Assessment of Different Commissioning Service Methods and their Ability to Achieve the Performance KPIs in Educational Buildings in Abu Dhabi-UAE

تقييم الطرق المختلفة لخدمة التكليف وقدرتها على تحقيق مؤشرات الأداء الأساسية في المباني التعليمية
في أبو ظبي، دولة الإمارات العربية المتحدة

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Abstract

The vibrant growth of Abu Dhabi's real estate, tourism and aviation sectors demand sustainable construction in the emirate, to minimise dynamic environmental impacts and to improve comfort levels in the built environment. The construction and operation of buildings contribute greatly towards climate change, global warming, energy crises and water crises, especially in hot-humid climatic zones, such as Abu Dhabi. The pearl rating system of the Abu Dhabi government is a dramatic move towards compulsory sustainable construction, which gives primary importance to water and energy savings. At the same time, building commissioning is a mandatory requirement of the pearl rating system and is the best cost-effective solution for reducing energy and water consumption. Studies show that Abu Dhabi's building commissioning is still in the infancy stage. Notable researches in this field are yet to be published and this paper is one of the very first researches investigating the analysis of commissioning of educational buildings in Abu Dhabi.

Worldwide, the construction industry follows various commissioning service methods, including third party directed commissioning, owner directed commissioning, engineer directed commissioning and designer directed commissioning. However, the selection of the commissioning service method is made typically on an advantage-disadvantage basis. The aim of this research is to go well beyond that, and to find the optimum commissioning service method by performing a thorough analysis of key performance indicators of building construction. Five educational buildings representing different commissioning service methods are selected for this research. Educational buildings have prime importance in the Abu Dhabi government's sustainability plans. At the same time, the performance of educational buildings will have a significant impact on the physical and mental health of coming generations. Performance analysis of these buildings will reveal the effects of different commissioning service methods on environmental, economic and service level performances of such buildings.

This research is classified into five phases. Quantitative analysis of buildings is the first phase, where the performance of four educational buildings are analysed against measurable key performance indicators. In Phase II of the research, qualitative analysis of expert opinions are conducted to analyse the non-measurable key performance indicators of the commissioning process. Phase III is designed to

select the optimum commissioning service method, based on the results obtained in Phase I and Phase II. The research then progresses towards the validation of the Phase III results, through real-life project application and its analysis, this marks Phase IV. The fifth phase of the research is to further fine-tune findings of Phase IV.

This research follows literature review, quantitative analysis of building performances and qualitative analysis of expert opinions. The literature review methodology helped to define the key performance indicators. On the other hand, quantitative processing of building trend logs as a preliminary step, supported by field measurements, aided in the analysis of building performances. This analysis revealed considerable differences in the performance of buildings. Buildings commissioned by third party consultants ranked highest in performance, followed by buildings based on owner directed commissioning. Concurrently, qualitative analysis of expert opinions was conducted through a three-stage Delphi study, to analyse those performance indicators that cannot be measured or quantitatively analysed.

The results of the Delphi study show that owner directed commissioning is the best in communication and collaboration, while third party directed commissioning is the best in verification and documentation. Designer directed and engineer directed commissioning service methods could not perform well in this analysis, as communication, collaboration and documentation were very poor in these cases, based on the Delphi study results. The results support a third party-owner combined commissioning to share the best practices from each service method. The third party will lead the commissioning service, but the communication and collaboration will be channelled through the owner of the project. The selected commissioning service method is further refined to improve the communication indicator, for advanced optimization. The results of this research can be used to establish key performance indicators for educational buildings in Abu Dhabi. At the same time, this study will help developers to understand various commissioning service methods, to assess their abilities to achieve building key performance indicators (KPIs) and to select the optimum method for constructing educational buildings in Abu Dhabi.

ملخص

النمو القوي الذي تشهده أبوظبي لقطاعات العقارات والسياحة والطيران، تحتاج للبناء المستدام في الإمارات، حتى تقلل وتحسن من مستويات الراحة والبيئة القائمة. البناء وتشغيل المباني تساهم الى حد كبير في تغير المناخ والاحتباس الحراري و أزمات في الطاقة والمياه، خاصة في مناطق مناخها حارة ورطبة، مثل أبو ظبي. نظام تصنيف اللؤلؤ من حكومة أبو ظبي، هي خطوة مثيرة نحو البناء المستدام الإلزامي، الذي تعطي أهمية أولية لتوفير المياه والطاقة. وفي نفس الوقت، بناء التكليف هو من المتطلبات الإلزامية من نظام تصنيف اللؤلؤ وايضاً الحل الأفضل فعالة من حيث التكلفة لتقليل استهلاك الطاقة والمياه. وتشير الدراسات إلى أن تكليف البناء في أبو ظبي ما زال في مرحلة الطفولة. لا يزال إصدار أي من الباحثون البارزون عن هذا المجال وهذه الورقة هي واحدة من أول الابحاث التي تحقق في تحليل التكليف على المباني التعليمية في أبو ظبي.

في جميع أنحاء العالم، صناعة الإنشاءات تتبع العديد من طرق تقديم خدمة تكليف، بما فيها من تكليف موجه لا لطرف الثالث، تكليف موجه إلى صاحبها، وتكليف موجه للمهندس وتكليف موجه للمصمم. ومع ذلك، يتم اختيار أسلوب خدمة التكليف عادة على أساس ميزة أو غير مؤات. والهدف من هذا البحث هو الذهاب إلى ما وراء ذلك، والعثور على طريقة الخدمة للتكليف الأمثل عن طريق إجراء تحليل شامل لمؤشرات الأداء الرئيسية للبناء. ولهذا البحث تم اختيار خمسة مباني تعليمية تمثل تكليف طرق التقديم للخدمة المختلفة. المباني التعليمية لها أهمية رئيسية في خطط الاستدامة لحكومة أبو ظبي. وفي نفس الوقت، فإن أداء المباني التعليمية قد يكون لها تأثير كبير على الصحة البدنية والعقلية للأجيال القادمة. وتحليل أداء هذه المباني سوف تكشف عن آثار طرق تقديم خدمة التكليف المختلفة على مستوى الأداء الاقتصادي والبيئية لهذه المباني.

يصنف هذا البحث إلى خمسة مراحل. أولهم هو التحليل الكمي على المباني حيث يتم تحليل أداء أربعة مبان تعليمية ضوء مؤشرات الأداء الرئيسية القابلة للقياس. ثم في المرحلة الثانية من البحث، يتم إجراء تحليل نوعي لآراء الخبراء لتحليل مؤشرات الأداء الرئيسية غير قابلة للقياس على عملية التكليف. صممت المرحلة الثالثة لتحديد أسلوب خدمة التكليف المثالي، وتستند على النتائج التي حصلت عليها في مرحلة الأولى والمرحلة الثانية. ثم يتقدم البحث باتجاه المصادقة على نتائج المرحلة الثالثة، من خلال تطبيق مشروع من واقع الحياة وتحليله. فهذا يمثل المرحلة الرابعة. المرحلة الخامسة من البحث هي زيادة النتائج الغرامة للمرحلة الرابعة.

هذا البحث عقب مراجعة الأدب، والتحليل الكمي عن أداء البناء وتحليل نوعي لآراء الخبراء. ساعدت منهج مراجعة الأدبيات لتحديد مؤشرات الأداء الرئيسية. من ناحية أخرى، التجهيز الكمي لسجلات البناء، خطوة أولية مدعومة بالقياسات الميدانية، تساعد في تحليل أداء المبنى. و هذا التحليل كشف اختلافات كبيرة في أداء المباني .المباني بتكليف من الاستشاريين الأطراف الثالثة في أعلى مرتبة في الأداء، ويليها المباني بتكليف صاحبها. وفي نفس الوقت، تم تحليل نوعي في ثلاث مراحل من خلال دراسة دلفي لآراء الخبراء ، لتحليل مؤشرات الأداء التي لا يمكن قياسها أو تحليلها كميا.

نتائج دراسة دلفي تظهر أن التكليف الذي يعتمد على توجه المالك أفضل في التواصل والتعاون، بينما التكليف الذي يعتمد على التوجه من الأطراف الثالثة أفضل في التحقق والتوثيق. في هذا التحليل التكليف

المعتمد على توجيه المصمم والمهندس لم تستطع أداء جيدا وكذلك التواصل والتعاون والتوثيق سيئة للغاية في هذه الحالات، استنادا إلى نتائج من دراسة دلفي. تدعم النتائج مشاركة بين تكليف الطرف الثالث وتكليف الصاحب لتبادل أفضل الممارسات في أسلوب خدمة. الطرف الثالث يقود خدمة التكليف، وسيتم توجيه التواصل والتعاون من خلال صاحب المشروع. ويتم تكرير أسلوب خدمة التكليف المختارة زيادة تحسين التواصل مؤشرات الأداء، لتعظيم الاستفادة المتقدمة .ونتائج هذا البحث يمكن أن تستخدم لوضع مؤشرات الأداء الرئيسية للأبنية التعليمية في أبو ظبي. وفي نفس الوقت، هذه الدراسة ستساعد المطورين لفهم العديد من أساليب خدمة التكليف، لتقييم قدراتهم لتحقيق مؤشرات أداء البناء الرئيسية (KPIs) واختيار الاسلوب الامثل لبناء المباني التعليمية في أبو ظبي.

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Glossary

AC	Alternating Current
AHJ	Authorities Having Jurisdiction
AHU	Air Handling Unit
ASHRAE	American society for heating, refrigeration and air conditioning engineers
BIM	Building Information Model
BMS	Building management system
BoD	Basis of Design
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CxA	Commissioning Authority
DC	Direct Current
FAHU	Fresh Air Handling Unit
GCC	Gulf corporation council
GSIFC	Georgia State Financing and Investment Commission.
HVAC	Heating ventilation and air conditioning
IAQ	Indoor Air quality
ICA	Independent Commissioning Agent
IDP	Integrated Development Process
IEQ	Indoor Environmental Quality
IESNA	Illuminating Engineering Society of North America
KPI	Key Performance Indicators
LBNL	Lawrence Berkeley National Laboratory
LEED	Leadership in Energy and Environmental Design
NEBB	National Environmental Balancing Bureau
NFPA	National Fire Protection Association
NIBS	National Institute of Building Sciences
OPR	Owner's Project Requirements
PBRS	Pearl Building rating system
PRS	Pearl Rating System
PV	Photo Voltaic
RFI	Request For Information
UPC	Urban Planning Council
VOC	Volatile Organic Compound

Chapter – 1: Introduction

1.1 Background and Motivation

The production of petroleum and natural gas was once considered as the major income generator for the United Arab Emirates (UAE). However, now, revenue from construction and real estate plays a vital role in the UAE economy and has become the second largest gross domestic product (23%) contributor in the Gulf Corporation Council (GCC) as stated by Khullar, Agarwal and Kumar (2010). The overall budget of the construction industry in GCC nations was more than US$ 1 trillion and about two-thirds of this was from the UAE (Khullar, Agarwal & Kumar, 2010). Abu Dhabi and Dubai are two dynamically developing cities in the UAE, which benefit the most from the vigorous growth of the construction-real estate sector. The UPC states that (UPC, 2010b) the market still has a greater demand than what is being supplied. In light of this high demand, the construction industry has given rise to multi-billion dollar projects in the suburbs of Abu Dhabi, such as the Al-Raha beach development, Masdar city project, Khalifa port and industrial zone development, Saadiyat Island development, Yas island development and a number of other developments in and around the city.

This dynamic development and urbanisation will have a great impact on the local, as well as global, environment. The government of Abu Dhabi has a clear vision to minimise the environmental impacts of buildings, through the pearl rating system (PRS) for built environment (UPC, 2010a). All new constructions in the emirate of Abu Dhabi must follow the PRS and obtain at least one pearl rating. This rating system is developed specifically to meet the built environment sustainability requirements of the local geographic region. The credit rating is distributed into seven different sections with maximum credit for water reduction and energy reduction (UPC, 2010a). Commissioning of buildings is a mandatory credit under the section covering the Integrated Development Process (IDP). Commissioning of all energy related systems like heating ventilation and air conditioning (HVAC) system, onsite energy generation, building management system (BMS), lighting system, lighting control system, domestic hot water system, domestic cold water system, on site water treatment system and automated control feature, are mandatory. Commissioning of these systems and assemblies has a great impact on the highest ranked credit sections of the PRS –

energy reduction and water reduction. The intent of the pearl building rating system (PBRS) credit basic commissioning is to make sure that the built environment is designed, built and operated in an efficient manner and for the wellbeing of its occupants (UPC, 2010a).

As per the American Society for Heating, Refrigeration and Air Conditioning Engineers (ASHRAE), commissioning is a collaborative endeavour, for achieving, verifying and documenting the owner's goals of energy efficiency, water efficiency and indoor environmental quality (ASHRAE, 2013a). ASHRAE is considered as the first non-profit organisation to develop an unbiased guideline for the building commissioning process (Turner, 2012). ASHRAE's first building commissioning guideline published in 2005, treats commissioning as a quality oriented process starting from the inception of the project until de-commissioning of the building through various phases, including pre-design, design, construction and operations (Ágústsson & Jensen, 2012). To accomplish the objectives of the commissioning process, the commissioning team must have experienced personnel from various fields of building construction, such as architecture, civil, mechanical, electrical, information & communication technology and controls. As explained in ASHRAE (2013a), an entity authorised by the owner to direct and coordinate the commissioning team is known as the commissioning authority (CxA). Nowadays, commissioning is considered as a business as usual model in mature construction markets, with different types of commissioning service methods, including third party directed commissioning, designer directed commissioning, owner directed commissioning and engineer directed commissioning. ASHRAE, as a reputed non-profit organisation in the construction industry, says that the commissioning team leader (commissioning authority) should be an independent body reporting directly to the owner and should not be an employee or sub-contractor of any organization involved in the design, supervision or execution of the project (ASHRAE, 2013a). In contrast, PRS guidelines state that the commissioning team leader (independent commissioning agent) can be an employee of any of the organisations involved in the project development process (UPC, 2010a). These contradictory statements are the motivation behind this research. As the quality of each service method will be different, the aim of this research is to establish an optimum commissioning service method for upcoming educational institution projects in Abu Dhabi.

