challenging since the beginning of the project. While no deficiencies were identified during commissioning, the system was not operating as intended in the design. According to a building manager, the backup heating system had been running in parallel to the main heating system during times when it was not required. While one of the heat pumps of the main heating system was off, the backup gas boiler had been operating. This unintended operation of the gas boiler explains the increased consumption of natural gas that we found in the energy consumption data for the first two years of operation (see Section 3.4.1 in Chapter 3).

Another challenge was the waste-heat transfer system of the CIRS building. While the commissioning report confirmed that the system was installed and operating according to the design drawings, the actual performance of the system was not evaluated as part of the commissioning process, as the system extended beyond the CIRS building site. According to one of the owner representatives, concerns were raised that the design of the heat-exchange system could not deliver the intended performance that was predicted at the design development stage, due to a malfunctioning system design of the connection with the EOS systems:

> We knew we had a problem. And the problem is not that CIRS isn't generating enough excess heat, the problem is not that we are not capturing enough heat from EOS, we know those things are appropriate, and properly sized. So the heat pumps were appropriately sized, the demand was appropriately forecast. All of that was properly estimated. It's how we are delivering the heat. And the problem is that because that building uses a hot deck cold deck system, they actually cool the air to be dehumidified before they distribute it. Which means that you can only supply useful heat in that building during those times of the year where you are not cooling the air to supply to the building. So that is below something like 12 degrees. So those times of the year where the air temperature is 12 degrees or lower, you are providing heat that's useful, because they are not dehumidifying before they distribute it. But any time the air

> temperature is 12 degrees or higher, they move the air from the mixing chamber into the cold deck to dehumidify it. They cool it, and then they heat it again, and then they distribute it to the building. (O2, personal communication, Mar 21, 2015)

A subsequent research study confirmed that the design of the unit, connected to the cold-deck/hot-deck make-up air unit (MUA) at the EOS building prevented the proper heat transfer (Fedoruk 2013). Despite the valid concerns during construction, designers and consultants defended the design implementation and did not pursue further measurements or verification of the design during the construction or commissioning process.

4.7.2 Commissioning Practices

While some of the deficiencies mentioned above were identified during commissioning, many deficiencies were only discovered once the building started operating. All three projects followed an enhanced commissioning process and received the same LEED certification credits for the process, but many stakeholders pointed towards a lack of thoroughness of the commissioning process. An analysis of the commissioning reports revealed that the depth and structure of the commissioning process varied significantly among the projects.

While the DEC building received LEED points for *best practice commissioning*, which includes re-commissioning of the building during the first year of operation, there was no re-commissioning performed of the entire building. Instead, a 're-commissioning manual' was prepared at the end of the commissioning process, before the actual project completion. The re-commissioning manual was intended to assist building managers to operate and maintain the building according to the design guidelines. The final commissioning report, which was completed at the same time, included a list of deficiencies that were supposed to be addressed by respective consultants, who were part of the commissioning team. However, no final report was provided that documented whether the deficiencies were actually addressed. In addition to the list of deficiencies, the report included a list of concerns. These concerns were not classified deficiencies, but could affect the functional performance, operation or maintenance of systems. For instance, the report identified that the designed control strategy for the air conditioning of the computer server room was insufficient in a case of system failure. According to the report, the controls contractor had been engaged to solve the problem, but an integral control module was missing in the design. While mentioned in the report, the issue was only addressed after the control system had failed a couple of times during operation, as a building manager reported. Furthermore, the deficiency had to be resolved outside of the commissioning process and required substantial changes in the system setup.

The same applied to other deficiencies, which were not addressed during commissioning. Only performance issues of the lighting control and security system were addressed in a re-commissioning process, after a series of complaints from building occupants and operators. Many deficiencies in the lighting control system that were revealed in the process had not been discovered during initial commissioning. Although the re-commissioning report did not report whether the identified deficiencies were actually addressed by consultants, a building manager reported that the issues could be resolved. Other issues that occurred after the warranty period, such as balancing issues of the hydronic system, had to be addressed outside of the commissioning contract.

The JPCE project followed a similar commissioning process to the DEC building. A month before project completion, a commissioning report was prepared by the commissioning agent with a list of outstanding issues. Different from the DEC building, only one outstanding issue was documented at the time of the report. A pump impellor still had to be exchanged, but based on the report the changes were was already in process at that time. Similar to the DEC building, the re-commissioning process was initiated by building managers, after problems occurred in the hydronic heating system. While tests were done as part of the re-commissioning process, the deficiency could only be resolved in an independent commissioning process by another agent, outside of the original commissioning contract. According to one of the consultants, a general challenge for this building case was the fact that it was a fast-track project, which limited the time for in-depth commissioning during the design and construction period. Together with the sophisticated building design, the tight delivery process diminished the effectiveness of the commissioning process, as there was little time to address all the issues, which occurred throughout the project.

Different from the previous two projects, CIRS underwent had an extensive the commissioning process throughout the warranty period. A significant number of commissioning meetings were held during the first year of operation, addressing various types of remaining deficiencies in building systems. This was partly due to the fact that the wastewater treatment system was on a separate development schedule than the rest of the building and not completed after the official opening of the building. Consultants and contractors were still working on several systems, while the building was already operating under partial occupancy. This led to an overall extended re-commissioning process, during which most of the identified issues could be resolved. Nonetheless, similar to the previous two projects, the commissioning process ended with a list of outstanding issues that should have been addressed by the respective consultants. Furthermore, the heat-transfer system was not part of the commissioning process, as the system extended beyond the boundaries of the building site, and thus shortcomings in the system design were not discovered in commissioning.

The challenges in identifying and addressing deficiencies in the three buildings indicate the complexity of the commissioning process and its limitations. A consultant explained that the commissioning process requires multiple steps throughout the building development process, starting with the review of shop drawings and design documents at the design stage, over to pre-start checks and operational checks during and after the construction stage, to warranty checks during building operations. This requires not only a close collaboration of representatives from all stakeholders involved in the process, but also careful consideration of system design from the beginning of the project. While the initial checks of design drawings can have a significant impact on the overall performance of building systems, system checks during and after construction are generally only snapshots in time, reflecting only certain environmental conditions and modes of operation. One of the consultants described the challenges of successful commissioning, particularly before project completion:

> You really need to be intimately knowledgeable with how it [the system] is supposed to run. It is checked, but again it is checked at the beginning, and it is checked at a moment in time. Not over an entire winter. So that's where that feedback loop has to happen. And whether it's with the energy manager and the operation team, or like an ongoing commissioning team, someone has to close that gap. […] So we'll check the sequence of operation and confirm these set points. But again, it's when the building is partly occupied, being run after finished construction by the construction team. In other words it's not in its full operational state, so things change. So there is a real need for, like I said, to close that

loop. For the information to make its way back to someone who can make an informed decision, whether it's a commissioning authority or whether it's the energy manager or whether it's the operations manager. Someone needs to have the information, I guess first what I'm trying to say is, the information has to be there. Similar to like, sub-metering would be great, it might not be realistic on every project, but sub-metering would be great. That information has to go to someone who has…someone who can make a decision. Someone who can say, "This is a problem. This boiler is not supposed to be running all the time because my commission report initially said it was set up like this." And then that person can then take corrective action, whoever it is. Again, whether it's the commission authority, the energy manager, the operations manager, whatever the case may be. (CA1, 0:40]

According to the consultant there is a gap of information about the continuous operation of the building and the identified deficiencies that need to be communicated back to the decision makers, such as the commissioning authority, building managers or owners. Although representatives of the development team were part of the commissioning process, actual performance results from commissioning were often not sufficiently communicated among stakeholders. In several cases, information was not available or not communicated to the right person in order to take corrective actions, which led to outstanding deficiencies and performance gaps after project completion.

4.8 Handover

The findings from the previous sections have clearly shown that a thorough commissioning process, in which results are communicated to consultant, managers and owners, is crucial to meet the energy performance goals of a building. Successful commissioning is also closely related to measurement and verification (M&V) processes at the handover stage of a building. While all three projects incorporated high-performance energy targets, only the CIRS building adopted M&V methods to verify estimated savings after project completion. The other two projects did not aim to achieve M&V credits as part of their LEED certification. However, as it turned out, the DEC building would have been an ideal candidate for an M&V process, as one of the consultants described:

[…] We don't advocate M&V on all buildings. It's a very intensive process and it's expensive. But this building…M&V is about risk management. So what you're managing is the risk of the building under-performing. And that comes into two sorts of perspectives. The first one is if the building inherently is going to use a lot of energy, M&V is [a] good insurance, because of the risk of under-performance. Five or ten percent under-performance can be big if the building's inherent form uses a lot of energy. The other risk of under-performance is in a building like this, where, if it's working properly, it may not use a lot of energy, but it's very complex to operate. And the risk of under-performance comes in through that risk of the building not being correctly operated. So this was an ideal candidate for M&V. We did raise

> that as well, but priorities, budgets, LEED points and everything else… and it wasn't pursued. But in retrospect that's obviously proven to be a big mistake. (C1, personal communication, Jan 14, 2015)

As pointed out by the consultant, the DEC building requires careful operation of systems, as both the design of the HVAC and control system is very intricate and requires a high level of management. In retrospect, performance issues could have been addressed through an M&V process. This process would have required sufficient funding and the installation of energy meters at the sub-systems level, as the consultant further explained. However, the sub-metering system was removed from the design early in the development process, as discussed in Section 4.4.4.2. The lack of sub-metering made it more challenging to pursue an M&V process, but also inhibited continuous commissioning and monitoring of the building after project completion, as pointed out in the previous section.

The JPCE project did not adopt any M&V method, but integrated an extensive metering system in the building. Therefore, a verification of estimated performance data could have been conducted after project completion. While the building energy consumption and the electricity production of the PV array were metered since the building started operating, metered data for sub-systems were not made accessible for the first two and a half years of operation. According to a building manager, initial issues in setting up the computer interface delayed the monitoring process for sub-systems in the building. While data for the energy consumption of the entire building and for renewable energy sources were logged, sub-metered performance data were only recorded three years after project completion and predicted performance goals were never verified after project completion.

The CIRS building adopted an M&V process that was based on LEED requirements in order to receive the M&V credit. The M&V process was done for the overall electricity consumption, and the energy consumption for the HVAC and lighting system. While these systems were evaluated, the waste-heat transfer system and the water treatment systems were not included in the M&V process. Although discussions about performance issue of the waste-heat transfer system had been raised during the construction stage, the problem was not addressed until research investigations confirmed the performance deficits of the system after project completion (Fedoruk et al. 2015; Terim Cavka et al. 2014; Salehi et al. 2015).

Another reason why the deficiencies of the heat-transfer system were not addressed was the lack of a proper handover process of the building. While training session were held, the handoff process to building operators and managers was “a huge dropped ball”, as one of the designers recalled (D4, personal communication, Jun 14, 2014):

> One [reason] is just, the whole handoff the facilities and operations people. Despite we all knew it was going to be an issue, it still ended up being not a train wreck, but a huge dropped ball. […] All I know was that the guy, operating it [the waste-heat transfer system], was unclear on some of the elements of the design intent. It also appears again, just second hand that some of the ideas of how the system would work in its interactions with the adjacent building, were not fully worked out and tested, and there was no budget to go fix it. It’s still possible when you are building something experimental to have a misconception that has to be now fixed. And nobody kind of said, “Ok, what if we’ve guessed wrong and we need to use a different kind of something”. There was no money left to go do that. (D4, personal communication, Jun 14, 2014)

Despite the fact that members of the development team knew that there were potential issues in the system design, nobody addressed the issue before project completion. On top of budget constraints came other factors such as liability issues that contributed to the situation. Furthermore, similar to the JPCE building, metered data of the energy consumption were not made available after project completion as intended in the design, to the surprise of members from the design team:

> I had expected from the beginning that I would be able to go see online how the building was doing in terms of its energy use intensity from day one. And I'm still talking to people about that, maybe I haven’t checked in a month, but the last time I checked we couldn’t do that. I was always surprised because that was always the intention. (D4, personal communication, Jun 14, 2014)

Although metered data were logged, they were only available to managers and researchers of the building. Eventually, in-depth research studies provided actual performance data and revealed that metered data were not always reliable, due to un-calibrated data points and misleading data variables (Fedoruk 2013; Terim Cavka et al. 2014).