Educational buildings are a top priority in the Abu Dhabi government's Vision 2030 development programme (UPC, 2010b). At the same time, educational buildings are suitable for analysis of the commissioning process, as the energy and non-energy effects of commissioning will have a great impact on the inhabitants. The Abu Dhabi government is spending more than 25% of the total federal government budget on education, including the development of infrastructure for education (UPC, 2010b). This 25% of the budget is a considerable amount and a great majority of the population receives the benefits of educational facility improvements. This shows the need to focus the research on educational buildings. Educational buildings are considered as the pilot buildings to spread the sustainability aspects of buildings to future generations. The very first pearl rated building in all of Abu Dhabi is a high school situated in the city of Al Ain. The Abu Dhabi government built this school as a pilot building to study the potential of the PRS in achieving sustainability goals. As it is a government building, all activities were under the direct control of Estidama (sustainable building construction program of Abu Dhabi government). On the other hand, the indoor environmental quality (IEQ) of educational buildings are of utmost importance, as activities taking place in educational buildings require good environmental conditions. A recent study conducted by Light, Bailey and Meetre (2015) confirms that indoor comfort conditions in classrooms have a great impact on the physical and mental health of students. Commissioning is an inevitable process for the construction and operation of any sustainable building (Enck, 2010). So, a research on commissioning of typical educational buildings in Abu Dhabi is very important in the present day scenario. This will help to develop an optimum commissioning service method for buildings in this region, in order to achieve maximum benefit in a cost effective manner.

1.2 The Research Question

Comprehensive building commissioning is a new concept in the UAE. Here, commissioning was once considered as simply the adjusting and balancing of the air and water flow of the HVAC system in buildings. However, now, the organised commissioning of energy related systems in buildings is made mandatory by the government as explained in the previous section. Currently, the industry follows different types of commissioning service methods, including third party directed commissioning, designer directed commissioning, owner directed commissioning and engineer (supervision consultant) directed commissioning. Each method has its own advantages and disadvantages. To date, the selection of the commissioning service method was made merely on the basis of the advantages or disadvantages of each method. Third party directed commissioning is considered as an independent commissioning service method to document and verify whether the owner’s project requirements are met in each phase of the project. However, hiring a third party will escalate project costs. The second option is commissioning by the owner’s staff. Yet, in most of these cases, this will end up as process commissioning and not as technical commissioning, as stated by McFarlane (2013). Process commissioning will simply oversee the documents but will not do actual field commissioning as conducted in technical commissioning. This is because, an owner directed commissioning team will have technical limitations and will have other obligations to the owner. On the other hand, both owner directed and third party directed teams will handle different projects at the same time, yet designer directed or engineer directed teams will have more knowledge about the specific project under consideration. This is the advantage of designer directed and engineer directed commissioning. However, in this case, the commissioning authority will purposefully hide design errors or supervision errors, which will result in an underperforming building, as stated by Turner (2012). These are the advantages and disadvantages of different types of commissioning service methods. Presently, most of the projects in Abu Dhabi select commissioning services merely based on a simple advantages and disadvantages assessment. The key question is, which commissioning service method has the ability to achieve key performance indicators (KPIs) of educational buildings? An assessment of different commissioning service methods against KPIs will help to address this question.

1.3 Aims and Objectives of the Research

The aim of this research is to establish an optimum commissioning service methods for achieving the key performance indicators of educational buildings in Abu Dhabi. This will help the building owners in this region to select the best commissioning service method for the benefit of the project. The objective is to identify the differences in performance of each building type, in terms of energy, water and occupant comfort. Based on ASHRAE (ASHRAE, 2013a), other aspects of commissioning, such as achieving the owner's project requirement, improving occupant productivity, improving communication, improving collaboration, improving documentation, improving operator knowledge, reducing change orders and minimising maintenance cost, will also be assessed. Although, the number of experienced commissioning professionals is limited in this region, experts from various other fields related to building construction can contribute to this research. The objective is to collect expert opinions on the subject matter and to analyse the data (Delphi study) to help define the optimum commissioning service method.

The current practice in the industry is to select a commissioning service method based on the advantages and disadvantages of different service methods, as stated by the Georgia State Financing and Investment Commission (GSFIC, 2010). A more detailed study to find the optimum service method will help the developers to select the best method for the benefit of typical building commissioning in the emirate of Abu Dhabi. Another aim of the research is to establish a strategy to overcome limitations of commissioning service methods currently practiced and to secure the best improvements from the building commissioning process. Pinpointing the limitations of current commissioning service methods is considered as one of the objectives of the research. The performance of buildings will be assessed based on key building performance indicators. Development of key performance indicators is another objective. The performance indicator will be developed to address all benefits of building commissioning addressed in the ASHRAE commissioning guideline (ASHRAE, 2013a). Following are the aims and objectives of this research.

Aims

- Identify the best commissioning service method for achieving the key performance indicators of educational buildings in Abu Dhabi.
- Establish a strategy to overcome limitations of commissioning service methods currently practiced.

Objectives

- Identify the difference in performance of buildings that have undergone various commissioning service methods through quantitative building performance analysis.
- Define the differences in performance of commissioning service methods through qualitative analysis of each service method.
- Pinpoint the limitations of current commissioning service methods.
- Establish performance KPIs for educational buildings in Abu Dhabi.

1.4 Expected Outcome of the Research

This research will light a path for the establishment of an optimum building commissioning service method for typical educational buildings in Abu Dhabi. A detailed study of different types of commissioning service methods will be discussed. Building commissioning is a new concept here and a number of developers are not sure about the type of service to be adopted. A comparison of different combinations of services will help owners to select the best method for their buildings. Moreover, this research will help to identify the performance indicators for energy efficiency, water efficiency and non-energy aspects of educational buildings in Abu Dhabi.

This research will help to create a practical method for trend data analysis of educational buildings in Abu Dhabi. Trend data of the building is a clear indicator of the performance of the building, if the control system of the building is properly functioning. A trend log data will have a large number of entries as stated by Raftery, Keane and Costa (2009). A proper method to analyse the trend data will be developed as part of this research.

Above all, research on building commissioning services is very limited in this region of the world. In mature markets, such as the United States and Europe, building commissioning has been the subject of extensive researches and a number of research methodologies have been developed to meet market requirements. The building development sector of the UAE can adopt technical and management tools used for this research. As regional research can help to find solutions for regional problems, this research will open a path for the UAE's building construction industry to benefit the maximum from the commissioning process. At the same time, this will help future researchers to concentrate more on building commissioning for the sustainable development of the built environment.

1.5 Research Outline

This research will be carried out through quantitative as well as qualitative analysis of building performances. A thorough literature review of building commissioning is the first step of this research, which is used to explore the backgrounds, trends and types of commissioning services. At the same time, the performance indicators of buildings will be studied in detail. Based on the criterion developed through literature review, selection of buildings for quantitative analysis is the next step. Detailed methodology of the research will be developed for the quantitative analysis. The research can be divided into five different phases as listed in Table 1.1. Analysis tools to minimise errors in each research phase will be developed and implemented.

Table 1.1: Research Phases

Phase I:	Quantitative performance analysis of existing buildings
Phase II:	Qualitative analysis of expert's Opinion (Delphi Study)
Phase III:	Selection of best service method (or combination)
Phase IV:	Evaluation of performance of the selected system
Phase V:	Refine the system to reflect lessons learned in Phase IV

During the first phase of the research, quantitative performance analysis of various buildings will be conducted based on trend data logs and field observations. In the second phase of research, qualitative analysis of expert's opinion will be performed. The results of these two phases will be compiled together to form an optimum solution for the commissioning service method for educational buildings in Abu Dhabi. In the first methodology, trend data of four existing educational buildings in the emirate of Abu Dhabi will be quantitatively analysed to identify the performance of each building. The buildings are selected to include maximum diversification of commissioning service methods (owner directed, engineer directed, designer directed and third party directed commissioning process). The second methodology of the research is a qualitative analysis of expert opinions. A comprehensive interview will be conducted to collect the opinion of the experts in building commissioning, building design and facility management sector. A thorough literature review on commissioning service methods and commissioning management will help to develop the comprehensive interview questionnaire. Different aspects of the building commissioning can be assessed through this approach. The energy performance of buildings directly shows the benefits of commissioning, and the non-energy benefits are indirect indicators, although the latter has a greater impact than the energy benefits. Data collected in the first and second phases of the research will be analysed in Phase III to select the best service method. During the fourth phase of the research, the selected commissioning service method will be implemented in one of the real-life projects in Abu Dhabi to find the benefits over other systems. The final phase of the research will fine tune the selected commissioning service method, based on the lessons learned in Phase IV.

Chapter – 2: Literature Review

2.1 Introduction

A thorough literature review is an essential part of any good research. However, building commissioning is a new technology in the Middle East and research on the subject is very minimum in this region of the world. Conversely, a research conducted by Ágústsson and Jensen (2012) states that building commissioning is considered as 'a business as usual model' in mature markets, such as the United States. However, new guidelines of Abu Dhabi government make building commissioning mandatory for all new building in the emirate as stated by UPC (2010a). This will make a big difference in the attitude towards building commissioning research. Additionally, as stated by Ye and Rahman (2011), building rating systems like LEED and ESTIDAMA gives wide acceptance for the commissioning process, that the building owner's approach is changed to undertake commissioning activities on their projects to earn building rating system credits.

For this research, various aspects of commissioning and their ability to achieve the performance KPIs are studied in detail, from a global perspective. According to Turner (2012) the commissioning guidelines published by ASHRAE is accepted globally as a standard for building commissioning. So the building commissioning procedure followed is more or less the same in various parts of the world. This literature review focuses on two subjects – the commissioning process and key performance indicators of buildings. Initially, the literature review concentrates on the current trends in the global commissioning industry, its evolution and various benefits of the process. Moreover, different types of commissioning process are discussed. A detailed study of different commissioning service methods is included in this section. On the other hand, flaws in the building commissioning process are also discussed.

Secondly, key performance indicators of buildings are discussed in facts. This will cover not just the construction process, but the entire life cycle of buildings. Performance of buildings must be studied in detail during the operations phase, as it is the most energy intensive and the longest phase of the building in its entire life span (Monno & Conte, 2012). Research in this field follows several globally accepted assessment methods. This literature review is riveted on development of building performance indicators and the influence of the commissioning process on it. The literature review takes both a building-centric approach and a holistic approach to study the different aspects of the performance of the building and its effect on the environment. At the same time, social and economic performance of the built environment are also discoursed.

2.2 Building Commissioning

For this research, a number of recent research studies on building commissioning are explored in detail, along with some conference proceedings, commissioning guidelines and official reports to understand the evolution of the building commissioning process, benefits of commissioning, structure of the commissioning team, and its functions. An article published by Ágústsson and Jensen (2012) claims that ASHRAE was the pioneering organization in establishing building commissioning processes and procedures. ASHRAE’s first commissioning guideline was published in 2005, in association with various other organizations, such as the National Institute of Building Sciences (NIBS), National Environmental Balancing Bureau (NEBB), National Fire Protection Association (NFPA) and Illuminating Engineering Society of North America (IESNA). ASHRAE’s description of the commissioning process (ASHRAE, 2013a) is prominent, and it can be summarised as a process to ensure that the project requirements of the owner are given the highest priority during all phases of the construction process, including pre-design, design, construction and occupancy. The same standard (ASHRAE, 2013a) systematically explains the building commissioning procedures, benefits, requirements and expected outcomes. Additionally, the US Department of Energy (Baechler & Farley, 2011), summarises the studies conducted by the Lawrence Berkeley National Laboratory, and affirms that the commissioning is a scheme for assessment and administration of risks in the construction process. Mills (2011) and Turner (2012) argue that the building commissioning process can be briefed as the most gainful process that could improve the water saving and energy saving potential of buildings. In short, the owner of the building is the financier and primary stakeholder of the building, whereas commissioning is the process to make sure that the owner's interests on building performance and cost savings are established, verified and maintained in a professional manner.

2.2.1. History of Building Commissioning

For centuries, commissioning was the term exclusively used to describe the formal acceptance of naval ships for sailing (McFarlane, 2013). A recent study conducted by Shi (2011) relates the history of building commissioning to ship commissioning. Similarly, Ágústsson and Jensen (2012) says that the commissioning of vessels is the initiative behind the building commissioning process for achieving, verifying and documenting whether the buildings are designed, constructed and operated as per the owner's project requirements. Again, Ágústsson and Jensen (2012), discusses the detailed history of building commissioning and confirms that, the Public Works department of Canada in 1977 was the first organization to use commissioning as a quality control process for buildings. Since then, building commissioning has been practiced in various parts of the world. A research paper published by Kats (2013) mentions that the commissioning actives were not unified in the earlier stage and commissioning was considered as an activity to be done just before handover of the project to test, adjust and balance HVAC system in buildings. ASHRAE is the first organization to come up with a guideline to unify the building commissioning process (Shi, 2011). As explained by Shi (2011) and Kats (2013) ASHRAE's commissioning guideline describes the processes and procedures for commissioning management, without specifying the technical requirements for commissioning of any particular building service system. Technical details of commissioning of different systems and assemblies are covered in the supplementary documents published by the participating organizations, such as NIBS, NEBB, NFPA and IESNA. As stated in ASHRAE (2013a), ASHRAE's guideline-1.1 is an example of supplementary documents that deal with the technical requirements for HVAC commissioning.

2.2.2. Commissioning Team and their Functions

A research paper published by Ágústsson and Jensen (2012) suggests that all professionals who are involved in the execution of the commissioning process can be considered as the commissioning team. Alternatively, Kantola and Saari (2014) provide a deeper view on this matter and list the commissioning team members in each phase of the construction project, along with the tasks to be undertaken. For a construction project, the very first entity hired by the owner will be the commissioning authority and the commissioning authority will report directly to the owner (Baechler & Farley, 2011). The commissioning authority will lead, coordinate, plan and schedule the commissioning team and its functions. Table 2.1 shows the structure and functions of the commissioning team during each phase of the project.

Table 2.1: Commissioning team members and their functions
(Kantola and Saari, 2014, p. 375)

Construction Phase	Commissioning Team	Functions of the Commissioning Team
Pre-Design	Commissioning Authority Owner Architect General Contractor	Develop and document owner's project requirement document (OPR).
		Develop a strategy to resolve issues that may come up during subsequent phases.
		Asses risks in the commissioning process
		Develop the pre-design phase commissioning plan
		Set energy and water targets of the project.
		Set the Indoor Environmental Quality (IEQ) goals for the project

Design	Commissioning Authority Commissioning Consultants Owner Architect General Contractor HVAC Designer HVAC Vendor	Schedule and conduct regular design phase commissioning meetings
		Develop Design Phase Commissioning Plan
		Commissioning review of Design Documents
		Review Basis of design document against owner's project requirement (OPR)
		Develop commissioning schedules
		Update commissioning issues log template and develop strategies to resolve issues
		Develop communication strategy to be followed within the commissioning team and with others.
		Develop Design Phase Commissioning Report
Construction	Commissioning Authority Commissioning Consultants Owner Architect General Contractor HVAC Designer HVAC Vendor	Schedule and conduct regular construction phase commissioning meetings
		Develop Construction Phase Commissioning Plan
		Commissioning review of Contractor submittals, Workshop drawings, Method statements, Operations & Maintenance Manuals and Record Drawings
		Lead pre-functional tests, functional performance test, system wide tests and integrated tests.
		Ensure that measures are taken to cater for the energy goals, water saving goals and indoor environmental quality goals.
		Update commissioning issues log and initiate team members to resolve issues.
		Develop Construction Phase Commissioning Report
Occupancy	Commissioning Authority Commissioning Consultants Owner Facility Management Team	Co-ordinate and review end user operations and maintenance training
		Conduct seasonal/differed tests and asses the performance of the building against energy, water and IEQ targets.
		End of warranty period review
		Fine tuning or re-balancing of systems in regular intervals.

2.2.3. Cost and Benefits of Commissioning

Mills (2011) in association with the Lawrence Berkeley National Laboratory (LBNL) conducted an extensive research on 643 buildings in the United States, to find the outcome of the building commissioning process. This research is considered as one of the most prominent works on cost-benefit analysis of building commissioning (Kantola & Saari, 2014). At the same time, a report published by the International Energy Agency (Friedman et al., 2010), gives a brief description of the realistic benefits of the commissioning process. The summary of this report is provided in Table 2.2. The US Department of Energy (Baechler & Farley, 2011), provides a detailed description of the energy related as well as non-energy related benefits of commissioning. Furthermore, a paper published by Altwies and Mcintosh (2011) and another paper published by Kantola and Saari (2014), also explain the energy and non-energy benefits of commissioning. Table 2.3 summarises the findings of Baechler and Farley (2011), Altwies and Mcintosh (2011) and Kantola and Saari (2014).

Table 2.2: Important Benefits of the Building Commissioning Process
(Friedman et al., 2010, p.36)

Design Phase
Optimum sizing of equipment Improved equipment Layout
Construction Phase
Proper project planning Proper strategy for roles and responsibilities Minimum change orders Minimum disputes Reduce service call-backs Reduced cost More Collaboration

Occupancy Phase
Quite handover process Reduces service disturbances Proper monitoring of warranty period services Safe work environment Reduced legal issues.
Other Benefits
Earn building rating system credits Improved occupant comfort conditions Improved equipment life

Table 2.3: Energy and non-energy benefits of building commissioning
(Baechler & Farley, 2011, p.4, Altwies & Mcintosh, 2011, p.2 and Kantola & Saari, 2014, p.375)

Energy Related Benefits	Non-Energy Related Benefits
Peak energy demand reduction for best price per unit of energy use.	Better indoor environmental quality provided improved end user well-being, health and productivity.
Control sequence errors are pointed out early and corrected for improved energy savings and comfort conditions.	Improved equipment performance.
Monitoring excess energy and water use, to reduce wastage of the same.	Commissioning helps to earn building rating systems credit points.
Optimized equipment time scheduling, for energy use reduction.	Extended life expectancy of equipment, as a result of proper installation and maintenance tracked trough commissioning.
Optimized equipment sizing, for energy use and capital cost reduction.	Extended life expectancy of the structural and architectural components, as environmental effects are minimised through air leakage reduction.
Proper operation of equipment will help to save energy and water. This will be achieved through documentation of operations and maintenance manual and through proper training.	Reduction in change orders, conflicts and information requests

Seasonal alterations on system set points provides energy and comfort benefits	Reduced Risks
Data logging of electricity and water consumption will help to establish baseline limits for similar buildings in same climatic region.	Lessons learned are well documented and will help decision making in future projects
Improved institutional and individual controllability of services provides energy savings, comfort and environmental connectivity.	Better coordination, collaboration and communication for overall performance improvement during construction and operations.
	Improved project scheduling, tracking and on time completion
	Proper records of operations and maintenance manual and training will help to reduce operations guidance call backs.

Additionally, Turner (2012) performed a detailed cost-influence analysis of the commissioning process and concluded that the effect of the commissioning process decreases and cost impact increases with time. Figure 2.1 shows the cost-influence curve of the commissioning process. The commissioning process has the highest potential to impact a project, only if it is included during the pre-design phase or design phase of the project. Gultekin et al. (2013), confirms that the performance of the building largely depends on the design decisions.

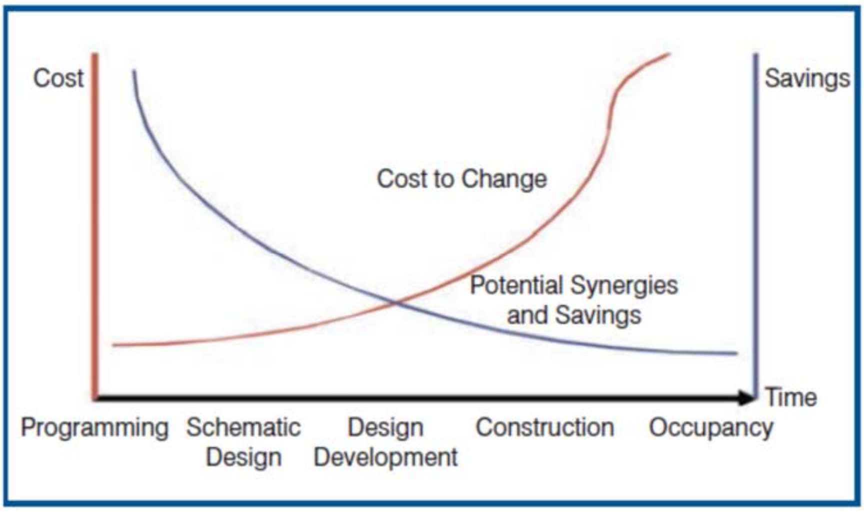

Figure 2.1: Cost Influence Curve of the Commissioning Process
(Turner 2012, p.58)

The benefits of the commissioning process are clearly reflected in cost savings, either directly through savings in utility bills or indirectly through improved reputation of the building (Smith, 2015). Commissioning is a quality focused process and it helps to avoid imperfections in the design, construction and operations of buildings. Thus, a cost savings calculation is difficult even after completion of the commissioning process (Kantola & Saari, 2014). Considering this fact, Altwies and Mcintosh (2011) proposed a cost-benefit methodology to estimate the savings from commissioning. This methodology estimates avoided costs, by theorising that no commissioning is performed on the building. Total avoided cost is estimated as the sum of money lost because of unresolved commissioning issues and the cost to resolve them. Equation 2.1 explains the same (Altwies & Mcintosh, 2011). Friedman et al. (2010) conducted cost benefit analysis for twelve different types of buildings and found that the median cost per square foot of commissioning of existing buildings is around $4 and the pay-back period is 3.2 years. Conversely, a widespread research by Mills (2011) on 643 buildings revealed that the median commissioning cost is less than $0.30 and the payback period is around 1.1 years. The big difference in the results of these two studies is basically because of the difference in the number of buildings analysed and the depth of the studies. Notably, Mills (2011) offers more reliable information and is widely accepted among researchers and commissioning professionals (Kantola & Saari, 2014). In a nutshell, Mills (2011) declares that, with commissioning, less carbon emission is economical than emitting more carbon.

$$\text{Total Avoidable Cost} = \text{Issue Resolution Cost} + \text{Issues Cost Effect} \quad (2.1)$$

2.2.4. Categories of Building Commissioning

Building commissioning has evolved through various stages of development and at present, there exist several trends in the industry. Although, basic concept is the same, trends differ in application classes. According to Baechler and Farley (2011), building commissioning is broadly categorised into two – new building commissioning and existing building commissioning. New building commissioning is considered as a rigorous process starting from the very beginning of the pre-design phase and extends to the early occupancy phase or even till the decommissioning of the building, ideally. This is often referred as comprehensive commissioning, since it provides an opportunity for the building to find cost effective solutions to design issues. Turner (2012) announces that the capability to make a difference decreases as the project progresses from the pre-design, to the design phase, to construction and ultimately to occupancy. New building commissioning can be further divided into design-bid-build (DBB) project commissioning and design-build (DB) project commissioning (Turner, 2012). In design-build projects, design process overlaps to the construction process. This requires phased design reviews. Unlike design-bid-build projects, some aspects of the design might not be finalised, by the time basic concepts are finalised and construction begins. Consequently, design-bid projects may be forced to follow phased reviews to stick to the project schedule (Turner, 2012).

Existing building commissioning is broadly divided as re-commissioning and retro-commissioning (Baechler & Farley, 2011). If commissioning is performed on an existing building, which is already commissioned during the construction phase, then it is known as re-commissioning. And commissioning of an existing building which has never been commissioned is known as retro-commissioning (ASHRAE, 2013a). Re-commissioning contracts are usually covered in the comprehensive commissioning process and are scheduled for the early occupancy phase, i.e., within the first two years of handover of the project. However, retro-commissioning is performed on buildings which experience severe operational issues and unexpected utility bills, as advised by GSFIC (GSFIC, 2010). Therefore, retro commissioning is not done during early occupancy, but during late occupancy, roughly at the end of five years or ten years of occupancy. A recent study conducted by Wang et al. (2013), pointed out that the retro-commissioning process goes far beyond the scope of an energy audit, where particular importance is given to the implementation of the recommendations and the verification of the same. Automatic commissioning or monitoring based commissioning is the latest development in the existing building commissioning industry (Wang et al., 2013). For automatic commissioning, trend data of the building are analysed to identify unnoticed issues in the building. This is as energy related issues are not easily identified by operators or end users (Smith, 2015). Schiendorfer and Zimmermann (2012) developed a unique tool for automatic continuous commissioning and fault detection. This tool compares the trend data against an energy simulation model, to pinpoint utilities savings potentials and to detect faults. This tool can be scheduled to perform analysis in pre-set intervals and the commissioning authority can even access results remotely from any location over the internet. Conversely, Shi (2011) states that the automatic commissioning tools cannot substitute hands-on field measurement commissioning, as sensor precision may become unreliable after a certain number of years of operations.

Ye and Rahman (2011), states that commissioning is primarily done for the building rating system certification. Another classification of the commissioning process is based on the requirements to meet the building rating systems (Turner, 2012). LEED and ESTIDAMA are considered as the most popular rating systems in this region and the commissioning requirements of these rating systems are studied in detail. Both LEED and ESTIDAMA differentiates commissioning as basic commissioning and enhanced commissioning. In LEED basic commissioning covers only the construction phase of the project. The enhanced commissioning starts from the pre-design phase and extends until the re-commissioning stage (USGBC, 2013). On the other hand, for ESTIDAMA, even basic commissioning starts from the pre-design phase and extends until the construction phase. Enhanced commissioning lasts until the re-commissioning stage (UPC, 2010a). However, both LEED and ESTIDAMA focuses on commissioning of energy related systems only.

Again, commissioning can be classified as technical commissioning and process commissioning based on the depth of the process (McFarlane, 2013). Process commissioning is more or less managing the commission process by reviewing the results of tests performed by someone else. On the contrary, technical commissioning includes hands-on tests on-site as well as management of the commissioning process. Technical commissioning is considered more effective and fruitful to meet the owner’s project requirements (Turner, 2012). Additionally, McFarlane (2013) states that process commissioning may turn out to be a dispute between stakeholders accusing each other for the responsibility of issue resolution.

2.2.5. Commissioning Service Methods

The Georgia State Financing and Investment Commission (GSFIC) provides in-depth advice on different commissioning service methods (GSFIC, 2010). The selection of commissioning service method is very important in a construction project. The first step for the selection of a commissioning service method is setting up the scope of the service. This depends on the complexity of the systems and probability of errors in the system. Simultaneously, Ágústsson and Jensen (2012), state that the budget of commissioning is an important factor in determining the scope of commissioning. Once the scope of the commissioning is set, an appropriate service method can be selected. However, the GSFIC recommends (GSFIC, 2010) to select the commissioning service method early in the pre-design stage; this will have a great impact on the benefits.

Research performed by Kantola and Saari (2014) recommends the selection of third party consultant directed commissioning for an unbiased performance. Third party consultant directed commissioning is the most common service method in the industry worldwide (GSFIC, 2010). Third party consultants will be financially and contractually independent to work and report only to the owner of the project (ASHRAE, 2013a). The GSFIC recommends that the third party commissioning authority should have good technical expertise in design, construction and operation of similar buildings (GSFIC, 2010). The third party commissioning team will include members specialized in various building services, and the team will be led by a qualified commissioning authority. As the commissioning team is independent, the aim of the team will not be biased. Furthermore, the various specializations of different team members will add value to the project (ASHRAE, 2013a). On the other hand, some specialists in this field believe, that this is an extra layer of complication and the task can be performed either by the designer or the engineer, who already has a good understanding of the project.

The designer directed building commissioning process is followed in some projects where a design entity will direct the commissioning process. A paper published by Enck (2010) highlights the requirement of a separate commissioning contract with the design firm, detailing additional tasks and deliverables. Design professionals will be familiar with all aspects of the design and construction, so it will be an advantage for them to coordinate and execute the commissioning process (GSFIC, 2010). This method offers, better communication and co-ordination between team members and enhanced reliability and availability of professional services. This offers a simple and straight forward solution for building commissioning requirements. However, this service method often fails to meet the owner's intent to the fullest, as often measures are taken to conceal design imperfections.

Similarly, engineer (supervision consultant) directed commissioning also offers a simple and straight forward solution for commissioning requirements. The commissioning contract will be between the owner and the construction supervising engineering company (GSFIC, 2010). Here the advantage is the well-defined authority during the construction phase to implement the commissioning activities (GSFIC, 2010). As explained in the previous section there will be conflicts of interest in this service method too. Moreover, the construction supervision company will be on-board only during the construction phase. This will limit the scope of commissioning to the construction phase. Commissioning during pre-design phase, design phase and occupancy phase will be out of scope and this will have a serious negative impact on meeting the owner's requirements.