4.9 Operation

Methods of measurement and verification are not only beneficial to designers and consultants but can be particularly important for building managers, who are responsible for operating and maintaining the building once completed. Changes of operation or maintenance strategies from the original design intent can alter performance outcomes significantly.

4.9.1 Changed Sequences of Operation

In all three projects major changes in the sequence of operation and maintenance affected the performance results of each building. The DEC building underwent the most significant changes among the three projects. As described in Section 4.4.3, the geo-exchange field of the building was connected to a small adjacent building in order to provide cooling during the summer months. It was assumed that the capacity of the geo-exchange field would be sufficient in serving both buildings during the summer months. However, in the first year of operation, the DEC building had major issues to meet the cooling requirements of the building. Besides the connection to the adjacent building, further reasons contributed to this situation: first, several chilled beam units were under-sized and thus, did not work properly under full capacity (see Section 4.6.3). Second, the hydronic distribution system for the heating and cooling was operating under higher than intended water pressures, leading to insufficient space heating and cooling in several spaces (see Section 4.7.1). Furthermore, as it turned out, the computer server room, which was added early during the construction phase, required significant amounts of cooling throughout the year. In addition to these technical issues, occupants complained about overheating, particularly on the south side of the building during summer months. At first, airflow rates were increased in order to meet the cooling demands, but these operation changes were not sufficient to meet the cooling requirements in the building. As a result, interior blinds were installed in all building spaces to reduce the solar gain and glare issues in the building. While this helped to reduce glare issues, air flow rates were changed again, as spaces were now overcooled due to reduced heat gains.

Despite these changed design and operation strategies, the building kept encountering cooling issues. According to the building manager, the heat pumps failed a couple of times leading to significant cooling issues, since the building was not equipped with a backup cooling system. The lack of a backup system caused overheating issues in the server room and enormous food losses due to failing freezers and coolers in the café of the building. In addition to the failing heat pumps, it turned out that two loops of the geo-exchange field were leaking. Multiple pressure tests helped discover the leaks in two of the 36.5-meter deep wells two years after project completion. However, in order to repair the well pipes, the entire field under the parking lot would have to be dug up, as a building manager explained. As this would imply significant costs, owner representatives decided to install a second cooling source in the building. At the time of the interviews, decisions were made to install a fluid cooler on the roof of the building. The big radiator, which would be served by a large fan and pump that would require additional electricity, could provide additional cooling in the building when required. The installation of the backup system would not only change the sequence of operation, but also the electricity requirements for the building.

Opposite to the DEC building, the JPCE building had to install a backup heating system to prevent potential freezing in the hydronic distribution system (see Section 4.4.4.1). An electric boiler was installed a year after project completion. But according to a building manager the system was only used in emergency situations, when the heat pumps were failing. The exchange of a water distribution pump in the hydronic system had a more significant impact on the building performance. A larger water pump was installed after re-commissioning of the system, as the intended water pressures could not be reached with the installed system. The open-loop geo-exchange system initially did not cause any problems, although it had to be operated constantly at very high pressures to avoid deposition of sediments in the system. However when the building encountered heating problems in the first winter, a specialist, who was hired by the building management, found that the well pumps were deteriorating over time due to the high pressures and sediments in the water. At the design stage, nobody had considered that the water conditions could affect the performance of the well system over time. As a result, two of the well pumps had to be replaced after only two years of operation. According to the building manager, all six wells will have to be replaced over the next few years. In order to reduce the energy load for pumping and further wear of the system during times when the building was operating in part-load, pressure sensors were installed at the wells in the third year of operation.

Similar to the JPCE building, in the CIRS building a pump in the water distribution system needed to be replaced by one with a higher capacity. According to a building manager, the required water pressure could not be reached with the implemented system. Another major change in the CIRS building was the refurbishment of the waste-heat transfer system. As discussed in section 3.4.4.1, research findings showed that the system was not working as intended. Based on these findings, owner representatives re-commissioned the system and planned the refurbishment of the rooftop unit in the third year of operation. As part of a campus wide conversion of the district heating system from steam to hot water, the air-handling units on the roof of the adjacent EOS building were exchanged. The heat-transfer system from the CIRS building was then transferred from the old make-up air unit to the new air-handling units at the rooftop and in the mechanical room of the EOS building. According to one of the owner representatives, predictions for the performance of re-commissioned system were not made, as no energy model had been done for the new installation. However, currently recorded energy consumption data will reveal if the new system can meet the initial performance targets.

Another major issue was the overheating of hydronic solar systems in the CIRS and the JPCE building, which produced more hot water than required. In the CIRS building, a radiator was installed to resolve the problem by releasing the surplus energy back into the atmosphere. This was a "short-cut" solution, but not an energy efficient solution, as an owner representative explained (O2, personal communication, Mar 21, 2015). Since the system was designed as a stand-alone system, it was only connected to the domestic hot water system, but not to the heat pump system of the building. Therefore, the energy produced by the solar thermal system could not be used internally in the HVAC system. In the JPCE building, the excess heat produced by the solar plates and solar tubes was stored in expansion tanks that were added to the system to allow for more hot water storage. But this system change was not sufficient to prevent the system from overheating, as the expected maximum demand was not met during the first year of operation. Therefore, the system was connected to the geo-exchange system to transfer the heat to the ground, as it is not needed in the building during the summer months.

4.9.2 Changed Lighting and Control Strategies

Similar to the excess of preheated hot water, all three buildings encountered issues with an increased energy load for the lighting system. In both, the DEC and the JPCE building, parking lot lights could not be regulated individually and were not included in the predicted energy consumption. Similar control issues were found in the interior lighting system in all three buildings. As described in Section 4.4.4.3, the zoning of lighting controls was not very well translated into the final design of the building control system. In CIRS some of the lighting control issues could be addressed during the re-commissioning process, but the emergency lights that were connected to lights in office areas and in the atrium were running constantly. According to building codes, emergency lights did not have to be turned on when sufficient lighting levels could be reached through daylighting, as a designer found out during the re-commissioning process. As a consequence, emergency lights were connected to photocells to reduce the lighting load in the second year of operation. The JPCE building is currently planning a similar approach for retrofitting emergency lights in stairwells. Furthermore, plans are made to control exterior lights through a wireless network system that allows turning individual lights on and off as required.

As discussed in Section 4.7.1, the entire lighting control system in the DEC building was re-commissioned and adjusted to meet the design goals during the first year of operation. However, independent from the re-commissioning process, building managers and owner representatives decided to change the control strategy of the lighting and HVAC system, as it was interfering with the security system. The control system for lighting, HVAC, and security were originally intended to be controllable for eight separate zones in the building to adapt the energy use to occupancy levels for individual zones of the building. However, the security system to could not be controlled independently from the lighting and HVAC system due to a lack of detail in implementing the original design strategy. According to a building manager, the lighting and HVAC system had to be turned on for the security system to be turned off. In order to avoid triggering the security system when the custodial staff was working after general operation hours, building managers decided to keep all building zones active, as long as one part of the building was occupied. Consequently, the lighting and HVAC system for the entire building was left on and running during extended operation hours, including times when most of the building was unoccupied.

4.9.3 Operator Training

While all three buildings adopted fairly complex operation strategies, building operators and managers mainly received a standard training. As part of the enhanced commissioning process, all three projects provided training sessions for the mechanical and electrical system, and the DDC system. The DEC building provided four training sessions with owner representatives and building managers, which included system walk-throughs, orientation about new equipment locations, as well as operation and maintenance requirements. Although several innovative systems such as the chilled beam system were new to the building management team, no specific training was provided. Only after building managers had to deal with a couple of service complaints, they requested a specific training session for the chilled beam system with the technology provider.

Similarly, the JPCE project provided standard training sessions for the management and operations team, although many of the design strategies were new to the team. One of the building managers described how the management team had to learn over time how to operate and maintain technologies that were either new or integrated in an unusual way. For example, the PV array was new to the team and required continuous maintenance, which had not been mentioned at the handover stage of the project. After first performance issues occurred, building managers needed to find a qualified professional to inspect the system, since the manufacturer was no longer in business. As no expert was available, an electrician of the management team had to acquire a better understanding of the system. Together with building mangers, defective PV panels could be identified and maintenance strategies were developed over time. Now, converters and connections of individual panels are regularly checked, cleaned, and tightened. The similar was the case with the open-loop well system, which was new and a one-off system for building managers of the college. The system was introduced without specific training, as the design team did not anticipate specific maintenance requirements for the system. However, as mentioned in Section 4.9.1, building mangers accidentally found out that the well pumps required regular maintenance to prevent system failure through erosion in the well pumps. A separately hired specialist informed the building management team about the maintenance requirements for the system according to the specific site conditions.

Similarly to the previous two projects, building managers and operators of the CIRS building did not receive training beyond the basic training sessions. An additional online training was only provided for the wastewater treatment plant, as one of the managers reported. However, the online training was not sufficient to meet the qualification requirements to operate the water treatment facility. After project completion, owner representatives found out that the operation of the treatment plant required an operator with a *Class IV* certification, the highest training level for water operation systems in Canada. However, designers and the building owner had not anticipated the need for additional funding for the training, operation and maintenance of the facility. As a result, the treatment plant has not been operated since its test phase, shortly after the completion of the system. According to a building manager, the operation of the wastewater facility would require a half-time position that was not funded by the building owner.

4.9.4 Management Capacities

While the building faced similar challenges in terms of sufficient training for operation and maintenance of novel design features, the management capacities to operate the buildings differed drastically from each other. The DEC project had the fewest resources available to operate the building. According to one of the managers, 15 facility managers were responsible to operate and maintain more than 120 buildings in the school district. Since the school district has been facing increasing budget and resource pressures, the team has been heavily under-staffed to operate and maintain buildings as originally intended. Managers often only have the capacity to prevent system failures, but have not been able to implement a preventative maintenance program, as the manager described:

> And there's almost no time. We are doing what I call triage. We are constantly reacting to failures, whereas if the building is still getting heat, there is nothing that is flashing, alarming the users, we don't hear about it. We're a 'fix if broken' and technically as much as it's not working to design, it's not technically broken at that time. […] And that's beyond frustrating for me. I wish had another ten guys that I could put on preventative maintenance programs and stuff, and the end checks and all that (M1, personal communication, Mar 27, 2015)

In addition to the tight resources, the management team was not used to the innovative system design of the DEC building, as only three of the 120-plus buildings have a geo-exchange system. There was a lack of knowledge and training to operate and maintain new technologies, such as the chilled beam system, appropriately. Consequently, the management team has been working "a little bit on the bleeding edge" in order to meet the operation requirements for DEC building (O1, personal communication, May 21, 2014).