The owner directed commissioning process is the process in which experienced professionals who work for the owner's company will be in charge of executing the building commissioning process (GSFIC, 2010). At the same time, the GSFIC highlights the fact that, owner directed commissioning can be utilized only in projects where the owner's team members have the qualifications, time and experience to undertake the commissioning process. In practice, commissioning is considered as a secondary task among the owner's employees. So time allocated for the process will be very limited compared to other aspects of the project, such as project management and commercial management. Thus, the team may experience difficulties in performing commissioning related duties (GSFIC, 2010). Above all, this method offers the best authority over other entities and coordination between phases of the project, as the commissioning team will be available in all phases of the project. The interest of the owner will be held in place in this service method.

2.2.6. Limitations of the Commissioning Process

A research conducted by Ye and Rahman (2011), highlights that the real reason behind performing commissioning in most construction projects is simply to earn building rating system credits. Considering this fact, Enck (2010) identified that commissioning should go well beyond the minimum requirements set by the rating systems to gain the maximum benefits of sustainable, healthy, high performance building. Taking this fact into account, Ágústsson and Jensen (2012), suggests that authorities having jurisdiction (AHJ) shall enforce the commissioning process in all new buildings, especially in public buildings. On the other hand, Mills (2011) clarifies that the main barrier to the commissioning process is the uncertainties about the benefits and pay-back period. In most cases, cost savings from commissioning are not recorded and the first cost of commissioning is established clearly. This makes the owners treat commissioning as an undesirable activity (Altwies & Mcintosh, 2011). At the same time, it is not easy to calculate the cost saving of commissioning, but avoided cost can be estimated. Ye and Rahman (2011) and Altwies and Mcintosh (2011) found that, most of the commissioning providers do not conduct this exercise and it is a barrier in establishing the cost benefits of commissioning. At the same time, Ye and Rahman (2011) explain the need to attract the attention of building owners about the energy, water and comfort effects of poorly commissioned or not yet commissioned buildings. This highlights the advantages of an unbiased commissioning process. Buildings commissioned by financially and contractually independent consultants provide the best solutions compared to other methods, as stated by Kantola and Saari (2014).

One of the most important functions of commissioning is to improve the collaboration between project team members (ASHRAE, 2013a). At the same time, proper documentation, communication and long-term interrelationships between team members will help to avoid conflicts and to deliver more reliable buildings in terms of maintenance, utility costs and comfort, as suggested by

Enck (2010) and Altwies and Mcintosh (2011). However, methodologies for improved collaboration are not yet established in the industry and this can be considered as another obstacle. An extensive study was done on different buildings by Lohne et al. (2015), and established that, many owners assume that they will never establish the building exactly as intended and they are mentally prepared to accept underperforming buildings. The benefits of commissioning should be made well-known to the stakeholders in order to overcome this misconception. Another obstacle is in following the commissioning schedule, as stated by Turner (2012), that the testing should be done at the equipment level, system level and integrated level. However, in most cases equipment start-up is considered as an acceptable criteria of commissioning, this attitude should be changed to obtain the maximum benefit of commission.

2.3 Key Performance Indicators

The performance of a building involves various aspects. Toor and Ogunlana (2010), argue that each stakeholder will have different perspectives on project performance. In this report, the focus will be on meeting the owner’s project requirements, as the owner is the most important stakeholder and the financer of the project. Moreover, the main objective of the commissioning team is to make sure that the owner’s project requirements are met in each phase of the development (ASHRAE, 2013a). As stated by Toor and Ogunlana (2010) and Langston (2013), traditionally, performance of a building was assessed based on time, budget and quality of deliverables (golden triangle). Additionally, a study conducted by Eriksson and Westerberg (2010) states that, key performance indicators can be broadly classified as short-term goals and long-term goals. Optimum budget and on-time project delivery are the short term goals of a project. On the other hand, commercial success, occupant comfort, environmental performance and functional performance of the building are the long-term goals. From the project commissioning perspective, commercial objectives are out of scope. The owner expects the commissioning authority to oversee and coordinate construction activities to deliver the project on time. It is the responsibility of the commissioning authority to make sure that the project sticks to the schedule (Turner, 2012). Although detailed tracking will be performed by other parties, the commissioning authority is expected to verify the achievement of milestones. This is not just limited to the testing and balancing of services, but also the purchase and delivery of major equipment, development of drawings and documents and so on. This is as a delay in any of these activities will result in overall delay in the project delivery process. The quality of a building depends on the performance of passive and active components of the building. It is the responsibility of the commissioning authority to verify the performance of building components though a series of tests (ASHRAE, 2013a). Additionally, this will serve the objectives of environmental performance, and occupant comfort.

As far as commissioning is considered as a process from the pre-design to the occupancy phase of a building, both asset rating (estimated performance of the building during the pre-occupancy stages) and operational ratings (measured performance of the building during the occupancy phase) are very important for building energy management (Goldstein & Eley, 2014). On the other hand, Gudnason et al. (2015) follows the fuel type breakdown method to determine the energy performance of buildings. In this method consumption of each type of fuel during operations is calculated to identify the performance. At the same time, Sisinni (2013) conducted an extensive research to find system wise performance indicators of buildings like HVAC system performance, lighting system performance, domestic hot water system performance and so on. Concurrently, Monno and Conte (2012) declare that operational performance reflects the real performance of a building, existing building commissioning helps to discover this.

Langston (2013) states that key performance indicators are set to measure the performance of the building, so it must be measurable and must not exceed ten items. Alwaer and Clements-Croome (2010) also believe that Key Performance Indicators (KPIs) must be measurable and the paper explains the desirable criteria of such KPIs. Conversely, Abd et al. (2013), concludes that 47 KPIs, including measurable and non-measurable KPIs, are essential to evaluate the performance of buildings. Based on this background information, KPIs can be classified into non-measurable and measurable items.

2.3.1 Non-Measurable KPIs

ASHRAE (2013a) identifies four service level KPIs as communication, collaboration, verification and documentation, which are non-measurable. Good communication helps in overall performance improvement including resolution of project issues. This has a significant commercial impact as stated by Baechler and Farley (2011). At the same time, a good communication strategy can reduce change orders, contractor call back and requests for information (RFI). Light, Bailey and Meetre (2015), state that communication and collaboration between various disciplines in the construction site are necessary for the construction stage indoor air quality management. This will eventually help to attain good air quality throughout the life of the building. At the same time, collaboration between different parties on site are needed to reduce conflicts, change orders and budget overruns. As per USGBC (2013), integrated project delivery requires collaboration among various project team members in all phases of the building project. At the same time, proper collaboration and communication helps to meet project time schedule (Eriksson & Westerberg, 2010). Verification of design documents, construction documents and on site verification of system performances help the building to meet the owner’s project requirements, as stated by McFarlane (2013). Verification helps to improve equipment life, to improve energy efficiency and to reduce risks. Enck (2010) declares that documentation is the key to develop a maintainable building. Proper and concise construction documents are needed for on time project delivery, best bids and to reduce change orders. At the same time, proper operations and maintenance documentation reduces contractor call backs and extends equipment life.

2.3.2 Measurable KPIs

Researchers like Monno and Conte (2012) and Vogt, Robinson and Dashja (2014) believes that the performance of a modern building does not merely depend on the financial aspects of time, budget and quality (golden triangle), but also on other sustainability aspects, such as environmental impact and social impact. Considering the climatic, cultural and social situation in Abu Dhabi, assessment of educational buildings needs to focus not only on time, budget or quality, but also on environmental and social aspects. Based on this information, the selected KPIs for this research are shown in Table 2.4. KPIs are classified into service level, environmental and economic items. The service level category includes both measurable and non-measurable KPIs. At the same time, KPIs in both environmental and economic categories are all measurable.

Table 2.4: Key Performance Indicators selected for this research

(ASHRAE, 2013a, pp. 3-10 and Vogt, Robinson & Dashja, 2014, pp. 63-66)

Environmental KPIs		Service Level KPIs		Economic KPIs	
KPI	**Units**	**KPI**	**Units**	**KPI**	**Units**
Electrical Energy Reduction	kWh	Time to take actions on reported defects	Minutes	Return on Investment (ROI)	Years
On site electrical energy production	kWh	Time to respond to end user feedback	Minutes	Socio-Economic Return	Ratio
Electrical Energy Peak Demand Reduction	kWh	Acceptable Indoor Air Quality	Litters/ Second	Reduction of First Cost	Currency
Cooling Savings	kWh	Acceptable Indoor Light Quality	Lux	Reduction of operating Cost	Currency
Hot Water Savings	m^3	Acceptable Indoor Thermal Quality	Degree Celsius		
On site hot water production from renewable energy.	m^3	Acceptable Indoor Humidity Level	Percentage		
Water re-use	m^3	Communication	Not Applicable		
Cold water saving	m^3	Collaboration	Not Applicable		
		Verification	Not Applicable		
		Documentation	Not Applicable		

Service Level KPI's

The end user's comfort and owner's satisfaction are the key players in the service level category. The user's comfort can be assessed by directly measuring the indoor environmental quality of the building, including thermal quality, light quality, humidity level and air quality (CO level, CO2 level and VOC level). Good indoor environmental quality can offer better productivity and a healthier atmosphere (USGBC, 2013). Thermal comfort and lighting comfort are very important, especially in a building where educational activities are taking place. At the same time, humidity level and air quality directly affects the physical and mental health of the inhabitants, particularly when the majority of the inhabitants are in their growing age (Light, Bailey & Meetre, 2015). The building operator's services are also included in this category, in order to assess the average time taken to respond to complaints, which is a direct indicator of effective building operations and operational training (Goldstein & Eley, 2014). Non-measurable KPIs in the service levell section are already explained. In short, service level KPIs can be used to assess the productivity levels and risk levels in buildings.

Environmental KPI's

Environmental KPIs are mainly based on the water and energy impacts of the building on the environment. Proper commissioning of a building will help to achieve these KPIs. Electrical energy generation in Abu Dhabi depends mainly on fossil fuel power plants. Reduced energy consumption and on-site renewable energy generation reduces greenhouse gas emissions, which in turn minimises global warming and local air pollution (Vogt, Robinson & Dashja, 2014). The size of a power plant depends on its peak demand. A reduction in peak load of a number of buildings served by the utility provider can reduce the plant size. On the other hand, the efficiency of the plant is at its maximum near full load condition. If the plant can run near full load for a maximum number of hours, then the running cost will be minimum. This will reduce the embodied carbon emission and operational emission of the plant (Goldstein & Eley, 2014). Due to the geographical characteristics of the region, space cooling consumes more than 40% of total energy use of a typical building in Abu Dhabi (UPC, 2010b). Savings on this will have a great impact on energy use.

At the same time, geographic characteristics demand intense water savings in Abu Dhabi. The municipality depends mainly on sea water desalination plants for the supply of domestic water. Sea water processing is an energy intensive process and recent studies show that it will have an impact on marine life. This demonstrates the importance of water savings, through reduction and reuse. Concurrently, climatic conditions favour on-site hot water generation, from solar energy. The technology is simple and cost effective and this can minimise electrical energy use for domestic water heating.

Economic KPI's

The economic KPIs of a building depend on capital investment and running cost. Research conducted by Gultekin et al. (2013) on the performance of green buildings establishes that a properly commissioned green building's operational costs are much lower than traditional buildings and it provides a healthier environment. A number of technical and non-technical factors affect economic KPIs. Buildings cannot survive if the return on investment is not reasonable. At the same time, reduced first cost and reduced operating cost are key factors in achieving the return on investment. Commissioning helps to minimise the costs by optimizing other energy saving technologies used in the building (Mills, 2011). Optimum sizing, improved life period, efficiency and proper operation of active and passive components of the building offers the best return on investments (Chan & Chan, 2012).

Occupant comfort levels in a building make it attractive to the users. At the same time, comfort conditions affect the physical and mental health of occupants. This implies that, the socio-economic return has a great monetary impact on extra-financial value of buildings, which cannot be assessed directly (USGBC, 2013). This extra financial value is related to the productivity of occupants and the number of sick days taken. Mills (2011) states that comfort conditions in a properly commissioned building helps to minimise sick building syndrome and improves productivity.

2.4 Summary

This literature review focused primarily on two factors, the building commissioning process and key performance indicators of buildings. The literature review helped to understand various aspects of building commissioning and its evolution as a quality orientated process. Different commissioning service methods are studied in detail. The advantages, disadvantages, limitations and performance outcome of each service method is assessed in detail. The cost of different commissioning service methods varies widely and depends on the local market conditions (GSFIC, 2010). The literature review helped to develop a thorough idea about the required skills and accomplishments of a successful commissioning team. The roles and responsibilities of the commissioning team in various phases of building development are realised through the literature review. Expected outcome of the commissioning process in each phase of the process is clearly mentioned in ASHRAE's guideline (ASHRAE, 2013a). The performance of buildings are measured against pre-set bench marks. In order to develop bench marks, KPIs of the building are developed. Building performances are divided into economic, environmental and service levels. The KPIs of each category is explained in detail. At the same time, the commissioning process has a crucial role in meeting the KPIs of a building.

Chapter – 3: Methodology

3.1 Introduction

Research on building commissioning in Abu Dhabi faces many barriers, as the market is still in the developing stage. On the other hand, this is a well-developed research stream in mature construction markets (Ágústsson & Jensen, 2012). In this section, based on the literature review, various different types of research methodologies applicable for this research will be discussed in detail and the best methodology will be selected. Furthermore, advantages, disadvantages and limitations of the research methodologies are described in detail. Justification of the selected research methodology is also provided. An in depth, step-by step research approach is explained to give a clear idea about the processes and procedures adopted in this research.

3.2 Applicable Research Methodologies

A number of research studies were reviewed and it was found that researchers followed different methodologies. Details of each methodology will be discussed in this section. Most of the papers used quantitative building performance analysis through empirical study of building logs. This methodology is cost effective and saves time (Mills, 2011). On the other hand, quantitative performance analysis through field measurement is the second most preferred methodology among the papers reviewed. Next comes qualitative analysis of expert opinions through Delphi surveys. This methodology also has a positive impact on the cost and time of the research, as it can collect a lot of information in a short time period (Chan & Chan, 2012). On the other hand, other research methodologies such as energy simulation and literature review were also adopted by various research papers. The work by Schiendorfer and Zimmermann (2012) is an example that adopted the simulation methodology.

3.2.1 Quantitative Analysis of Building Logs

In general, quantitative analysis is the research methodology used by most of the scholarly articles referred to for this research. Papers published by Smith (2015), Altwies and Mcintosh (2011), and Gudnason et al. (2015) are examples of the research studies that were bound to the empirical study of logs. The fundamental idea behind this methodology is to collect building performance data relevant for assessing key performance indicators and to process data quantitatively using statistical techniques (Mills, 2011). Based on the aim of the research, different researchers examined different data sets. Ágústsson and Jensen (2012) analysed the energy and water trend logs of the building to identify differences between commissioned buildings and non-commissioned buildings. Data were collected from energy and water sub-meters. Building management systems (BMS) can produce logs easily. However, as stated by Kantola and Saari (2014), BMS is not used to its maximum potential in most of the buildings projects assessed.

On the other hand, Mills (2011) collected operational data for 643 buildings to produce a database and quantitatively analysed the cost and benefits of commissioning. This paper analysed on-site renewable energy generation logs, equipment energy performance logs, indoor air quality logs, lux level logs and space temperature logs to come up with the conclusion that emitting less carbon through commissioning is economical than emitting more carbon. Kantola and Saari (2014) performed empirical analysis of log data of both commissioned and non-commissioned buildings and concluded that the commissioning process helps to avoid costly mistakes in the construction process, during the early phases and so it is difficult to calculate cost savings. Conversely, Altwies and Mcintosh (2011) analysed logs and estimated the cost avoided as a result of commissioning. This is a direct indicator of monetary benefit of the commissioning process. Based on the quantitative analysis of data on change orders, request for information, scheduling problems and conflicts, the collaboration of team members is treated as the most important benefit of commissioning (Altwies & Mcintosh, 2011). At the same time, details of change orders, project cost, project duration and comfort conditions are collected and analysed in Gultekin et al. (2013), to establish the outcome of the commissioning process. Going one step further, Smith (2015) and Wang et al. (2013) established that current technologies are capable of collecting trend data remotely and analysing this data automatically to commission the building automatically – this is known as monitoring based automatic commissioning.

Trend log analysis can be considered as one of the most cost effective research methodologies, as stated by Mills (2011). Contradictorily, this has the highest capital cost, because installation and maintenance of permanent sub-meters and sensors in each line in the service circuit is quite expensive. So this research methodology is limited to buildings that already employed building management systems and utility sub-metering. However, most modern complex buildings are furnished with this. At the same time, analysis of trend logs over a short period of time does not make sense, as a lot of external factors like climate, time of day and occupancy schedule, affect the log data (Smith, 2015). So, analysis of trend data for at least a full seasonal cycle of the year is required to perform a reputable research (Friedman et al., 2010). If the researcher is able to obtain the historic trend data, then research can be performed straightway. Another limitation of this methodology is the lower accuracy and reliability of sensors and other instruments as explained by Shi (2011). Nevertheless, these limitations are bypassed through its advantage of treating the building as an integrated system instead of individual systems. This is as the effect of other systems and ambient climatic conditions on the system under study are catered for automatically and no adjustments are needed to consider external effects.

3.2.2 Quantitative Analysis of Field Measurements

Shi (2011), Toor and Ogunlana (2010) and Enck (2010) believe in quantitative analysis of field measurements, in order to achieve the best results. In this methodology, on-site tests will be done on each equipment, system and inter-system. Here, equipment level measurements are done as a first step and then the analysis advances to the system level and inter-system level, to understand the characteristics (Turner, 2012). During the field measurement process, parameters are recorded and processed to discover the performances (Shi, 2011). On the other hand, the effects of other systems on the system under study can also be studied, but need further steps. Recorded data will be processed statistically to find the performance of the building based on the key performance indicators. Subsequently, the optimum commissioning service method can be recommended. Monno and Conte (2012) suggest that field measurement during the operational phase is the best methodology to monitor the system wise performance, as this represents the real characteristics of the building. No other process, like simulation or estimation, can produce the same results. Simultaneously, McFarlane (2013) points out that filed measurement is straight forward and can be easily demonstrated to anybody, but good technical skills are required to perform measurements. In short, field measurement can be used in this research too, if the necessary resources are available.

The field measurement methodology is considered as one of the most accurate methodologies as the instruments used for the measurement are highly accurate and properly calibrated. Concurrently, the reliability of the methodology is ranked high among other methodologies, as field measurement results will not be unilateral as in the case of other methodologies. At the same time, test results can be directly read from the test instrument itself. Additionally, field observation methodology is considered as one of the most expensive methods in research. The cost of test equipment, skilled professionals and time resource contributes to this high cost (Kantola & Saari, 2014). Measurement reflects instantaneous value and adjustments are needed to satisfy seasonal effects. Similarly, system effect will not be reflected in most tests, so the result requires further adjustments. This methodology requires a lot of time, specialised instruments, and skilled technicians to perform the task. Measured values must be tabulated and processed manually to find the results. This too demands a lot of resources. Another disadvantage is that the field measurement causes minor disturbances in building services. So, it is limited to buildings where occupants can tolerate outages. In other words, this is impractical in critical service buildings and is limited to unoccupied periods in non-critical buildings (Toor & Ogunlana, 2010). Equally, occupational safety during field measurement is a major concern as described by Lohne et al. (2015). Risks during measurement must be identified in advance and adequate actions must be taken to handle hazards. At the same time, permissions like working at height, fire, chemical permission and barricading is required in certain cases. Above all, Enck (2010) advises that proper coordination between various services and professionals are required to undertake field measurements, as failure to obtain access or permissions will end up in aborting the measurement process.

3.2.3 Qualitative Analysis of Expert Opinions (Delphi Study)

Qualitative Analysis of Expert Opinions is a research methodology followed by some of the papers referred to for this research, like Lohne et al. (2015), Chan and Chan (2012) and Abd et al. (2013). In this methodology, the research view of experts, within the building construction industry will be analysed in a systematic and interactive way, as described by Chan and Chan (2012). A multi-staged and detailed interview will be conducted with selected experts in the field. The interview particularly spans over two or three stages. Information collected in the first sitting will be processed and summarised by the researcher and will be forwarded to the interviewee for next stages. Experts will be allowed to review the results and to further shape their previous responses. This process will be repeated to unify the results and to eliminate any errors in the process (Chan & Chan, 2012). The Delphi approach is quite different from a regular survey. Generally, Delphi studies are conducted on a small number experts of ten to twenty interviewees, as the quantity of data collected is very large and the availability of experts will be very limited in most cases (Alwaer & Clements-Croome, 2010). At the same time, Delphi interview questions are descriptive in seeking to find the opinions of the interviewee and to explain the reasons behind their opinions. Results are processed qualitatively not quantitatively. Delphi interviews are very effective, especially in studying the non-energy benefits of commissioning services. This is because, comfort conditions depend on a number of factors that cannot be measured (Friedman et al., 2010). An expert interview will light the path to compare the non-energy performance indicators of buildings against the pre-set KPIs, wherein an expert’s views on different commissioning service methods will be discussed in detail. Their opinions on improvement opportunities will also be recorded. Descriptive replies to interview questions, with supporting project details will be assessed qualitatively. In this methodology, an expert’s opinion is considered as valid and a reliable source upon verifying the credentials.

A research paper published by Chan and Chan (2012) reveals that the most important advantage of the Delphi system is the cost effectiveness. Compared to other methodologies like field measurement and trend log analysis, Delphi interviews do not cost much. Indeed, the capacity to collect a large quantity of information in a comparatively short time is the most significant characteristic of this methodology. Additionally, this can be considered as an exchange of information or learning for both the interviewer and interviewee, as it may sometimes help the interviewee to further research the topic while on the job. Contrariwise, the interviewer too learns a lot from the interview. So, this can be considered as a mutually beneficial learning exercise. Unlike regular objective type surveys, a Delphi study is considered as a highly accurate methodology, if performed systematically. On the other hand, cases are reported that the response of the participants were biased where the identities of participants were disclosed. This is mainly due to the pressure from peers for conformity or due to the psychological motives of the participants to blindly follow the majority. Yet, the idea of this methodology is to exploit the available resources to the maximum extent. Furthermore, the available resources are the experience of the professionals gained may be through hard work over several decades. Therefore, as a return on their investment, most researchers offer the results of their work for personal and professional use of the participants (Kantola & Saari, 2014).

3.2.4 Simulation

Schiendorfer and Zimmermann (2012), Friedman et al. (2010) and Wang et al. (2013) followed a simulation as one of the methodologies to progress their research studies. This methodology is considered as a valid research tool, among researchers. With this methodology, the calibrated simulation model of the building estimates the parameters of the building and compares it with real-time trend logs in order to detect faults in the system. The calibrated simulation model is nothing but a simulation model that is calibrated to account for the real performance of the building (Raftery, Keane & Costa, 2009). Although a simulation model is generally developed during the design phase of the project, and is based on a certain set of assumptions, factors such as occupancy schedule or climatic conditions might change, in the real occupancy phase. Thus, the model will be updated to accommodate genuine as-built information related to the project. In this methodology, during comparison, if parameters deviate significantly from the estimated value, this can be considered an indicator of sensor error. On the other hand, an unexpected number of peak values within a certain time period acts as an indicator of a control philosophy error and subsequent cycling of the equipment according to Friedman et al. (2010). This methodology offers better controllability and workability on the parameters. This is a cost effective research methodology, if the required skills are available.

On the other hand, the capital cost associated with this methodology is very high; to purchase and install sensors, sub-meters and the control system is very expensive. Additionally, the accuracy and reliability of simulation methodology is still under question. The selection of the climate data file and software validation are very crucial and vulnerable to errors. Therefore, most of the papers, except for Schiendorfer and Zimmermann (2012), used additional research steps to support the findings of this methodology. The time required is very limited for this methodology, as the results are automatically generated by the system. However, the overall time required is very large for a respectable analysis, as the building should be monitored for at least a year, to cater for all external effects, including seasonal effects (Friedman et al., 2010). Notably, the advantage of simulation methodology is that, it can be executed without any interruptions to the day to day business needs of the facility (Schiendorfer & Zimmermann, 2012). Upon meeting some pre-requisites, this can even be done remotely over the internet from any geographical location. As such, a simulation can be employed even in critical buildings where some other methodologies cannot be employed. While on the contrary, the cost related to hiring a skilled modeller is the most important hindrance of this methodology. Furthermore, most modern building projects employ simulation modelling during the pre-construction and construction stages, as part of building rating system requirements or regulatory requirements. For this research, buildings under research can be modelled and differences in performance can be easily discovered, by comparing against the real-time measured values or trend logs. This will help to pin-point the optimum commissioning service method.

3.2.5 Literature Review

Friedman et al. (2010) declares that a literature review is considered as one of the most reliable methodologies to develop any scholarly article. This methodology helps the researcher to find data or information required for the research, in relatively easy steps and reduced time. Literature will be studied deeply and key arguments, along with the main topics and methodologies employed, are systematically tabulated to review them further based on the aim of the research. Then, study contents are compared and analysed to find the most relevant information and data. This is not limited to just a review of journals, but also to various standards, guidelines and regulations (Ágústsson & Jensen, 2012). Furthermore, it helps researcher to keep up to date on the research topic as stated by Lohne et al. (2015). All research papers reviewed for this research used a literature review as one of their methodologies. In general, it is believed that research studies are not complete without a proper literature review. At the same time, a proper literature review will help to refine a broad research topic into a more focused research question. Literature reviews often help to evaluate research objectives. In order to achieve this, the researcher should make sure that the sources are reliable and independent. Randolph (2009) warns that extreme care should be taken to avoid biased and outdated results. Most of the reputable academic papers published are peer reviewed to maintain maximum reliability. The time required for a good literature review is enormous, as the researcher has to find relevant papers, sort them and study them systematically to get the required data or information. Thus, the task is tedious, but the results are fruitful, if performed systematically.

3.3 Selected Methodology for the Research

Various different research methodologies have been discussed in previous sections. Quantitative performance analysis of logs and field measurements, supported by qualitative analysis of expert opinions can be considered as the best methodology for this research. This opinion is based on a detailed study of various research methodologies considering the advantages, disadvantages and limitations of each methodology. A simulation has a lot of limitations in terms of software validity, professional skills and climate data. At the same time, other methodologies yield better results than a simulation. Field measurement is time consuming and costly, and trend logs are not completely reliable. Considering these facts, trend analysis will be done during Phase I of the research to pinpoint issues that require further investigations and field measurements will be done as a further step. Following that, a quantitative analysis of expert opinions (Delphi study) will be conducted in Phase II of the research.

During Phase 1 of the research, a quantitative performance analysis of buildings will be done on water and electricity consumption trend logs, temperature, pressure and humidity logs, contractor call back logs, change order logs, project duration, project cost, and utility bills. As stated by Kantola and Saari (2014), heating refrigeration and air conditioning systems are considered as the most energy intensive systems among all types of buildings. Especially, in the case of school buildings, air conditioning systems consume a lot of energy. A recent study on the continuous commissioning process by Mills (2011), shows that about 65% of the energy lost in buildings is due to improper balancing and control sequence errors. Trend data analysis helped to pinpoint the systems and equipment that perform the worst. Field measurement of identified systems and equipment was performed to investigate further and to find the hidden performance deficiencies in buildings. The buildings under consideration followed different commissioning service methods. Quantitative analysis of the performance data of these buildings will help to prove whether the owner's project requirements are met during the operations phase. This in turn will help to come up with a cost effective commissioning service method.

The research will then progress to the qualitative analysis of expert opinions (Delphi Study) – Phase II of this research. The literature review and Phase I of the research will help to frame the Delphi study questions. A number of experts in the construction industry will be selected for the Delphi study. The Delphi study will be performed as a detailed, three-stage interview. The outcome of each stage of the interview will be qualitatively processed and the results will be distributed among the interviewees. Again, interviewees will be requested to review and update their answers in previous stages (Chan & Chan, 2012). This helps to perform a reliable qualitative analysis. The interview will focus more on the cost effectiveness of the commissioning service methods, than the advantages-disadvantages analysis of different commissioning service methods. Experts will be encouraged to provide descriptive responses explaining the cost and benefits of various commissioning service methods, supported with real-life project experiences. This methodology will help to reveal hidden knowledge of the interviewees about particular problems in commissioning.