In contrast to the DEC building, a specific building management position was created for the JPCE building and the CIRS building. An on-site facility manager is solely looking after the JPCE building, controlling systems, and doing general maintenance of the mechanical and electrical system. Off-site, a team of managers is overlooking the monitoring system, and the preventative maintenance and performance improvements programmes of the building. According to the website, a team of specialists, engineers, electricians and facility managers, with over 20 people, is managing approximately 20 buildings on four campuses of the college. In addition to the high management capacity, the team is trained to continuously look for potential performance improvements, to reduce the resource consumption in the buildings. According to a building manager, a team of managers and engineers spend a significant amount of additional hours to fine tune building systems. A manager described the additional effort that he and his colleagues put into the building to improve its performance:

> I was looking a lot after hours, a lot online, a lot during the day. And I was lucky because I worked with a controls individual who was very passionate about his work too. […] There were times when I said to Richard[31], "Let's come over here on a Sunday evening. Let's come here at six o'clock. And let's go have a look and see what's actually in fact what's on and what's off." And you know, because here you are looking from a monitor, and we came down. […] We came to see what's going on. And all we saw here was one custodial and a security guard. But we noticed some of the lights were on, wasteful, so we tried to improve it. I think we want to do more still. (M2, personal communication, Feb 06, 2015)

While the facility management team had to learn about several new design strategies, such as the large PV array, a set of very experienced professionals was able to easily adopted new operation and maintenance strategies in the JPCE building.

The CIRS building has a building technician on site that manages the control system and performance data of the building. Together with owner representatives and researchers, the technician helps constantly to improve operation and maintenance strategies. Beyond his responsibilities, the technician oversees potential operation issues and communicates them to the facility manager. The facility manager, together with a team of seven tradespeople, is managing the CIRS building, along with 62 other buildings. A department for mechanical and electrical trades further supports the team with the department for Energy and Water Services, which

[31] Names have been changed to protect the identity of the people, who were involved in the project.

focuses on high-efficient energy and water strategies across the university campus. Thus, a network of support capacities has been available to operate and maintain the CIRS building.

4.10 Occupancy

Beside operation strategies, occupants' user patterns of building systems can have a significant effect on the energy performance of the building, as previously discussed in Section 4.5.4. In the DEC building, the regulation of room temperatures by inhabitants has been a continuous challenge. According to building managers, inhabitants were not used to the slow responses of the heating system to temperature adjustments of plus or minus two degrees Celsius from 21 degrees Celsius and therefore, often over-modulated the system. For example, meeting rooms were frequently overheated, as they were cooler when unoccupied, but became too hot once occupied. While the heating system was overused, operable windows were used simultaneously, regardless of whether the building was in cooling or heating mode. According to a building manager, it has been difficult to estimate the impact of energy losses through windows, as neither the windows nor the HVAC system were monitored. Therefore, the actual use of the building system and corresponding energy load could not be compared with design predictions made in the energy model.

The JPCE building faced similar challenges with operable windows. While a red/green light system indicated to occupants when best to close or open the windows, no system had been installed to monitor the window status. Therefore, the effectiveness of the indication system and its effect on the overall energy performance could not be evaluated. According to a building manager, occupants reported that the indication system worked well. Nonetheless, building operations tried to reduce potential heat losses and instructed custodial staff to close all windows after operation hours.

In CIRS building, the window status is monitored and connected to the heating and ventilation system for separate building zones to reduce heat losses. The heating system turns off when windows are opened in a particular building zone. The ventilation system switches to the natural ventilation mode when more than 30 percent of windows are open in an office wing. A previous study revealed that windows were often used when outdoor temperatures were below the heating set points, leading to significant heat losses (Salehi et al. 2015). Despite reduced energy losses at times when windows were opened, the system still had to reheat the building in order to meet the heating set points as soon as the windows were closed. The use of operable windows for ventilation during the heating season may relate to the fact that few people were aware of the adjustable air diffusers that are available to inhabitants in office and lab areas. A building manager found that in several cases diffusers were closed, while windows were open during the heating season.

In other instances, inhabitants did not follow the intended energy saving strategies and used additional equipment such as desk lights or computers or left equipment running after using it. One of the owner representatives described that the "last challenges [is] getting staff on board to quit using heaters and incandescent light bulbs, leaving their lights on, leaving their monitors on, leaving projectors running after leaving the room" (O1, personal communication, May 21, 2014). In both, the CIRS and the DEC building, inhabitants did not use the building system as intended in the design, due to a lack of sufficient information about the functionality of building systems.

4.11 The Building Stories – An Overview by Case Study

As the above discussion has shown, each case study faced particular challenges in the building development process, which contributed to performance gaps between predicted and actual energy consumption in the buildings. In the following sections, major reasons for performance issues and their effects on subsequent development and operation stages are discussed for each building. This is followed by a summary of lessons learned from each case study.

4.11.1 The DEC Building – The Importance of Building Management Capacities

The DEC building had very ambitious design goals striving for LEED Platinum certification with annual energy use intensity below 100 kWh/m^2. However, as the previous Chapter revealed, the DEC building required more than double the amount of energy as anticipated in the design predictions during the first two years of operation. While the electricity consumption was more than two times higher than predicted, the natural gas consumption was more than eight times higher than anticipated. As no energy metering system was installed, performance results were not available for individual building systems.

4.11.1.1 Reasons for Performance Gaps

The interviews with building designers, consultants and managers revealed that several reasons contributed to the identified performance gaps in the DEC building. Over the course of the project development and building operation, multiple factors reinforced each other leading to significant performance shortcomings in the building.

At the design stage, one of the major challenges was to develop a high-performance HVAC system for the building. While the project team had agreed upon the performance goals, stakeholders had conflicting opinions on translating the goals into design strategies (Table 4-2). During the integrated design process, several consultants and building managers raised concerns that the proposed novel HVAC system, a combination of geo-exchange, four-pipe fan coil system and chilled beams, was lacking in operational viability and robustness. However, the design team did not consider the actual management capacity available for the building when developing innovative design features. While a design-assist energy model was used to inform the development of passive design strategies, design decisions for major system components, such as the chilled beam system, were not based on the results from the energy model. Despite recommendations for a more energy-efficient and robust HVAC system, the design team pursued the initial design concepts of the system.

Similar shortcomings were found in the design of control systems. The initial design intent was to use passive design strategies to meet a high level of inhabitant comfort, while achieving high-performance energy goals. As a result, a complex control system with multiple occupant-interfaces was designed to regulate electric lights and the HVAC system in the DEC building. However, parts of the design were not translated into user-friendly control strategies. For example, the control systems for lighting, HVAC and security were interconnected, so that the systems could not be controlled independently. This led to changes in the control strategy, once the building started operating. While the lighting and HVAC systems were intended to be controllable for eight separate building zones to reduce the energy consumption when parts of the building were unoccupied, the security system would be triggered if building zones were not completely unoccupied. To avoid the interference with the security system, building managers changed the system control from individual building zones to a building-wide control system. As a result, the entire lighting and HVAC system were running at times when parts of the building were unoccupied. These changes in the operation strategy contributed to the overall higher-than-predicted energy consumption of the DEC building.

In most cases, the energy model could represent design strategies appropriately. For the HVAC system design, however, add-on calculations had to be developed, as the modelling software did not provide a modelling code to simulate the geo-exchange or chilled beam system. The energy model was also limited in considering system-usage by occupants. For example, it was assumed that operable windows would only be used when ambient temperatures were above heating or below cooling set points. However, as it turned out, inhabitants operated windows throughout the year. Furthermore, adjustable heating set points were often over-modulated leading to higher than anticipated heating loads.

Besides limitations of the modelling software, only limited data were available to accurately model occupancy and weather conditions for the building. The predicted number of occupants and operation hours were based on reference standards, such as ASHRAE Standard 90.1 2004 and MNECB, as no detailed information was provided by project owners or the design team. The comparison of predicted and actual occupancy data revealed that predicted occupancy numbers were 45 percent higher than actual numbers of occupants in a fully occupied building. On the other hand, predicted operation hours were close to actual hours (i.e. 3 percent below actual operation hours). While lower-than-predicted occupancy numbers would reduce the fan power of the HVAC system, air-handling units were operating unless the entire building was unoccupied, due to the changed operation strategies.

Early during construction, a major change was made to the design of the building, by replacing the parkade in the basement of the building with a computer server room, offices, and storage space. The energy model was updated based on these changes, but the design of the heating and cooling system, including the design of the geo-exchange field was not altered along with the design changes. While the implementation of these changes did not affect the construction process, they had an impact on the operational viability of the cooling system, as no backup cooling system was designed for the server room.

One of the main challenges during construction was the implementation of new technologies such as the chilled beam system. An inaccurate size of the chilled beams was installed in several areas of the building, which remained unnoticed until project completion. Similar installation issues occurred in the hydronic system when balancing valves were installed backwards. While the installation issue of chilled beams was discovered during final commissioning, the imprecise implementation of balancing valves was not discovered until building operation. These installation issues could eventually be addressed during the first year of operation. However, the commissioning team did not discover balancing issues in the hydronic system. Four years after project completion, a separately hired commissioning agent discovered that water pressures in the hydronic system were three to four times higher than intended in the design, leading to a significantly higher energy consumption of water pumps. The high pressures also led to the cavitation of more than 500 heating valves, which all had to be replaced.

One of the reasons why this issue was not discovered during commissioning was that building systems were not re-commissioned during the warranty period. Only the lighting control and security system was re-commissioned, after sever control issues of the lighting system occurred during the first six months of operation.

Despite the intricate design of the HVAC system and the control system, no measurement and verification (M&V) methods were adopted to evaluate the system performance after project completion. For example, energy meters for building systems were removed from the design early at the design development stage. As the HVAC system design required careful operation and a high level of management, an M&V process would have been beneficial in order to meet the energy performance targets.

As it turned out, the operation of the HVAC system became one of the main challenges during building operation. In the first year of operation, the system could not meet the cooling demand of the building due to several reasons: First of all, a second building had been connected to the geo-exchange field, which was only designed for the predicted heating and cooling load of the DEC building. The additional connection to the geo-exchange field was supposed to provide cooling to the adjacent building, but simultaneously reduced the available cooling capacity for the DEC building. This design change was made without consultation of the design team of the DEC building. In addition to the reduced cooling capacity, there were several deficiencies in the distribution system of the HVAC system. An incorrect installed chilled beam system and insufficient balanced hydronic system led to cooling issues in the building. As a result, airflow rates were increased and blinds installed at all windows to meet the cooling requirements and to address complaints from occupants about glare and overheating issues. Despite these operation changes, the building kept encountering cooling issues. Building managers discovered that two of the well pumps in the geo-thermal field were leaking, which further reduced the heating and cooling capacity of the system. As a result, pumps and fans were operating at lower efficiencies, but much higher loads than anticipated in the design, contributing to the performance gap.

Furthermore, heat pumps were failing several times, leading to fallouts of the cooling system. As no backup cooling system had been designed for the building, a fluid-cooler was eventually installed in the fourth year of operation – at the same time the balancing issues in the hydronic system were addressed and pumping pressures adjusted. With these current design and operation changes, the actual performance of the building will again change, requiring further analysis.

Similar to the cooling system, the heating system was not operating as intended in the design. For example, the backup gas boiler for the heating system was running for extended periods of times, while one of the heat pumps was not working. This explains the significantly higher natural gas consumption for the operation of the gas boiler. Despite its observation, the management team was limited in allocating sufficient time and resources to correct the malfunctioning system operation.

Despite the intricate building design, building managers only received standard training sessions for the mechanical, electrical, and DDC system. Upon request of the operation team, special training was provided for the chilled beam system. Besides the chilled beam system, building managers had little experience with the geo-exchange system. Similar to operators, inhabitants did not receive sufficient training to properly use the available control systems in the building. As a result, the heating system was overused and windows were operated during the heating season.