Third phase (Phase III) of this research is to process all information gathered through quantitative analysis and qualitative analysis to select the best commissioning service method suitable for the local market of Abu Dhabi, especially for the commissioning of educational buildings. Furthermore, in the next phase (Phase IV) of this research, the selected service method will be implemented in one building construction project in Abu Dhabi. Results will be further studied through quantitative analysis of building data. Then, the final version of the results describing the best commissioning service method or combination of methods, will be published. In short, the findings of this research will be applied in a project and will be verified and modified to best fit the needs of the construction industry in the emirate of Abu Dhabi. This is the fifth and final phase (Phase V) of the research.

Chapter – 4: Results and Findings

4.1. Introduction

Building commissioning is analysed in this research through qualitative and quantitative research methodologies. This research is classified broadly into five phases as explained in Table 1.1 in the introduction section. In Phase I trend data log and field measurement logs of four school buildings in Abu Dhabi were analysed. A Delphi study comprises Phase II of the research, where quantitative analysis of various commissioning service methods is performed. Trend log analysis, supported with field measurements helped to evaluate the overall energy performance of buildings. On the other hand, a qualitative Delphi study helped to evaluate the non-measureable performance of buildings. During Phase III, based on the results of the previous phases of the research, the best commissioning service method is selected. This selected service method was implemented on an educational building project, in Phase IV of this research. Furthermore, quantitative performance analysis of that building is done based on trend logs, supported with field measurements. Phase V of the research is to refine the selected commissioning service method to incorporate the lessons learned in Phase IV.

4.2. Phase I: Quantitative Performance Analysis

In this phase, quantitative analysis of four school buildings is conducted based on both trend logs and field measurements. These buildings varied widely in commissioning service methods, but functions, floor area, geographic location and systems are similar. These buildings represent different commissioning service methods, including third party directed commissioning, designer directed commissioning, owner directed commissioning and engineer directed commissioning. All these buildings are completed and recently handed over. Abu Dhabi's building rating system (the Pearl Building Rating System) allows projects to follow any of the established commissioning service method as explained in the background and motivation section. The buildings under study are confidential, and the identity of the buildings cannot be disclosed as per the non-disclosure agreement.

Quantitative analysis focuses mainly on the energy benefits of the commissioning process, which is explained in Table 2.3. The performance of each building is compared against these KPIs. Trend logs of full seasonal cycles were analysed to identify behaviours during various seasons. On the other hand, field measurements were taken to determine the performance of equipment. Based on the site conditions, field measurements were scheduled after working hours of the institutions. Most of the issues were related to the HVAC system of buildings and next comes electrical lighting. Implementation of solutions had limited cost implications, as most of them were to re-calibrate, to reset the control philosophy or to reset parameter set points.

4.2.1. Building – 1: Al-Bateen School Building, Abu Dhabi

Overview

This is a public school building situated in the Al-Bateen area, Abu Dhabi. This school was fully commissioned and handed over in August 2013. Thumbnail layouts of building-1 are provided in figure 4.1 and figure 4.2. The commissioning process was directed by the in-house supervising engineers. All electromechanical systems in the building including HVAC, BMS, Lighting Control, Swimming Pool, Vertical Transportation, Fire Alarm, Fire Fighting, closed control television and Audio-visual system were commissioned. The commissioning process was limited to the construction phase only, as the design phase and occupancy phase commissioning were out of scope. Table-4.1 provides detail about this building.

Table 4.1: Building – 1 Details

(Estimated by the author No external reference available).

Location	Al-Bateen, Abu Dhabi
Gross Building Area (m2)	23,665 square meters (254,728 square feet)
Number of Storey	Two Storey
Construction Period	June 2012 to June 2013
Commissioning Service Method	Engineer Directed

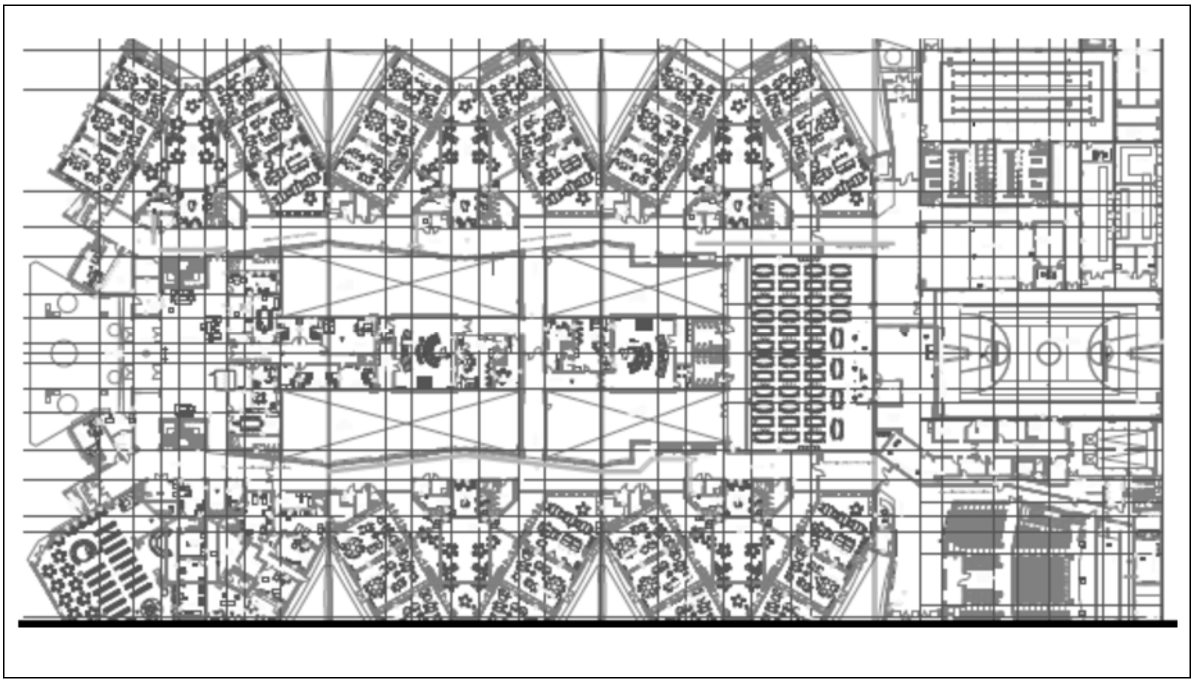

Figure 4.1: Ground Floor Plan Thumbnail of Building-1

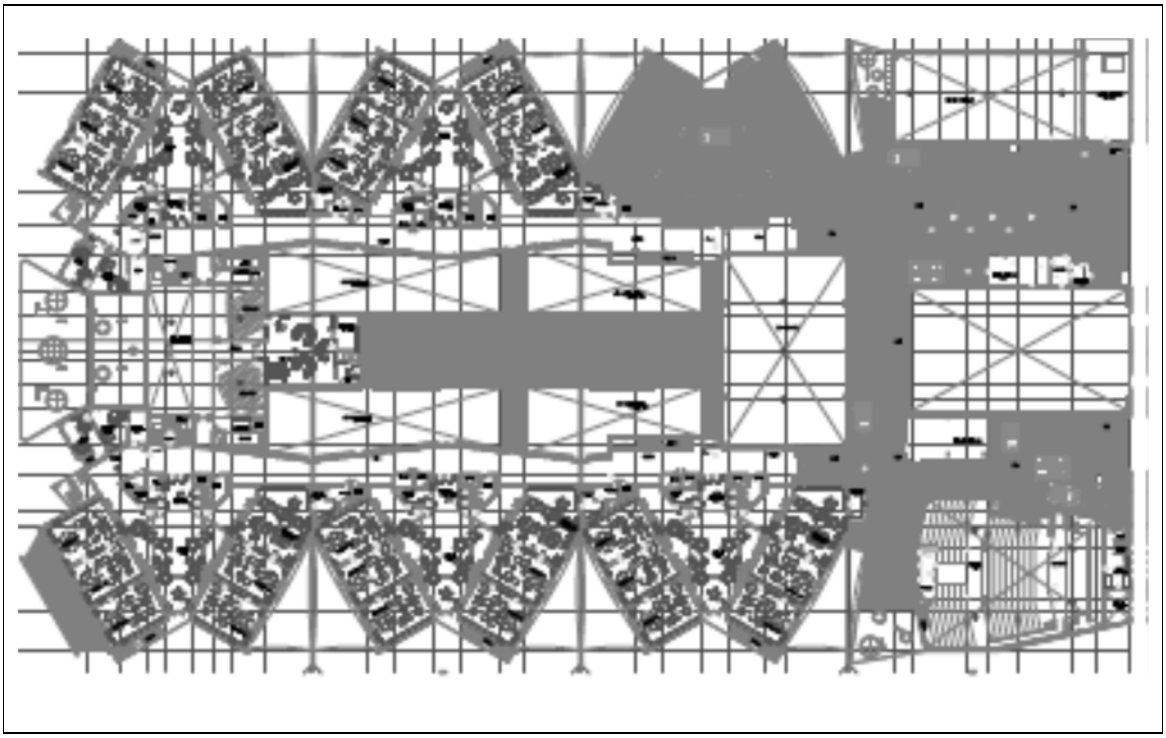

Figure 4.2: First Floor Plan Thumbnail of Building-1

Quantitative Analysis

The sub-meter log, zone temperature log, room pressure log, hygrometer log, and service log of this building were analysed. The most important findings revealed during the quantitative performance analysis of this building are explained in this section. The air handling and distribution system is the system which experienced the worst performance, followed by the lighting control system. As far as an educational building in Abu Dhabi is concerned, the performance of these two systems is vital for both energy and non-energy performance of such buildings. At the same time, the performance of the domestic water supply system and building envelope were also not satisfactory, based on NEBB guidelines (NEBB, 2013). Energy meter log analysis disclosed that the air handling units and chillers consumed a lot more energy than desired. An annual energy consumption graph is provided in figure 4.3. On the other hand, cooling load during winter was almost the same as that of the summer. As a further step, traversing air flow at the main ducts was measured in the field test. This showed that the air flow is undesirably very high even if cooling demand is low. A possible reason for this is the control sequence error, as stated by Smith (2015). Investigations revealed that simultaneous cooling and heating, due to a control sequence error was the reason behind this unusual behaviour and the oversized terminal heating units. On the other hand, the room temperature log showed that, some zones were very hot while the temperature in some other zones served by the same equipment were within acceptable limits. The reason behind this is the imbalanced supply of air and the location of the thermostats (Friedman et al., 2010). Record drawings showed that volume control dampers were not installed in the branches. So balancing was not performed and air was dumped to the zones near the fan, while other zones were not supplied properly.

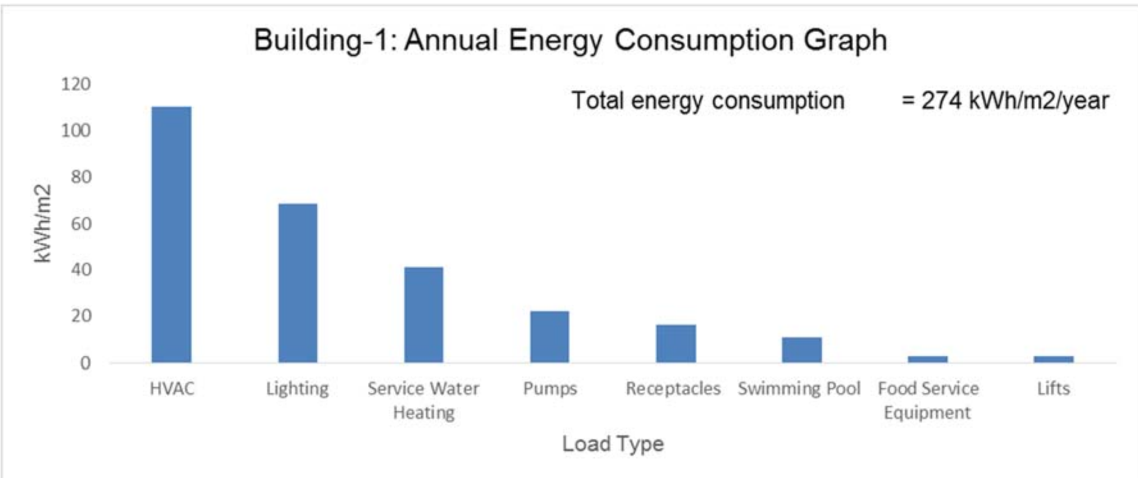

Figure 4.3: Building-1 Annual Energy Consumption Graph

Analysis of the hygrometer log illustrated the presence of high humidity in the conditioned space, especially during afterhours and holidays. High humidity boosted the growth of mould on partition walls and HVAC ducts, resulting in reduced air quality. A recent article published by Light, Bailey and Meetre (2015), states that unconditioned air will enter the building if the outdoor air dampers are open, while the machine is in standby mode. Resetting the control sequence of the outdoor air damper to close automatically while equipment is in standby mode or shut down will minimize mould growth. Subsequently, indoor air quality will be improved. Minor leaks in the domestic cold water system branches were detected, which also boosted mould growth. In addition to mould growth, this increased the water and energy wastage of the building. Water leak issues were reported by the end users, but the facility management team did not respond to this issue, as evidenced in the building service log. Similarly, hot water fixture flow rates were very high, and ended up in wastage of water and fuel required for heating.

A lighting control system was employed in this building, but trend logs show limited reduction in lighting energy. Further investigation showed that most of the external lamps were running, even if there was enough sunlight, since variation in sun-rise time and sun-set time were not taken into account. With the help of an astronomical time switch integrated with photo-sensors, running time of external lights can be optimized for better energy savings (Taleb & Mannsour, 2012). Indoor light quality was very bad in this building. Lux levels in selected classrooms were measured and found to be unacceptable, based on CIBSE code-L (Raynham, Boyce & Fitzpatrick, 2012). Details of lux level test are provided in Table 4.2. Lux level meters were used to directly read lux levels falling on the worktop level in each classroom. Calibrated photo sensors of the instrument can read lux levels and the instrument can display readings directly. Average lux levels in each classroom were calculated based on lux levels measured at regular grid points. Maximum distance between each grid point was obtained using equation 4.1.

Table 4.2: Interior Lux Level Measurements of Building-1

Room Tag	Measured Lux Levels
Classroom-1	220
Classroom-2	280
Classroom-3	225
Classroom-4	260
Classroom-5	245
Classroom-6	220
Classroom-7	270
Classroom-8	225
Classroom-9	255
Classroom-10	200
Classroom-11	285
Classroom-12	215

Equation 4.1: Lux Level Grid Points
(Raynham, Boyce & Fitzpatrick, 2012)

Maximum distance between grid points, $p = 0.2 \times 5^{\log d}$

d – Length of the longer dimension of the area being measured.