Table 4-2: DEC Building – Summary of Reasons for Performance Gaps

Stage	Category	Reason for Performance Gap
Planning & Design	Alignment of targets	Conflicting view points and concerns on how to realize performance targets were not resolved during the integrated design process (IDP), resulting in complex or unstable system designs
	User-friendly design	Operational viability and management capacities were not considered when designing novel building systems, such as intricate HVAC and control systems
		Control and monitoring systems were not well translated into design strategies, leading to complicated user-interfaces and malfunctioning systems
	Application of energy models	Design-assist model was not used to develop the design of major mechanical systems, such as HVAC system
		The impact of design changes, during and after construction, were not sufficiently evaluated or included in performance predictions.
Energy Model	Consideration of varying building usage	An ideal occupant behaviour was assumed for modelling the operation of building systems, without considerations of potential variation in use-patterns
	Accuracy of weather data	Local weather data from CWEC were not available to precisely simulate climate conditions (e.g. cloud coverage) at building site
Construction	Installation of Systems	Unfamiliarity with innovative design features, such as chilled beams, led to imprecise installation systems
Commissioning	Functionality of new systems	The hydronic heating and cooling systems were not correctly balanced, resulting in major performance issues in the water-distribution system
	Commissioning practice	Insufficient communication of commissioning results to responsible stakeholders led to outstanding deficiencies after project completion
		Re-commissioning was not performed for all building systems leading to several undetected deficiencies in major systems

Stage	Category	Reason for Performance Gap
Handover	Measurement & Verification	M&V methods were not pursued, despite intricate system designs, so that performance goals were never verified
		Sub-metering systems were not part of the design, impeding a continuous commissioning or M&V process
Operation	Sequence of operation	Unexpected performance issues in the hydronic distribution system for heating and cooling led to replacement of water pumps to ones with higher capacities
	Control strategies	Control sequence of the HVAC and lighting system was changed from individual building zones to an overall building control, due to conflicts with the security system, and resulted in unnecessary system operation of unoccupied zones
	Management capacities	Only limited capacity, resources, and experiences were available to accurately operate and maintain the building
Occupancy	Education of occupants	Lack of sufficient education of occupants about system functionality led to unexpected use of control systems and user-interfaces, such as operable windows and heating set points

4.11.1.2 Lessons Learned from the DEC Building

This case study has shown that performance gaps can stem from the lack of a careful consideration of building management capacities when designing intricate building and control systems. For example, a novel HVAC design was developed without consideration of the actual operational capacity of building managers. As the DEC building had only limited resources to operate a building system that required expert knowledge, a robust building design could have reduced the risk of performance deficiencies after project completion.

The impact of design changes, which occurred during and after construction, were not sufficiently evaluated or included in the performance predictions. As a result, operation sequences were changed to meet the heating and cooling requirements for the building, changing the actual energy consumption of the building. The impact of changes in the design on the operational viability of building systems needs to be carefully evaluated to avoid unexpected performance shortcomings.

Furthermore, innovative design features such as a complex HVAC system and control system were not accurately implemented during construction and commissioning of the building. This led to several unintended system operations, contributing to increased energy loads. This highlights that the implementation of new design strategies requires particular attention and close collaboration of contractors and technology providers to ensure a successful integration in the overall system. Furthermore, deficiencies that are identified during commissioning need to be followed through after project completion. One reason for outstanding deficiencies in the DEC building was the lack of clear communication of the commissioning results to consultants and project owners in order to take corrective actions and to close performance gaps. Enough time and resources need to be allocated to the final commissioning process to allow for a successful handover process of the building:

> I know I touched on this before, but it's really important that there is enough time for balancing and commissioning. Otherwise the owners are moving into a building that might not be operating correctly, and once they've moved into a building that isn't working properly, it's really hard to get them to see the building as working properly when it is. They, kind of, move in with the idea that it's a crappy building. And it's really hard to change that. It takes a lot to shift their thinking into "OK, it's not working right." (C8, personal communication, Feb 06, 2015)

Outstanding performance issues could have been addressed through a complete re-commissioning process of all building systems. Together with an energy metering system at the sub-system level, M&V could have helped to uncover further deficiencies promptly, as a consultant described:

> M&V is about risk management. So what you're managing is the risk of the building under-performing. And that comes into two sorts of perspectives. The first one is, if the building inherently is going to use a lot of energy, M&V is good insurance, because the risk of under-performance, five or ten percent under-performance, can be big if the building's inherent form uses a lot of energy. The other risk of under-performance is in a building like this, where if it's working properly it may not use a lot of energy, but it's very complex to operate. And the risk of under-performance comes in through that risk of the building not being correctly operated. (C1, personal communication, Jan 14, 2015)

And finally, sufficient training of building managers is required for successful operation and maintenance of intricate systems. Information sessions for inhabitants could have helped to use complex control systems as intended in the design and to avoid unnecessary building loads.

4.11.2 The JPCE Building – High Performance Through Simple Design

Similar to the DEC building, the JPCE building had ambitious design goals, aiming to achieve LEED Gold and Living Building Challenge certification. One main focus was to reach the zero-energy target. While the JPCE building required 20 percent less energy than predicted, the net-zero energy target was not met in the first two years of operation. As the previous chapter revealed, the PV array generated 22 percent less electricity than anticipated and could only cover 58 percent of the building's energy consumption. The energy breakdown had shown that less energy was required for lighting and plug loads, while the HVAC system and the DHW system required slightly more energy than predicted.

4.11.2.1 Reasons for Performance Gaps

The interview analysis revealed several factors contributing to the better-than-predicted performance of the JPCE building. First of all, the actual occupancy numbers were 75 percent lower and operation hours 20 percent lower than anticipated during the first two years of operation. While predicted occupancy numbers and operation schedules were based on software-internal templates, numbers were adjusted to the usual schedule of the academic school year. According to a consultant, these significantly lower numbers were mainly due to the fact that the local community did not use the facility as predicted in the design. Instead, mainly college students and staff were using the facility during the first few years of operation. The significantly lower occupancy numbers and shorter operation hours explain the lower lighting load, as most lighting systems were controlled through occupancy sensors. The lower-than-anticipated plug load is also related to lower occupancy numbers, as the load is mainly attributed to the use of equipment through occupants.

Furthermore, a very streamlined design process helped to realize the ambitious performance goals. The limited two-year time frame and budget for the project delivery was used to balance the cost between a carefully assembled project team and high-performance design strategies. A committed and supportive building owner helped to guide the integrated design process (IDP) by continuously enforcing energy performance targets and low life-cycle cost for the project. This approach and the tight timeline led to collaborative decision-making and creative problem solving, which involved designers, consultants, and managers (consumption of the HVAC system.

Table 4-3). As the building was intended to become a teaching tool for students of the college, the design team focused on simple control strategies, using the KISS (keep it simple stupid) approach as a guiding principle. For example, mechanical and electrical systems were designed to be easily accessible, interpretable, and maintainable for building operators, students, and inhabitants.

Despite these user-friendly design concepts, similar to the DEC building, the design of the lighting system was not well translated into actual control strategies. For example, lights in trade shops only dimmed down, but did not turn off during times when daylight conditions allowed for sufficient lighting levels. Furthermore, an extensive exterior lighting system was designed without adequate zoning to control individual light or areas. This led to a significant exterior lighting load that was not considered in the energy predictions of the energy model.

Similar to the DEC building, the impact of occupant behaviour on the energy performance was not considered in the model. The use of control systems, such as windows and electrical lights, was based on ambient weather and daylighting conditions. While a design-assist model was used particularly to evaluate different passive design strategies, add-ons and work-arounds were required to simulate systems in the energy model. Daylighting had to be modelled through external calculations and had to be added to the model. Complicated work-arounds, which were not third party approved, had to be developed to model the combined natural ventilation system with the in-slab heating system. Furthermore, the photovoltaic (PV) system was not included in the energy model. External calculations for the PV array were only compared with energy modelling results for compliance purposes after project completion. Interviews with consultants further revealed that the capacity of designed PV array would not allow the achievement of the net-zero energy target. Due to site and budget constraints, an expansion of the PV array was postponed to after project completion. The PV expansion has not yet been realized, four years after completion of the project.

Despite extensive modelling, implementation issues occurred in the hydronic system, leading to water balancing issues that were only discovered after the building started operating. Although lower-than predicted water pressures in the hydronic system were measured during commissioning, the issue was not reported to building managers. The commissioning authority, which was overviewing the entire commissioning process, also functioned as the commissioning agent for the mechanical system, reporting to the mechanical contractor. Due to the double function of the commissioning authority, there was a lack of sufficient communication among relevant stakeholders. Despite a re-commissioning process of the system, the commissioning authority and consultants disagreed over the cause of the deficiency in the hydronic system. An independent commissioning agent could eventually help to resolve the problem. Based on the agent's recommendation, a larger water pump was installed, which provided a higher capacity for distributing the water in the building, but also required more energy for the HVAC system than predicted in the design.

Similar issues occurred in the implementation of the solar thermal hot water system. After the first year of operation, building managers found out that the solar hot water system was producing more heat than required. As a result, the solar thermal system was connected to the geo-exchange system to redirect excess heat to the ground. This required an additional pumping load for the DHW system.

While the building was equipped with an extensive metering system, with more than 500 metering points, M&V measures were not adopted to verify the predicted performance of the project. Furthermore, sub-systems were only monitored in the third year of operation, due to initial installation issues of the computer interface. While data for the total energy consumption and renewable energy generation were recorded, the performance was not verified at the system level. During operation, performance issues were only discovered through investigation by the building management team. For example, a hired specialist discovered that the performance of the open-loop geo-exchange system was reduced over time, which had not been anticipated during the design of the system. Due to sediments in the groundwater, well pumps were wearing out and had to be replaced after only two years of operation. Pressure pumps were installed to reduce the operation schedule of the pumps that were operating constantly, based on the usage of the building.

Unexpected performance issues also occurred in the PV array, explaining the lower-than-predicted performance of the system. As building managers had not been trained to monitor and maintain the system, defective PV panels were only discovered after the system was re-commissioned by an electrician of the college. As it turned out, the large PV array required consistent maintenance to perform as intended in the design. Members of the management team had to acquire knowledge about the maintenance of the system over time, as the technology provider was no longer in business

Despite the focus on a user-friendly system design, several novel design features required additional training, which was not provided to building managers. For example, the open-loop well system required additional training to operate and maintain it as intended in the design. Despite the lack of specific training, the management team had sufficient capacity to deal with the operation problems over time. An on-site building manager looked after the general operation and maintenance of the building, and was supported by a team of more than 20 operation managers, engineers, and tradespeople that managed approximately 20 buildings in four locations. With a high capacity and great commitment to continuous performance improvements, the management team successfully learned and improved operation strategies of innovative systems in the JPCE building. For example, emergency lights that were running constantly in places with sufficient daylight levels were be changed to an adjustable system in the fourth year of operation.

Furthermore, according to building managers, occupants were using control systems such as operable windows responsibly. The adequate use of windows was supported by the window-status indication system (red light/green light system) that helped occupants to use windows according to ambient temperatures. However, no monitoring system was installed to check whether the indication system was actually used as intended in the design. Further investigations would be required to identify the impact of window use on the energy consumption of the HVAC system.

Table 4-3: JPCE Building – Summary of Reasons for Performance Gaps

Stage	Category	Reason for Performance Gap
Planning & Design	Quantitative targets	Energy performance targets were competing with budget and time constraints; this led to simple and effective design strategies
	Alignment of targets	The continuous enforcement of initial performance targets by owner representatives encouraged collaborative decision-making and creative problem-solving among stakeholder, and led to operationally viable design strategies
	User-friendly design	Lighting control systems were not well translated into design strategies, resulting in unintended lighting loads
Energy Model	Integration of systems	Innovative design features could not be accurately represented in the modelling software: geo-exchange systems and natural ventilation systems required work-arounds within the model, which were not third-party reviewed
Energy Model	Consideration of energy loads	Energy loads outside of the building footprint, such as exterior lights, were not included in the energy model
	Consideration of varying building usage	Energy models were lacking accurate information on anticipated occupancy numbers and operation hours for the building, resulting in an over-prediction of the building use
		An ideal occupant behaviour was assumed for modelling the operation of building systems, without considerations of potential variation in use-patterns
Construction	Change orders	Ventilation chimneys had to be changed from the original design during construction, without evaluation of impact on performance outcome
	Installation of Systems	Control and monitoring interfaces were not installed/set up, due to delays in development and implementation process
Commissioning	Functionality of new systems	Hydronic heating systems was not correctly balanced, resulting in performance issues in the water-distribution system
	Commissioning practice	Insufficient communication of commissioning results to responsible stakeholders led to outstanding deficiencies after project completion
		Re-commissioning was not performed for all building systems resulting in several undetected deficiencies in major systems

Stage	Category	Reason for Performance Gap
Handover	Measurement & Verification	M&V methods were not pursued, despite intricate system designs so that performance goals were never verified
Operation	Sequence of operation	Insufficient pressures in the hydronic heating system required the installation of a water pump with higher capacity
		Excess heat of solar thermal water system had to be removed through the geo-exchange system
		Backup systems for novel heating systems had to be installed after project completion
	Operator training	Operator training for new design features was missing or not consistently provided during the handover process of the building

4.11.2.2 Lessons Learned from the JPCE Building

One of the successful design strategies of the JPCE building was the continuous enforcement of initial performance targets by an owner representative throughout the integrated design process. This encouraged collaborative decision-making processes and creative problem solving among stakeholders and led to the development of operationally viable design strategies. One of the consultants described the importance of a successful collaboration during the design development as follows:

> The biggest thing I've learned is during this journey [...]: "collaborate, really collaborate". And I mean by really collaborate is getting all of the stakeholders involved, whether it's designing a cup or whatever you are designing, whatever you want to build, get every stakeholder that has an impact on the cost, on the design, and the lifecycle of that item. Get them all around a table and get them to truly collaborate to get the best product. We don't do that. We believe we collaborate. It's a huge cultural shift within our industry. And it has to happen. I see that this is the future of our industry. We haven't changed in centuries. Our industry and the building industry is…we did the same things that we did 50 years ago. Why? (C5, personal communication, Feb 06, 2015)

A close collaboration among stakeholders was key to a successful development of a user-friendly design of most of the building systems in the JPCE building. However, one of the major contributing factors to the better-than-predicted building performance was the lower occupancy and use of the building. As accurate occupancy numbers and operation hours were not available for the energy model, the use of the building was predicted higher than what was actually realized. This shows the importance of using accurate occupancy information, particularly for buildings with demand-controlled building systems such as lighting and ventilation systems.

Furthermore, the impact of changing occupancy numbers and operation hours need to be considered when modelling building systems and spaces.

In addition to lower occupancy, the development of simple and effective design strategies facilitated a successful operation and maintenance of most building systems. However, similar to the DEC building, several systems were not sufficiently commissioned. This led to outstanding deficiencies that were not adequately communicated to building managers. As a result, additional equipment had to be installed for the hydronic heating system and the solar thermal hot water system. Communication issues could have been avoided by following an independent commissioning process through a third-party commissioning agent. Furthermore, sufficient time for a careful balancing and checking of the new heating system could have reduced the risk of undetected deficiencies. A re-commissioning process with seasonal performance testing could have also helped to discover heating issues promptly.

Despite user-friendly design strategies, individual building systems have to be monitored promptly to ensure that performance targets are met. At the same time, training requirements for novel systems such as PV arrays need to be considered at the design stage and implemented at the handover stage to ensure that adequate operation and maintenance capacities are available. This could have helped to address performance deficiencies promptly and effectively.

4.11.3 The CIRS Building – Performance is in the Detail

The CIRS building had the most ambitions performance goals among the three case studies. Beside LEED Platinum and Living Building Challenge certification, the project aimed to reach a net positive energy performance, while staying within a fixed budget. Although the CIRS building consumed only 20 percent more than predicted during the first two years of operation, the main energy-transfer system significantly under-performed the design predictions. As discussed in Chapter 3, the waste-heat transfer system with the adjacent EOS building did not work as anticipated, so that the intended net positive performance goals could not be achieved. Furthermore, the lighting load and plug load was much higher than anticipated in the design.

4.11.3.1 Reasons for Performance Gaps

As the design of the CIRS project went through multiple planning phases for different building sites, committed owner representatives were crucial in remaining true to the initial high-performance targets. Despite these efforts, the alignment of project goals among stakeholders was one of the major challenges in the integrated design process (IDP), as a group of over 30 representatives were involved in the design development (

Table 4-4). Similar to the JPCE building, the translation of design goals into design strategies was challenging, particularly for innovative design features, such as the waste-heat transfer system. Insufficient information about the existing infrastructure at the adjacent EOS building should become a major issue in the implementation of the heat-transfer system.

Similar to the DEC building, the design of the HVAC and control system was intricate and did not primarily focus on user-friendly design strategies. Instead, the extensive control and monitoring system was designed to serve as a tool for building research, with more than 3,000 measurement points. Nonetheless, the building faced similar implementation issues in the lighting control system, as in the previous two projects. For example, occupancy sensors were overriding daylight sensors leading to additional lighting loads, which were not anticipated in the design.

While several models – design-assist and compliance models – were used, a complete building model was not done during the design development stage. In several cases, the model followed design decisions rather than informing the design of new building systems. For example, detailed information about the waste-heat transfer system was only provided for the energy model during the construction documentation phase when the system had been already designed. As a result, the system design was based on preliminary data leading to malfunctioning implementation strategies.

While missing information limited the energy modelling of the building in several cases, in other cases modelling requirements prohibited the accurate representation of building loads. Both compliance models did not include process loads in the energy calculations. For example, loads related to the operation of the waste-heat transfer system and the wastewater treatment system were not represented in the LEED compliance model. While the design-assist model took process loads into account, both innovative design features could not be simulated in the modelling software. The heat-transfer system, the wastewater treatment plant, as well as daylighting strategies were added to the model through external calculations. Furthermore, work-arounds were required to model natural ventilation, in-slab heating, and the geo-exchange system, while variations in building-use and operation were not considered in the model. As a result, predicted energy loads for ventilation and heating differed from the actual energy loads and thus contributed to the energy performance gap (Salehi et al. 2015).

Similar to the JPCE building, occupancy numbers and operation hours were adjusted to use-patterns of the auditorium in order to consider holidays and lower occupancy numbers during the summer months. However, typical schedules of the university were not reviewed for the predictions. The comparison of predicted and actual occupancy numbers revealed that the building was 45 percent lower occupied than predicted and 31 percent less operated than anticipated in the energy model. Lower-than predicted occupancy numbers were mainly due to the fact that classes in the auditorium were often smaller in size than the anticipated maximum number of students fitting in the theatre. Furthermore, operation hours of the auditorium were shorter than anticipated during summer months and office hours were shorter throughout the year. A previous study revealed that lower occupancy numbers slightly affected the energy consumption of the building (Salehi et al. 2015). An as-built model showed that the energy consumption shifted from cooling to heating with lower occupancy numbers, due to complex interdependencies within the energy model.

During construction, one of the main challenges was to build the wood structure of the building during the major rainy season, without compromising the performance. According to a consultant, the construction team did not have previous experience in building a large wood structure, as it was required for the CIRS project. The exterior curtain-wall design was also new to the construction team. The insulation benefits of the new curtain-wall design had to be communicated to the construction team to ensure the correct assemblage of the wall system. Furthermore, the intricate control system required the construction team to develop new installation practices. For example, multiple contractors had to be coordinated to guarantee the right sequence of implementation of the complex control and monitoring strategy. For example, the installation of sensors and controls of operable windows required a significant team effort of the construction manager, tradespeople, and technology providers.

While the challenges described above could be mastered without noticeably compromising the effectiveness of systems, several challenges in the construction process significantly altered the building performance. The construction of the wastewater treatment plant was one of these challenges. First, the implementation was on a different schedule than the rest of the project. Furthermore, the system was designed and installed by a single contractor, following a design-build approach. This unusual situation led to several wrong implementation strategies. For example, the wrong type of glazing was used for the treatment room, which was only discovered after project completion. As a consequence, additional light sources had to be installed to keep the aquatic plans alive, resulting in an increased lighting load.

Another challenge for CIRS was the implementation of the computer-based control interface for the lighting and HVAC system. As the development of the computer interface was delayed, the contractor did not feel responsible for the installation of the system after project completion. As a result, lights in office areas could not be turned off during times of sufficient daylight levels. Instead, lights turned on, as soon as internal occupancy sensors were triggered, and only dimmed down light levels based on internal daylight sensors. In addition to this unanticipated lighting load, lights that were connected to the emergency system had to be constantly turned on, as they were not controllable based on daylight levels. As it turned out, this lighting strategy was not required by safety standards, but led to an increased lighting load that was not anticipated in the predicted energy performance.

Similar to the previous two projects, several design deficiencies were not addressed during commissioning. The most striking example was the malfunctioning design of the heat-transfer system. While several members of the project team were aware of potential performance issues of the system, shortcomings were not addressed during the construction or commissioning process. The system was not part of commissioning since it extended beyond the building site of

CIRS. Although an M&V process was performed, the heat-exchange system was not verified. As a designer described, budget constraints and liability issues further complicated the resolution of the problem. This led to a significant under-performance of the heat-transfer system, the main component of the net positive energy concept of the CIRS building. These internal performance changes affected the efficiency of power transformers, which required more energy than anticipated in the energy model (Salehi et al. 2015).

As several of the identified deficiencies had not been addressed during the warranty period of the commissioning process, systems had to be re-commissioned outside of the project scope. After a research study had confirmed the deficiencies of the heat-transfer system, owner representatives decided to refurbish the system after the second year of operation. The refurbishment was part of a conversion project of the university's district heating system. This design change was supposed to improve the performance of the system in order to meet the original design targets. However, the performance of the new system has not been predicted or modelled. Continuous metered energy data will provide performance results of the refurbished system. A similar re-commissioning approach was taken to reduce the lighting load for the security system. Photocells were installed to reduce the lighting levels in areas, where lights could be turned off under sufficient daylight conditions. However, changes could only be made in places where lights for different building zones were not wired together on one circuit.

Furthermore, several operation changes were required that resulted in an increased energy consumption of the building. In the second year of operation, a larger water-distribution pump needed to be installed to meet the required pressures in the hydronic heating system. For the solar hot water system, an additional radiator had to be installed to avoid overheating of the system. And as already mentioned, the wastewater treatment plant required additional lighting in order to maintain the aquatic plant in the facility.

Although the water treatment plant was functional, the system could not be operated, due to the lack of an available certified operator. As it turned out, the training requirements for the management of the treatment plant had not been considered during the project development. As a consequence, there were no financial resources to hire a certified manager after project completion. Only an on-site technician was hired to manage the control system, in addition to a facility manager and seven tradespeople responsible for the operation and maintenance of the CIRS building. Although the treatment plant could not be used for building purposes, the system kept consuming energy in order to maintain the aquatic system.