Key Performance Assessment

The performance of building-1 is assessed against KPIs. As stated in the literature review section, KPIs are classified as environmental, economic and service level. Table 4.3 shows the performance of this building against key indicators. This building failed to achieve any credits in environmental KPI's. Electrical energy use was very high in this building due to control sequence errors. There was no provision to generate energy on site, even though the setting of the building is conducive to on-site energy production. Cooling load was very high in this building due to infiltration and imbalanced supply of air as described in the previous section. Wastage of hot water and cold water was found in the domestic water supply systems, resulting in high water demand. On the other hand, return on investment (commissioning) was very poor as the commissioning process directed by the engineer could not meet the owner's project requirement. Furthermore, the operating cost was very high, due to wastage of utilities. However, the first investment was significantly lower as the contract for commissioning process was covered in the supervision contract between the owner and the engineer. Mould growth affected the quality of indoor air and reduced lux levels, affected the overall indoor environmental quality, which are major performance indicators in the service level section. The facility manager could not attend service requests in this building on time, which ended up in losing performance indicators in the service level section.

Table 4.3: Building-1 Key Performance Indicators

Building-1					
Environmental KPIs		**Service Level KPIs**		**Economic KPIs**	
KPI	**Remarks**	**KPI**	**Remarks**	**KPI**	**Remarks**
Electrical Energy Reduction	Not Achieved	Time to take actions on reported defects	Not Achieved	Return on Investment (ROI)	Achieved
On site electrical energy production	Not Achieved	Time to respond to end user feedback	Not Achieved	Socio-Economic Return	Not Achieved
Electrical Energy Peak Demand Reduction	Not Achieved	Acceptable Indoor Air Quality	Not Achieved	Reduction of First Cost	Achieved
Cooling Savings	Not Achieved	Acceptable Indoor Light Quality	Not Achieved	Reduction of operating Cost	Not Achieved
Hot Water Savings	Not Achieved	Acceptable Indoor Thermal Quality	Not Achieved		
On site hot water production from renewable energy.	Not Achieved	Acceptable Indoor Humidity Level	Not Achieved		
Water re-use	Not Achieved				
Cold water saving	Not Achieved				

4.2.2. Building – 2: Al Foah Kindergarten Building

Overview

This is a kindergarten building situated in the Al-Foah area in Al-Ain, Abu Dhabi. Figure-4.4 shows the thumbnail of the building plan. This building is commissioned by professionals in the building owner's organization. Energy related systems like HVAC, BMS, lighting control and building envelopes are commissioned. Comprehensive commissioning in the pre-design, design and occupancy phases were carried-out. Details of Al-Foah kindergarten is provided in Table-4.4.

Table-4.4: Building – 2 Details
(Estimated by the author, no external reference available).

Location	Al Foah, Al Ain
Building Type	School
Gross Building Area (m2)	4,652 meter square (50,074 square feet)
Number of Storey	Single Storey
Completion Date	September 2013
Commissioning Service Method	Owner Directed

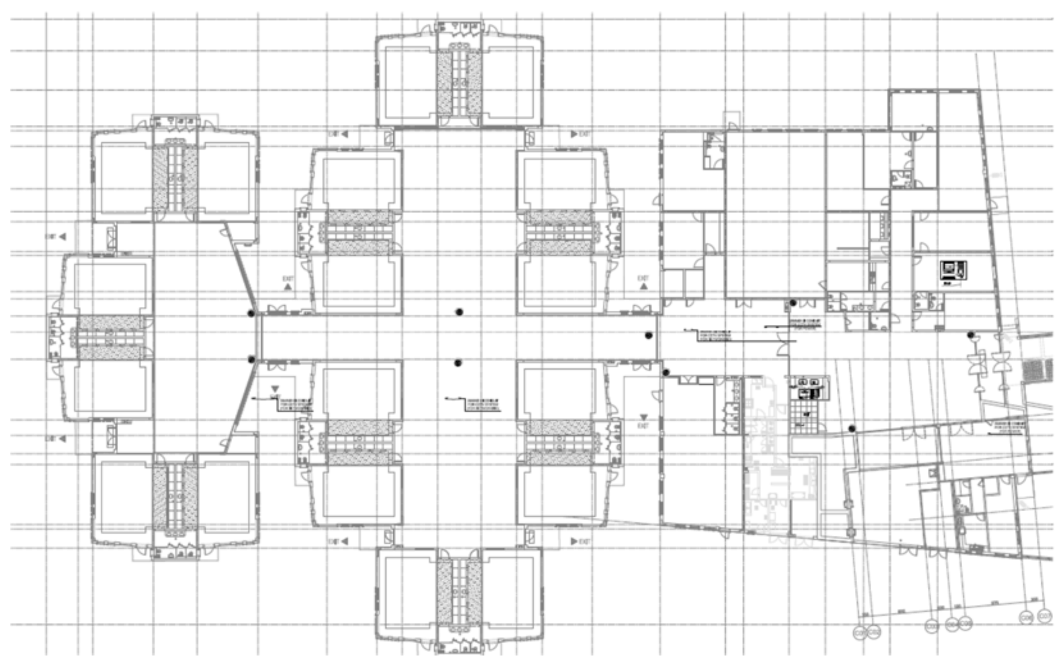

Figure 4.4: Ground Floor Plan Thumbnail of Building-2

Quantitative Analysis
The centralised air conditioning system of this building employs three air handling units (AHUs) and variable air volume terminal units. Indoor air quality (IAQ) at different points, at various time intervals were measured to assess IAQ conditions of the building. Handheld IAQ measuring instrument, capable to measure levels of volatile organic compound (VOC), carbon monoxide (CO), carbon dioxide (CO_2) and humidity was used. In this building, indoor air quality was noticeably very bad, as the AHU inlets were located very close to the exhaust and resulted in air shortcuts. ASHRAE (2016) states that a minimum of a five-meter distance must be maintained between building air intake and exhaust louvers. Due to air shortcuts, the building operator purposefully closed the outdoor air intake damper of some AHUs to avoid air shortcuts. This further worsened the case as outdoor air supply was stopped. At this point, the system operates as a recirculating system. Furthermore, indoor air quality was reduced due to flying duct liners in the conditioned space.

Another major issue was the limitation to access equipment for maintenance. Scheduled maintenance of HVAC filters is a must for good indoor air quality. In this building, filters were clogged up with debris, as the maintenance access was very limited. On the other hand, sub-meter log of fans showed that the exhaust fan was working at full capacity throughout the day. Further investigation of the service log revealed that the static pressure sensor was not calibrated even after the calibration expiry date. The pressure difference between the interior space and exterior of the building was measured using a calibrated differential pressure meter. There was a considerable difference between the measured readings and readings of installed sensors. This indicates that the sensors are out of calibration. These design, construction and operation errors led to another serious issue – negative pressure in the building. Field measurement of building differential pressure measured at various intervals showed that the building is subject to negative pressure. Air infiltration due to negative building pressure introduced unconditioned air to the building through openings, cracks and gaps in the envelope (NEBB, 2013). Consequently, humidity levels in the building were very high, as evidenced from the hygrometer log of the building. High humidity levels nourished the growth of mould in buildings (Light, Bailey & Meetre, 2015) as in the case of this building and air quality was reduced further. Eventually, infiltration introduced unconditioned air to the building and cooling load increased due to this (ASHRAE, 2013b). Increase in cooling load caused high energy use in the building.

Oversized HVAC machines including AHUs and chillers were another reason for high energy use. The trend log shows that, most of the time these pieces of equipment were running at less than 50% of full load capacity. Two Air handling units were rated 40,000 cfm, which is considerably oversized for the requirement and this reduced the redundancy of the system. A system designed for 50% less load would have met the building HVAC requirements. Replacing these air handling units will be a herculean task. The interior lighting system of this building experienced a lot of drawbacks, as personal controlling of lighting is not possible in classrooms. Controlling was limited to institutional control from the central control room. Each person is different and controllability of lighting is a critical criterion for occupant wellbeing. Control sequence errors of automatic blinds were found to be a significant nuisance during the operational hours of the school, as blinds moved up and down every now and then, based on the signal from the photo-sensor. Ideally, blind control should be integrated to an astronomical timer-photocell combination to avoid unwanted operations (Shi, 2011). Improper operation of blinds even resulted in natural light glare in the classroom, which is considered a serious indoor environmental quality issue, as stated by Taleb and Mannsour (2012).

This building is equipped with a photo-voltaic (PV) energy generation system and solar hot water system, which contributes about 7% of annual energy consumption. The solar PV system produces grid quality power, but the local service provider does not allow the system to connect to the grid. So power is fed to the main distribution panel of the building during day time. Polycrystalline solar modules are used to generate a direct current (DC). PV modules are connected to string inverters, which converts the DC voltage to 400V, 50Hz alternating current (AC). The output from each individual string inverters are terminated at a

LV collection board at roof. The combined power output of all inverters is connected to the main distribution board of the building after the utility energy meter. The string inverters are connected to the data acquisition unit for real-time monitoring of the system parameters and data logging, through BMS. On the other hand, a solar hot water system with back-up electric heater is installed to serve hot water to all domestic areas. This is an integrated system which consists of various equipment and devices. Flat plate solar panels collect and transfer solar radiation to the hot water circuit. A Calorifier with auxiliary electric heaters, buffer vessel, circulation pump, emergency cooler and control system are other components of the circuit. The owner of the building was particularly interested in savings through on-site energy generation. Energy sub-meter data of the building is processed to produce an annual energy consumption graph, which is shown in figure 4.5.

At the same time, condensate drain from the HVAC machines were collected through a dedicated network to a tank located in the basement. Collected condensate drain water is processed and used for irrigation, to save water. A domestic water supply system and chilled water system were equipped with leak detection system. Any leak in these systems should alert the operator about the leak and helps the operator to find the exact location of the leak. This helps to improve the water and energy use reduction of the building. However, unfortunately, the alarm function of the building management system was purposefully turned OFF by operators. Simultaneously, the building management system graphics was incomplete and tags were missing. The service of the system might be improved, if better man-machine interface is offered (Wang et al., 2013).

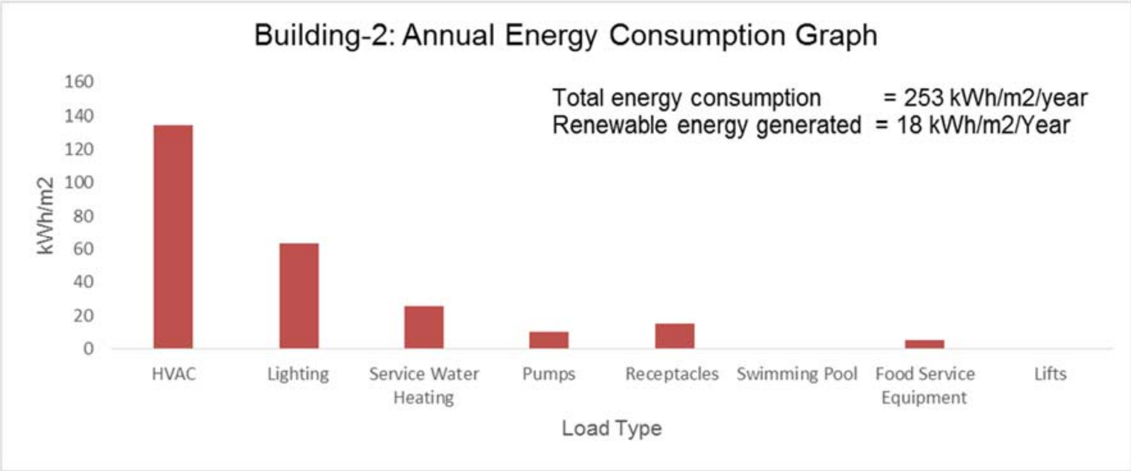

Figure 4.5: Building-2 Annual Energy Consumption Graph

Key Performance Assessment

Performance of building-2 is assessed against environmental, economic and service level KPIs. This building managed to achieve most of the indicators in the environmental KPI. On site energy generation through a solar hot water system and photo-voltaic system helped this building to achieve credits. This school is operating during day time only, while the renewable system can produce energy, so energy produced is utilized efficiently to minimize the peak demand. Hot water and cold water saving measures, such as water recycling and controlled flow helped attain environmental KPIs. On the other hand, performance of the building against cooling savings was very poor due to infiltration and improper operation of the HVAC system.

The economic performance of this building is very poor. The main reason behind this is the oversized equipment in the HVAC system. Another reason is high cooling load demand due to infiltration. Proper design, construction, and operation of the HVAC system and building envelope would have provided a good return on investment. Operational deficiency leads to a long pay-back period and reduced occupant comfort. In contrast, the initial cost for building commissioning was significantly lower, as members of the building owner's organization performed the commissioning activity.

The service level performance of this building was the worst among all other buildings considered for this research. Indoor environmental quality was very poor, especially the air quality, as the fresh air supply to the building was found to be zero. At the same time, lighting quality was very poor and the controllability of lighting was minimum. The humidity level in the building was unacceptably high and was a key reason behind reduced quality of indoor air. Thermal comfort quality inside the building was very bad due to the introduction of hot unconditioned air to the building through cracks and gaps. This restricted the building from achieving a major indicator in the service level performance. Building service log analysis revealed that the response to user complaints was very poor. Sometimes, the facility manager failed to close the complaints raised by the end users. The KPIs of this building are shown in Table 4.5

Table 4.5: Building-2 Key Performance Indicators

Building -2					
Environmental KPIs		**Service Level KPIs**		**Economic KPIs**	
KPI	**Remarks**	**KPI**	**Remarks**	**KPI**	**Remarks**
Electrical Energy Reduction	Not Achieved	Time to take actions on reported defects	Not Achieved	Return on Investment (ROI)	Not Achieved
On site electrical energy production	Achieved	Time to respond to end user feedback	Not Achieved	Socio-Economic Return	Not Achieved
Electrical Energy Peak Demand Reduction	Achieved	Acceptable Indoor Air Quality	Not Achieved	Reduction of First Cost	Achieved
Cooling Savings	Not Achieved	Acceptable Indoor Light Quality	Not Achieved	Reduction of operating Cost	Not Achieved
Hot Water Savings	Achieved	Acceptable Indoor Thermal Quality	Not Achieved		
On site hot water production from renewable energy.	Achieved	Acceptable Indoor Humidity Level	Not Achieved		
Water re-use	Achieved				
Cold water saving	Achieved				

4.2.3. Building – 3: Saadiyat School Building, Abu Dhabi

Overview

This is a private school campus, built over seven hectares of land in Saadiyat Island, Abu Dhabi. Gross building area is 33,634 m^2. A small version of the overall site plan is shown in figure 4.6. Commissioning of these buildings was carried out by a dedicated third party commissioning service provider. Energy related systems, such as solar photovoltaic system, HVAC, BMS, Lighting Control, swimming pool and building envelopes are commissioned. Table 4.6 shows the most important characteristics of the buildings. This project is completed and operational since October-2014. The campus consists of the following buildings:

1. Building: A1 – Staff Accommodation
2. Building: C1 – Junior School
3. Building: C3 – Science Block
4. Building: C10 – Service Zone
5. Building: C11 – Estate Management
6. Building: C4 – Sports Centre
7. Building: C5 – Senior School & Auditorium

Table-4.6: Building-3 Details

(Estimated by the author, no external reference available).