Despite available management capacities, some of the systems were still not working as intended in the design in the fourth year of operation. For example, the inhabitant-control interface for the lighting and HVAC system had not been implemented until the fourth year of operation, resulting in unanticipated energy loads. The available manual control systems, such as operable windows and ventilation diffusers, were often not used as intended in the design (Salehi et al. 2015). According to building managers, inhabitants often neglected diffusers, but opened windows instead, as they were not aware of the availability or functionality of the heating system. Furthermore, additional equipment, such as laptops and additional computer screens, was used in office areas, which led to a much higher-than-anticipated plug load.

Table 4-4: CIRS Building – Summary of Reasons for Performance Gaps

Stage	Category	Reason for Performance Gap
Planning & Design	Consideration of contextual variables	Lack of sufficient information about existing infrastructure for multi-building systems led to a malfunctioning design strategy
	User-friendly design	Operational viability and management capacities were not considered when designing novel building systems, such as the wastewater treatment plant
		Control and monitoring systems were not well translated into design strategies, leading to complicated user-interfaces and malfunctioning systems
	Application of energy models	Design-assist models often followed design decisions rather than informing the decision-making process, resulting in malfunctioning system designs
Energy Model	Integration of complex systems	Innovative design features could not be accurately represented in the modelling software: geo-exchange systems and natural ventilation systems required work-arounds within the model, while a multi-building system required add-on calculations to the model, which were not third-party reviewed

Stage	Category	Reason for Performance Gap
Energy Model	Consideration of varying building usage	Energy models were lacking accurate information on anticipated occupancy numbers and operation hours for the building
		An ideal occupant behaviour was assumed for modelling the operation of building systems, without considerations of potential variation in use-patterns
Construction	Installation of systems	Contractor designed and implemented systems, such as the wastewater treatment plant, were not correctly integrated in overall building system, leading to a additional lighting loads
		Control and monitoring interfaces were not installed due to delays in development and implementation process
Commissioning	Functionality of new systems	The heat-transfer system was not part of commissioning, which led to undetected deficiencies of the design implementation
	Commissioning practice	Re-commissioning was not performed for all building systems resulting in several undetected deficiencies of major systems
		Outstanding and potential performance issues of the heat-transfer system were not addressed during the hand-over process of the building, due to a lack of sufficient budget
Handover	Measurement & Verification	Process loads of innovative building systems were not part of the standardized M&V process, so that deficiencies of systems could not be discovered
Operation	Sequence of operation	Insufficient pressures in the hydronic heating system required the installation of a water pump with higher capacity
		Excess heat of solar thermal water system had to be removed an additional radiator
	Control strategies	Lights that were part of the emergency system were constantly turned on
	Operator training	The water treatment plant was running, although it could not be used for building purposes, as adequate training was missing to allow the operation of the treatment plant
Occupancy	Education of occupants	Lack of sufficient education of occupants about system functionality led to unexpected use of control systems such as operable windows
		Additional equipment was used in offices leading to higher plug loads

4.11.3.2 Lessons Learned from the CIRS Building

One of the major challenges to meet the performance goals for the CIRS building was the successful design and implementation of innovative design features. The challenges with the heat-transfer system have shown that site-specific information is key for a successful design strategy. This includes the consideration of contextual variables, particularly for multi-building system, such as the heat-transfer system, that is connected to existing infrastructure outside of the building site:

> The challenge is, and I think this is something that we uncovered through CIRS, is that we weren't designing one building. We were designing a binary system, a two-building system, where we had a symbiotic relationship between two buildings. But ninety-nine percent of the effort was spent here [at the CIRS building], and only point one percent there [at the EOS building]. So that point one percent needed to be five percent. But it was point one percent… (O2, personal communication, Mar 21, 2015)

Detailed data need to be acquired early during the design phase, so that design strategies can be modelled promptly to inform the design of novel building systems. Furthermore, intricate control and monitoring systems need to be carefully translated into user-friendly and flexible design strategies to avoid unintended or wasteful operation of systems.

Furthermore, the impacts of changing user behaviour needs to be considered when modelling complex HVAC and control systems. A sensitivity analysis of energy consumption patterns would have helped to better predict a range of performance outcomes based on inhabitant behaviour. Similarly, changing occupancy numbers and operation hours need to be considered in the design predictions to the risk of under or over-prediction of system loads.

During construction, innovative design characteristics need to be carefully implemented into the overall building system. For example, the design-build approach for wastewater treatment plant resulted in several incorrect implementation strategies, affecting the performance of the system. Such unusual implementation strategies require particular attention and close collaboration of contractors and technology providers to ensure a successful integration into the larger system.

At the commissioning and verification stage, a rigorous evaluation of new design features is required to ensure the proper functioning of the system. As it turned out, the enhanced commissioning and M&V process, which were part of the LEED certification, did not include the review of process loads related to new building systems. As a result, design issues of the heat-transfer system were not addressed in the commissioning or M&V process. A lack of sufficient resources and liability issues further complicated the situation at the handover stage of the project. As a result, the building was left to building operators, despite uncertainties about the accurate performance of the heat-transfer system. According to a designer, this has been a common issue of novel building projects:

> There was essentially no budget to go "oh, we shouldn't have used this kind of heat exchanger or we should have used this other kind of heat exchanger". And that was certainly; I mean that's a problem that not every building should have to face because not every building is kind of at the bleeding edge. But, every building does have this phenomenon that there were things that, you know, were unexpected and that the crew operating the building, getting a clear sense of what the design intent of the system engineers were, in addition to the architects. Capturing that often fails, and so you often find the guy who is dropped in his lap and says, "nobody told me X". (D4, personal communication, Jun 14, 2015)

A rigorous commissioning and verification process during the design and construction process could help to address deficiency promptly. The same is the case for intricate control and monitoring systems that are key for the proper operation of building systems.

Outstanding deficiencies can otherwise lead to changed operation strategies in order to compensate malfunctioning systems. Furthermore, complex systems require sufficient training of facility managers and building inhabitants to allow operating systems as intended in the design.

4.12 Discussion of Reasons and Lessons Learned

As revealed in this chapter, several similar reasons contributed to the energy performance gaps in the three case studies. While some contributing factors obviously changed the performance outcomes, others had a minimal or undetermined influence on either performance predictions or actual performance of the buildings. In the following section, we will discuss the overarching reasons for performance gaps and provide particular lessons learned from the case studies. A summary of lessons learned can be also found in Table 4-5.

4.12.1 Collaborative Design for User-friendly Buildings

Different than anticipated in the literature, quantitative energy targets were available for all three building projects. However, there were shortcomings in the successful integration of performance targets in the design process. A close collaboration of stakeholders was critical for successful translation of performance goals into design strategies during the integrated design process. While continuous enforcement of initial performance targets by owner representatives encouraged collaborative decision-making processes and creative problem solving among stakeholders, unresolved performance discussions led to shortcomings in the design of innovative building features in several cases. As the case study of the DEC building has shown, it is key to considering knowledge and experience from multiple expert groups to ensure robust and operationally viable design strategies.

A close collaboration among stakeholders was equally essential for the development of a user-friendly building design. The lack of consideration of management capacities for novel building design resulted in complex control strategies of building systems. This led to unintended energy requirements in several instances, confirming findings from previous studies (B. Bordass, Cohen, et al. 2001; Fedoruk et al. 2015; Morant 2012). Therefore, control strategies need to be carefully translated into user-friendly and flexible system designs to avoid unintended performance outcomes. For example, code requirements for security systems have to be considered during the design to avoid unnecessary operation of building systems such as lighting systems.

4.12.2 The Importance of Accurate Energy Assessments

Another key factor for a successful building performance is the consideration of energy modelling results during the design phase. While all three building projects used design-assist models, in several cases, design decisions for major building systems were based on preliminary data. The lack of sufficient use of energy models for design decision-making was confirmed by findings from previous studies (e.g. Schlueter 2009). To ensure the development of sound design strategies, information about contextual variables, such as existing infrastructure, has to be assessed at the planning stage. This way, energy models can function as informative tools for major design decisions.

At the same time, limitations of assessment tools have to be taken into account when predicting the performance of innovative building characteristics. In several cases, the applied modelling software was limited in representing intricate building systems. For example, geo-exchange systems and natural ventilation systems required work-arounds within the mode. More innovative features, such as the heat-transfer system, could only be evaluated through external calculations or models, which were not always third-party reviewed. This is still an unresolved issue that has been mentioned in the literature (e.g. Wang 2012, Ohba 2010).

Furthermore, energy models need to reflect the total site energy consumption of the building. In several cases, renewable energy systems, exterior or multi-building systems were not part of the modelling requirements for building certification. This is key to ensuring that published design assessments reflect the actual performance of buildings.

4.12.3 Considering Building-Use and Occupancy

Another major shortcoming of performance assessment tools is the lack of careful consideration of anticipated building occupancy and usage patterns. Energy models of all three building projects were lacking accurate information on predicted occupancy and operation hours. As a result, reference standards were applied or served as the baseline for estimation of occupancy numbers and operation schedules. Although annual variation of occupancy levels were anticipated for the two academic buildings, predicted values were still significantly higher than actual occupancy levels. This finding has been confirmed by another research study, indicating that occupancy patterns of academic buildings need to be considered in terms of the specific usage (e.g. research, classrooms, and recreation) (Davis & Nutter 2010). Information about anticipated occupancy levels needs to be provided by building owners to ensure a more accurate estimation of usage patterns. This information is critical for equipment sizing and allocation of capital costs.

Furthermore, the impact of a changing building usage has to be considered when modelling demand controlled building systems (e.g. CO_2-sensor-controlled ventilation systems). Energy loads should be evaluated as a function of occupancy numbers and operation hours in order to determine the effect of changing usage patterns. Previous studies applied this approach to evaluate the operating energy of different building types (e.g. Koike 2005). Depending on the building design, the energy consumption of individual systems can depend to a varying degree on occupancy numbers and operation hours. In order to be able to make reliable performance predictions, energy models have to take these dependencies into account.

Similarly, occupant behaviour has to be considered when modelling the building control systems. As it turned out, inhabitants often did not use building systems as anticipated in the design, leading to unanticipated energy loads. It is key to accounting for variation in use patterns in the energy model to reflect a range of potential performance outcomes of a building. Several research studies have shown that such an agent-based modelling approach provides more reliable energy performance predictions for buildings and building systems (Azar & Menassa 2012; Erickson et al. 2009).

4.12.4 Collaborative Implementation Strategies

During constructions, major performance issues occurred in the implementation process of new design features. For example, new systems were not accurately installed due to an unfamiliarity of the construction team with the design strategy. Unusual design and implementation strategies may require specific training and a high level of collaboration between engineers, contractors, and technology providers. Furthermore, the integration of innovative design features needs to be carefully planned and coordinated to avoid implementation flaws. The planning has to happen during the design phase to prevent on-site system changes that can compromise the effectiveness of design strategies.

While change orders had a minor impact on performance outcomes, the installation and set-up of intricate control systems was of significant importance. In several instances, control strategies were not well translated into control systems, resulting in malfunctioning user-interfaces and system operations. For example, the design of control systems conflicted with the design of other systems or the room layout, and had to be changed during construction. In other instances, control systems and monitoring interfaces were not set up as intended in the design. For example, computer-based control systems were missing or conflicting with system-internal controls. This has been confirmed by previous studies (e.g. Fedoruk et al. 2015). In order to avoid conflicting control strategies, the initial design intent has to be carefully communicated to control contractors and technology providers, to guarantee a successful translation of design goals into reliable control strategies.

4.12.5 Continuous Commissioning Starting at the Design

In order to develop reliable and intricate building systems, design and implementation strategies have to be reviewed throughout the building development process. As case studies have shown, new building systems often bear unanticipated design and implementation challenges, which can lead to significant performance issues. To ensure that designed systems will meet the performance requirements, commissioning strategies need to be specified for innovative design features as part of the commissioning plan that was made at the design stage. Commissioning strategies should be developed with technology providers, as new systems may require specific verification procedures that go beyond standard checklists and testing plans.

During the construction phase, implementation strategies need to be promptly reviewed to avoid undetected deficiencies after project completion. Similar reviews and functional tests are required at the start-up phase, before the handover of the project. As it turned out, several identified deficiencies were not addressed during the handover phase of the projects. This confirms findings from the literature (e.g. De Wilde 2014, Fedoruk 2013). In several cases, outstanding deficiencies were not dealt with, as they were not sufficiently communicated to responsible stakeholders. Clear procedures and guidelines are required to ensure that deficiencies of novel systems are resolved during commissioning. For example, an independent commissioning agent has to be responsible for the final commissioning process to ensure a third-party review of all building systems. Furthermore, outstanding deficiencies have to be clearly documented in the final commissioning report, to avoid outstanding deficiencies after project completion. A clear communication of the commissioning results to consultants and project owners is required to ensure that corrective actions are taken and performance gaps are promptly closed.

Although all three projects followed an enhanced commissioning process, seasonal testing was not included in the review process, leaving several deficiencies undetected at the end of the warranty period. In two cases, not enough time and resources were allocated to the start-up phase, resulting in undetected deficiencies of major building systems. According to Preiser & Vischer (2006), short-term diagnostic monitoring should be part of the warranty phase and performed several times during the first year of operation. This can help to prevent unexpected performance deficiencies under different weather conditions and operation modes.

4.12.6 The Benefits of Monitoring and Verification

Similar to enhanced commissioning measurement and verification (M&V) methods can be essential for a successful building performance (Jump et al. 2007). Two case studies did not apply M&V processes and, consequently, did not verify predicted performance goals during the handover phase. M&V processes could have helped to address system deficiencies and to better manage the risk of under-performance of systems.

M&V not only reduces the risk of under-performance, but can also assist building managers in monitoring the building at the system level. It is key to ensuring that potential performance shortcomings are properly addressed in collaboration with the building management team. Otherwise, mistakes in designs may be repeated due to a lack of sufficient feedback (e.g. Bordass et al. 2004). The involvement of building managers can help to educate the team about functionality and potential weaknesses of systems. Sufficient resources and time needs to be allocated for M&V to be able to address potential shortcomings during the handover process. That way, M&V can be used to set the stage for continuous commissioning to ensure a correct operation and maintenance of complex building systems after project completion.

This requires the availability of energy metering for individual building systems. As the DEC case study has shown, the lack of energy meters can complicate the accurate operation and maintenance of a building. A readily available energy metering system provides a verification tool to building operators and can enhance a successful building performance.

4.12.7 Preparing for Building Operation

As not all deficiencies were addressed during commissioning, several systems could not be operated as intended in the design. Unexpected operation of several systems required adjustments to the sequence of operation, leading to additional energy requirements. While the literature indicated that system operations were often changed based on occupants' needs (e.g. Cheshire & Menezes 2013, Bordass et al. 2001), the case studies revealed that most changes were made due to malfunctioning systems. This highlights the importance of developing design strategies that are robust and suitable for the available management capacities to avoid operation changes.

Management capacities for building operation and maintenance have to be considered particularly when designing intricate design features. If the facility management team is understaffed with limited resources available, there is a risk that building systems cannot be operated and maintained as intended. The same applies to intricate control systems that need to be carefully designed to allow for flexible operation of major building systems depending on the actual building usage. At the same time, adequate operation skills and experiences of the management team need to be available to guarantee a successful building performance. This may require additional training of facility managers for the operation of innovative design features, such as water treatment systems, along with the standard operator training at the handover phase of the project. The case study has shown that training requirements have to be considered early during the design process, to guarantee that enough resources are allocated to operate and maintain building systems as intended.

4.12.8 Informing Inhabitants

Similar to the management team, building inhabitants have to be well informed about the functionality of building systems, to avoid unexpected usage of control systems and user-interfaces. In several instances, control systems were not used as intended, as occupants were not aware of available control systems or their functionality. This led to over or under-use of systems changing the overall performance of the building. This has been confirmed by many other case studies (e.g. Mahdavi 2009, Fabi et al. 2012). It is, therefore, key to informing and educating inhabitants about the design intent and basic functionality of building systems, in order to ensure that control systems are used as anticipated. Education requirements of building occupants have to be considered at the design stage, to ensure that prospect building users will be available to learn and adopt new control strategies for building systems.

Table 4-5: Summary of Lessons Learned

Stage	Category	Lessons Learned
Planning & Design	Alignment of targets	➢ A supportive building owner is a key asset to enforce performance goals and ensure the alignment of targets among stakeholders through the IDP process ➢ Collaborative decision-making and problem-solving across disciplines can help to develop robust design strategies
	User-friendly design	➢ Design strategies for new building and control systems need to consider operational capacities of the building management team to avoid inadequate operation strategies
	Application of energy models	➢ Energy models have to be used as informative tools for major design decision to help prevent malfunctioning system design ➢ Design changes need to be considered in performance evaluations to guarantee operational viability of systems and to avoid unexpected performance shortcomings
Energy Model	Integration of complex systems	➢ Limitations of modelling tools have to be taken into account when predicting the performance of innovative design features
	Consideration of energy loads	➢ Modelling requirements (e.g. for compliance models) should reflect the total site energy consumption of a building, including all building systems
	Consideration of varying building usage	➢ Information on anticipated occupancy numbers and operation hours need to be provided to the energy model to ensure an accurate representation of building usage ➢ Variation usage pattern and occupant behaviour has to be considered in the energy model to reflect the potential range of building performance outcomes
Construction	Change orders	➢ Innovative design strategies have to be carefully implemented to avoid on-site changes, which may compromise the effectiveness of design strategies
	Installation of systems	➢ New design and implementation strategies may require additional training and/or a high level of collaboration between contractors and technology providers

Stage	Category	Lessons Learned
Commissioning	Functionality of new systems	➢ Commissioning strategies for innovative design features are required to guarantee a successful system commissioning according to the design intent
	Commissioning practice	➢ Clear commissioning procedures are required to ensure that outstanding deficiencies are communicated and appropriately addressed ➢ Commissioning has to be performed by independent commissioning agent to ensure a third-party review of all systems ➢ Enhanced commissioning should include seasonal performance testing of all building systems during the warranty phase
Handover	Measurement & Verification	➢ M&V can be crucial for a successful building performance after project completion and should be considered as part of continuous commissioning during the first year of operation
Handover	Measurement & Verification	➢ Energy sub-metering systems is required to be able to verify performance goals and to uncover potential deficiencies after project completion
Operation	Sequence of operation	➢ Operational viability of novel building systems need to be considered to avoid unintended system changes that could affect the building performance
	Management capacities	➢ Management capacities for building operation and maintenance need to be considered when designing control systems or intricate design features to ensure that required skills and experiences are available to manage the building
	Operator training	➢ Training requirements to operate new building systems have to be part of the standard operator training to ensure the availability of operation and maintenance capacities for all building systems
Occupancy	Education of occupants	➢ Occupants need to be well informed about the functionality of building systems to be able to use control systems as intended in the design

Chapter 5: Conclusion

This study provided an in-depth analysis of the differences between predicted (modelled) and actual (measured) energy performance for three high-performance buildings in British Columbia and reasons contributing to the identified performance gaps. A literature review provided the contextual understanding of the energy performance, as a result of an intricate building development process that led to the actual performance of buildings (Chapter 2). The literature review showed that reasons for performance gaps in buildings could occur as a result of shortcomings happening at different stages in the building lifecycle. These stages include planning/design and modelling, through to construction, commission and handover, to building operation and occupancy. The range of potential performance-gap reasons encouraged a framework of evaluation that focused on the building development processes. First, an energy performance evaluation for three high-performance buildings provided information about differences between modelled and measured energy consumption (Chapter 3). Based on the results and the findings from the literature review, reasons for performance gaps were evaluated for all three case studies (Chapter 4). Criteria of evaluation became the understanding of how design, implementation, and operation processes affected the energy performance of each building.

5.1 Design Documentation & Benchmarking

The importance of energy performance evaluation of certified green buildings has been illustrated through three building case studies in British Columbia, as presented in Chapter 3. As indicated by the literature, differences between predicted and actual energy performance have been found in all three LEED-certified buildings. Actual consumption confirmed findings from previous studies showing that the actual energy consumption were often higher or lower than predicted. The JPCE building was the only building to outperform the predictions (by 20 percent). The CIRS building required 20 percent more energy than predicted. Both buildings did not achieve their initial net-zero or net-positive energy goals, even though occupancy was significantly lower than predicted. In the case of the JPCE building, the implemented PV array was not only too small to reach the net-zero energy target, but also generated 22 percent less electricity than anticipated in the design. Similarly, CIRS did not reach the net-positive goal, as the heat-transfer system transferred less than a third of the predicted energy. The DEC building significantly under-performed its energy targets, with energy consumption twice as high as predicted in the design.

Although all three buildings stayed below the energy consumption of similar building types in British Columbia, they added to the list of high-performance buildings that did not perform as intended in the design. Energy performance gaps also occurred at the sub-system level, such as heating, ventilating and air conditioning (HVAC), lighting, plug load, and domestic hot water (DHW), in cases where data were available. The analysis further revealed that actual energy consumption data were not consistently sub-metered in the buildings, complicating a successful energy performance evaluation. Similarly, energy predictions varied in detail and completeness of representing energy loads in the building. To inform building owners as well as industry partners, it is key that predicted and actual performance data are readily available.

Improved standards of documenting design predictions and actual energy consumption of certified 'green' buildings are needed in order to guarantee readily available information for performance evaluations. While energy-related quality assessments often focus on design calculations (Zero Carbon Hub 2013), there is a need for better documentation of actual energy performance data. Energy metering at the sub-system level is key to identifying sources for performance shortcomings in the building. The consistent use of programs, such as EnergyStar and CarbonBuzz, can help to make tracking of actual building energy performance a common practice among project owners. The application of such benchmarking programs often requires the enforcement through policies at the municipal level to ensure a consistent data gathering (see, for example, PlaNYC 2012). Such benchmarking can help to make actual building performance data available, which can be used to provide continuous feedback to the design and construction industry, and to allow for in-depth performance analysis and further research.

5.2 The Stories of the Gap

> *It is not the knowledge itself that is lacking but a sufficient mechanism to feed this knowledge back into building processes, supported by reliable measurement. We need to know when something has gone wrong that will impact the energy performance of the building. Testing at the end of the build may be too late to make significant impact but it will help to highlight issues and cause a shift in consciousness. (National Measurement Network 2012) (p.5)*

In Chapter 4, an evaluation of reasons for energy performance differences in the three case-study buildings revealed that causes found in the literature occurred in at least one or several projects. Identified reasons covered all evaluated stages of the building lifecycle: from planning/design and modelling, through construction, commissioning and handover, to building operation and occupancy. The results of the interview analysis suggested that differences between predicted and actual performance were closely related to shortcomings in energy-design concepts, development procedures, and operational practices that were applied in the three buildings.

In the case of the DEC building, one of the main contributing factors to the performance gap was the lack of careful consideration of **management capacities** in the building. While the design aimed to integrate novel technologies and advanced management and control systems, the available management capacity to operate the systems was not carefully considered. This, together with shortcomings in the design and implementation of the intricate HVAC system, led to significant energy performance gaps.

In the JPCE building, one of the major reasons for the energy performance differences was the lower-than-predicted occupancy of the building. Accurate occupancy numbers and operation hours were not available to the energy model at the design stage, leading to significantly higher energy predictions than what was actually required in the first three years of operation. Inaccurate **operation and occupancy schedules**, as well as the lack of consideration of occupant behaviour led to significant changes in the actual energy-use patterns. This shows the importance of considering use and function of the building carefully in order to predict energy consumption patterns accurately.

One of the major challenges to meet the performance goals for the CIRS building was the lack of a **site-specific design** of new building systems. The lack of specific information of existing infrastructure led to an incomplete design of the heat-transfer system, the major energy system. Furthermore, the system was not sufficiently modelled, as it was not part of the design-assist model. As a consequence, the net-positive energy target could not be met.

Both, the DEC and the CIRS building faced major performance challenges due to shortcomings in the **implementation of innovative design features**. In both cases, the lack of careful implementation of intricate systems such as control networks affected the overall functionality of building systems. Practices in building constructions were lacking sufficient communication between stakeholder groups that tended to work in silos, impeding the successful implementation of modern design concepts. Furthermore, with the increasingly interconnected and automated buildings systems, conventional practices of commissioning building systems did not sufficiently capture the complexity of new technologies and their performance. As a result, several deficiencies were not addressed during the commissioning process.

The case studies further revealed that commissioning processes varied in scope and focus, depending on available resources for the project. Although all projects followed an enhanced commissioning process (as promoted by LEED NC 2009), insufficient time and attention was allocated for final **commissioning and re-commissioning at the handover stage** and during the warranty period. Other factors, such as insufficient training of building managers for new building systems, unexpected occupant behaviour and use of control systems, further added to the energy performance gaps in the three projects.

5.3 Towards Interdisciplinary Project Delivery Processes

While the importance of factors contributing to the identified performance gaps was unique for each case study, common themes were found across the buildings. As mentioned above, **management capacities** for building operation and maintenance have to be considered when designing novel building systems. A lack of sufficient management capacities can lead to significant performance shortcomings, if systems cannot be operated and maintained as intended.

Designers, owners and building managers alike, have to be engaged in the development process of novel control and management systems. This could not only help to prevent the risk of insufficiently prepared facility management teams, but also to provide enough time to plan resources and training requirements in order to be able to operate the buildings as intended.

In general, the case studies revealed that a **user-friendly and flexible design** of innovative building systems is key to successful building operation and usage. Systems, as well as controls have to be easily accessible and interpretable for facility managers in order to meet operation targets of the building. This requires a shift of perspective away from a technology-focused approach to a user-friendly approach. Therefore, experienced building operators and facility managers are key stakeholders in the building-design process. They can function as a major consultant in the integrated design process (IDP), by providing practical information for optimal conditions for building operations – the longest phase in the building lifecycle. Facility managers can further add crucial information on the capacity and regulations of current building operations. As a result, user-friendly design can become a form of risk-management to reduce potential barriers to a smooth building operation process.

The case studies further highlighted that energy models were often not used to their full potential during the design stage of the building. While **design-assist energy models** are advertised as informative tools for the design development, the case studies revealed that the final building design is often done without an entire-building energy model available. In order to provide feedback on the performance and reliability of design strategies, the energy model has to be part of the design development process rather than following design decisions for the building. The energy model can hence be a valuable energy performance tool for the design of buildings.

Furthermore, the predicted energy consumption values of the models differed from the compliance models in two of the three cases. The literature has been pointing towards similar shortcomings of compliance models (e.g. De Wilde 2014). Compliance testing does not always reflect the predicted design, but is bound to regulatory restrictions of representing energy demands of buildings. This highlights the need for more **flexible compliance-model**

frameworks that allow the accurate representation of unprecedented energy systems and net-zero or net-positive energy concepts.

Energy modelling further requires accurate **information input** on anticipated building occupancy and operation schedules in order to predict energy consumption of a building. Without accurate information provided, reference standards are often applied as a default option, but these rarely reflect the actual use of the building. At this point, building owners and energy modellers have to communicate about required information, such as anticipated occupancy numbers and operation hours of the building. Modelling has to further consider the effects of occupant behaviour on system operation and how that could lead to a range of performance outcomes of a building. An agent-based modelling approach could help to develop more reliable energy performance predictions, as suggested by other studies (see Azar and Menassa 2012, Erickson et al. 2009).

The construction process is another pivotal point for accurate realization of the design goals that requires **continuous collaboration** of architects, engineers, and contractors. The research demonstrates that innovative design strategies have to be carefully planned and coordinated among stakeholders to avoid implementation flaws and performance shortcomings. A successful integration of novel technologies requires **information sharing** among engineers and contractors. This requires a fundamental change of current construction practices towards processes that guarantee a collaborative alliance of all stakeholder groups of the project team. One way of approaching this is to use project delivery arrangements such as integrated project delivery (IPD). IPD can foster a collaborative construction process and help to improve performance outcomes through shared risks and rewards between stakeholders (Lahdenperä 2012; Kent & Becerik-Gerber 2010).

The case studies further demonstrated the importance of the commissioning as an essential part of the development process of high-performance buildings, beyond what was indicated by the literature. **Enhanced commissioning** has the potential to be a key driver throughout the building development process: First, commissioning has to ensure that design strategies are workable, particularly for new building systems and intricate control strategies. Detailed commissioning requirements for the design and construction documents are key for a proper implementation and installation of building systems. Furthermore, sufficient time has to be allocated for an in-depth commissioning process and functional tests of large building systems before project completion. Clear procedures and guidelines are required to ensure that deficiencies of novel systems are resolved before or during the handover stage. Seasonal testing is key to detecting deficiencies under real operation conditions as part of the warranty process after project completion. This should become a standard requirement for high-performance buildings in order to prevent unexpected performance deficiencies under changing operation conditions. Commissioning can further enhance the understanding of new building systems through comprehensive system manuals and commissioning reports for building operators and managers. This could help to prevent re-commissioning cost after project completion to address missed performance issues.

Verification and Measurement (M&V) practices are another key element in reducing the risk of under-performance of buildings. As part of the handover or warranty process, M&V can help the project team to address performance shortcomings in collaboration with the building management team. The involvement of the prospective management team allows informing of facility managers about potential weaknesses of building systems and reduces risks of under-performance. Furthermore, rating systems needs to become more outcome based to guarantee a successful implementation of design goals. For example, certification could require post-occupancy verification of the building performance.

Prior to the handover stage, facility managers have to be effectively trained for all operation and maintenance requirements of the building, with a particular focus on modern building and control systems. This may involve **training sessions** by technology providers of design-build technologies that have been delivered independently from the overall project. In addition to building operation, inhabitants need to be informed about control strategies and related system functionality to ensure that building systems are used as anticipated in the design. The case studies confirmed that insufficient communication of design strategies could lead to over or under-use of building systems, changing the overall performance of the building. Introduction sessions to control strategies and user guides can become essential communication tools to prevent performance gaps in buildings (e.g. Morant 2012).

5.4 Moving Forward

> So what I wish is…what I hope for is […] there will be a tendency to, I don't want to say cover it up, but there will be a natural modesty about talking about the problems. And I think, you don't want to become recriminatory, but you do want to… if anything, this is a building that we should be learning from. Greater transparency rather than 'boosterism' would be nice. (D4, personal communication, June 14, 2014)

Overall, this thesis has added to the list of case studies of certified 'green' buildings that are not performing as intended in the design. In the context of these findings, the research highlights key factors contributing to performance gaps in the case studies and illustrates common findings from the literature with practical examples. As stressed by De Wilde (2014) "it is also important to realize that each individual building will have a specific, individual performance gap" (p. 46). With this in mind, the findings indicate general shortcomings in the current design, construction and management practices of high-performance buildings that require the attention of building owners and industry partners alike. The interviews with experts helped to identify a number of key lessons learned from the case studies.

The research emphasises the importance of creating a greater transparency of development procedures and collaborative approaches to successfully design, build and operate high-performance buildings. The challenges faced by project teams to integrate novel technologies calls for robust design solutions that can be easily translated into implementation strategies and operation procedures, which meet available building management capacities. This requires a close collaboration of stakeholder groups that are involved in the design, construction, and operation process of a building. An interdisciplinary project delivery approach, which considers building and institutional requirements, is needed, as well as the technical and human component of high-performance buildings. Novel and smart technologies require equally innovative and smart development strategies to guarantee a successful performance of buildings and their systems.

Therefore, further research is required to evaluate current design, construction, and management practices and how they affect the performance of highly energy-efficient buildings. A more detailed evaluation of the design, construction, and commissioning process would help to identify common shortcomings in the adoption of new energy-efficient technologies. This includes an assessment of the challenges in meeting performance targets within current industry procedures and regulations. While this study has indicated key factors contributing to performance gaps for the three case studies, further evaluations would be necessary to quantify how much each factor contributed to the performance gap. Energy measurements at the sub-system level would help to specify performance deficits of modern technologies and control systems. Similarly, it would be valuable to assess the impact of changing occupancy numbers, operation hours, and occupant behaviour on the performance of individual building systems. This would entail monitoring of building usage and a detailed comparison with modelling results. Finally, further case studies are necessary for a better understanding of common and specific performance gaps of innovative buildings. As described by Leaman et al. (2010):

> *In our experience, nothing betters case studies of named buildings backed by thorough data collection, benchmarked against a national sample, finishing with a list of lessons learned, preferably including reflections on the results by the parties directly involved, and especially the design team. Circumstances should be clearly explained so readers can judge for themselves the likely effects of any influential factors current at the time. Ideally, cases should tell a meaningful story with some surprises, and be written up in a balanced, non-judgmental style.* (Leaman, Stevenson & Bordass 2010b) *(p.567-68)*

It would be of considerable value to evaluate a set of buildings in order to understand reasons for performance shortcomings for different building types. A comparison of performance-gap reasons for different building types, including educational, office, and mixed-use buildings, could provide valuable insights into procedural challenges of reaching initial performance targets. This could help to close the feedback cycle to the building industry to allow for change of current development practices in order to overcome shortcomings in the energy efficiency of buildings in general.

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Appendix

Detailed Occupancy Schedules for the JPCE and CIRS Building

Table 5-1: JPCE: Occupancy Levels by Building Area & Seasons – predicted vs. actual

Building Area	Time Period	Typical daily occupancy during operating hours			Typical weekly operating hours		
		Predicted	Actual	Difference (%)	Predicted	Actual	Difference (%)
Office & common areas	May – Apr	11	27	245	50	50	0
	Sept – Apr	45	27	60			
Classrooms & trade shops	May – Aug	114	29	25	50	58	116
	Sep – Apr	455	84	18	50	66	132
Gym area	May – Aug	163	2	1	105	45	43
	Sep – Apr	163	8	5	105	70	67

Table 5-2: CIRS: Occupancy Levels by Building Area & Season – predicted vs. actual

Building Area	Time Period	Typical daily occupancy during operating hours			Typical weekly operating hours		
		Predicted	Actual	Difference (%)	Predicted	Actual	Difference (%)
Office & common areas	May – Apr	103	80	78	75	45	60
Auditorium	May – Aug	177	48	27	60	40	67
	Sep – Apr	251	130	52	60	58	96