Location	Saadiyat Island, Abu Dhabi
Building Type	School
Gross Building Area (m2)	33,634 square meters (361,901 square feet)
Number of Storey	Two Storey
Construction Period	June 2013 to October 2014
Commissioning Service Method	Third party directed

Figure 4.6: Overall Site Plan Thumbnail of Building-3

Quantitative Analysis

This school's trend logs are analysed and field measurements of certain parameters are performed to analyse building performance against the KPIs. The HVAC system consumes more energy than any other system in this building. The annual energy consumption graph of this building is provided in figure 4.7. A number of measures are taken to optimise the energy performance of the system. Locking of temperature set points is a major action towards this. In this building, through the building automation system, temperature set points are locked at 30^0C (T_{max}) and 21^0C (T_{min}). Users cannot go beyond these set points, to help save energy and optimise the performance of the HVAC system (ASHRAE, 2013b).

Demand controlled ventilation through carbon dioxide monitoring employed in this building is another step towards optimizing energy performance. Minimum fresh air will be supplied to each ventilation zone based on the concentration of carbon dioxide in the zone (Ahmed, Kurnitski & Sormunen, 2015). On the other hand, fresh air supply is limited to diluting high carbon dioxide concentration, thereby cooling load is reduced. Based on the hygrometer log, humidity levels in the building are well maintained, as just the minimum required amount of outdoor air is introduced to the conditioned space. At the same time, cleaning and maintenance of humidistats installed in the return air duct is a good indication of proper end user training delivered as part of the building commissioning process. Humidistats installed in the return duct offer the best control of humidity levels in the space as oversaturation will never occur, but return ducts may accumulate dust and debris in the room (ASHRAE, 2013c). So, frequent maintenance of humidistat sensors is required for a guaranteed operation.

A proper metering and verification strategy is another characteristic of this building. Based on the measurement and verification plan, sub-meters are installed in both energy and water supply circuits in order to read instantaneous consumptions. Readings of the sub-meters are automatically compared against the calibrated water-energy model. If instantaneous value goes beyond the parameters of the calibrated model, an alarm will be sent to the operator through the building management system. The calibrated model is nothing but an energy model, which is calibrated to produce the exact energy behaviour of the building throughout the year, based on the real operational parameters and climatic parameters of the building. Alarms in this building are grouped according to their priorities, this will help the operator to attend high priority alarms immediately. The metering and verification strategy of this building helps it to save a lot of energy.

Concurrently, generation of on-site energy through solar photovoltaic and solar hot water systems contributes up to 9% of annual energy consumption of this building. At the same time, sun-tubes are installed in the building to provide natural light to the central core of this building. As the building operates only during daytime, sun-tubes save a lot of energy. Indoor air quality has primary importance in this building; proper ventilation, as well as frequent maintenance and replacement of air filters ensure this. Suitable maintenance access is also provided for all equipment, which can be treated as a commissioning effect.

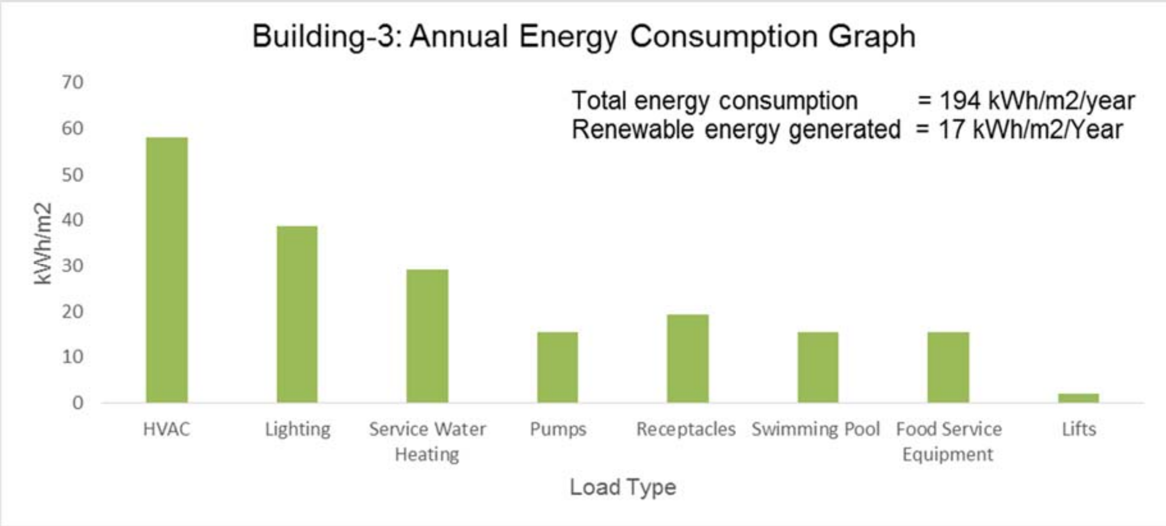

Figure 4.7: Building-3 Annual Energy Consumption Graph

The indoor lighting quality of this building is compromised because of the difference in colour rendering index (CRI) of various lamps. The service log showed that the replaced lamps do not follow the maintenance manual in selecting the CRI of lamps. Furthermore, some of the lamps have even not been replaced for a long time, even after the expected life time. Lux levels in classrooms were measured using digital lux meters and were found to not meet the minimum required level (300 lux), based on CIBSE code-L (Raynham, Boyce & Fitzpatrick, 2012). This is a serious issue in an educational institutional building, and affects the indoor environmental quality of the building. Another major issue that affected the indoor environmental quality is the inefficiency of thermostats in certain classrooms in reading space temperature, as sensors where covered with educational posters.

Key Performance Assessment

Assessing the key performance of this building revealed that most of the indicators are achieved through proper energy and water conservation and maintaining indoor environmental qualities. This building saves a lot of energy through optimum operation and time scheduling of equipment though building management system. Proper sealing of the building envelope for minimum air leakage and suitably controlled ventilation helps to minimise the cooling load (NEBB, 2013). The location of the building offers the very best capability to harvest solar energy through photovoltaic and solar thermal systems. Proper maintenance and cleaning of these systems helps the building to achieve the performance indicator of the building covering energy generation. At the same time, on site energy generation helps to reduce the peak load demand of the building. The domestic water supply system is optimised for water savings through flow control and leak detection. The building management system is capable of alerting the operator in case of over-usage or leakage of the water in the system. This helped the building to achieve the water saving indicator in the environmental section of the key performance indicator.

Although the initial cost of commissioning is high in this building, the costs avoided by the design, construction and operation of the building compensate for reduced overall operating costs of the building. The commissioning authority calculated the payback period for commissioning, considering only the tangible effects, and found that it is less than five years. This is considered as a reasonable period (Mills, 2011). A calculation that includes the effects of intangible benefits will further reduce the payback period drastically, but the calculation will be very complex, so has not been performed yet. Proper documentation of operation and maintenance of the building is performed, which helped in minimising the operational cost of the building. Furthermore, the full potential of the building management system is used in this building to minimise the operational cost of the building through time scheduling, integration with a computerised maintenance management tool and automatic trend log analysis. At the same time, the indoor environmental quality indicators of this building are achieved through maintenance of good indoor air quality, thermal quality, lighting quality and humidity levels. Other service level indicators of this building, including the time taken for servicing and for responding to user feedback, were also within the limits, but the quality of maintenance service was not up to the expected level as there were some issues on colour rendering index of lamps, lux levels and on-time replacement of lamps. Table 4.7 summarises the key performance indicators of this building.

Table 4.7: Building-3 Key Performance Indicators

Building -3					
Environmental KPIs		**Service Level KPIs**		**Economic KPIs**	
KPI	**Remarks**	**KPI**	**Remarks**	**KPI**	**Remarks**
Electrical Energy Reduction	Achieved	Time to take actions on reported defects	Achieved	Return on Investment (ROI)	Achieved
On site electrical energy production	Achieved	Time to respond to end user feedback	Achieved	Socio-Economic Return	Achieved
Electrical Energy Peak Demand Reduction	Achieved	Acceptable Indoor Air Quality	Achieved	Reduction of First Cost	Achieved
Cooling Savings	Achieved	Acceptable Indoor Light Quality	Not Achieved	Reduction of operating Cost	Achieved
Hot Water Savings	Achieved	Acceptable Indoor Thermal Quality	Achieved		
On site hot water production from renewable energy.	Achieved	Acceptable Indoor Humidity Level	Achieved		
Water re-use	Achieved				
Cold water saving	Achieved				

4.2.4. Building – 4: Mussafah School Building, Abu Dhabi

Overview

This is a typical educational building in Abu Dhabi, which has been fully operational since October 2014. Figure 4.8 and figure 4.9 provide the thumbnail image of the building plans. This building is commissioned in the design phase and construction phase by the firm that undertook the design process. All major building services required for a modern educational building are installed and commissioned in this building and have been successfully operating since handover. Table 4.8 illustrates important particulars about this building. The building is situated in the Mussafah community in Abu Dhabi and is a major educational service provider for the local community.

Table-4.8: Building-4 Details

(Estimated by the author. No external reference available)

Location	Mussafah, Abu Dhabi
Building Type	School
Gross Building Area (m2)	14,900 square meters (160,382 square feet)
Number of Storey	Two Storey
Construction Period	June 2013 to October 2014
Commissioning Service Method	Designer directed

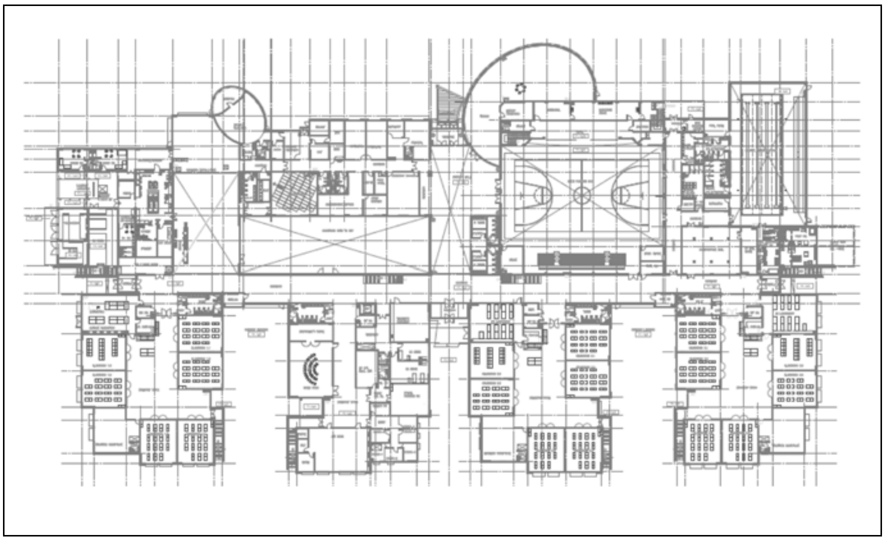

Figure 4.8: Ground Floor Plan Thumbnail of Building-4

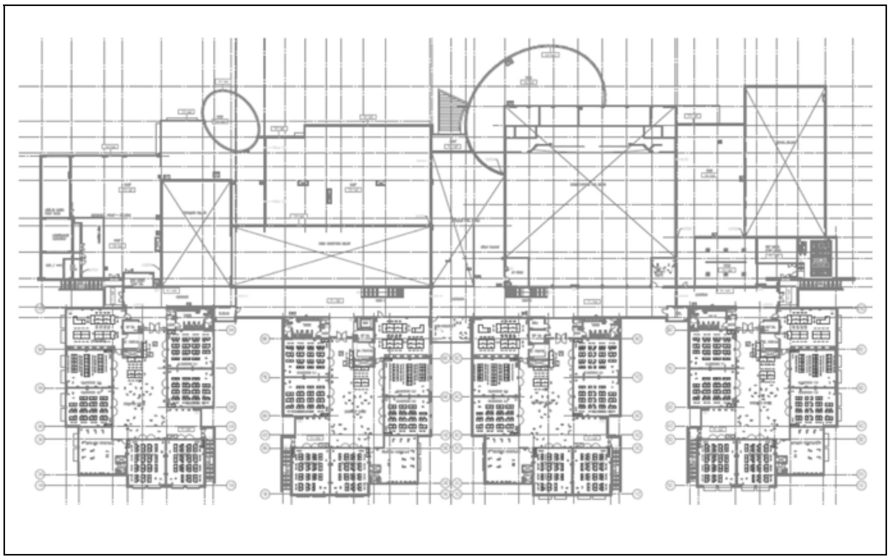

Figure 4.9: First Floor Plan Thumbnail of Building-4

Quantitative Analysis

The trend logs and field measurements of this building show a lot of opportunities for improvement. The construction stage assessments were rarely conducted in this building, which ended up in high energy loss in the HVAC system, primarily due to high duct static pressure drops. Although, the design addressed this issue in the design documents, the construction process failed to take actions to minimise losses. Consequently, the overall efficiency of the exhaust system was reduced by 33%. This ended up in the building having a high energy demand. On the other hand, in the supply air system, duct leak tests were not performed and during operations, treated air leaked through the duct joints. Energy demand was further increased as a result of leakage. Similarly, outdoor air damper motors were not installed and dampers were left open the whole year. This introduced untreated air to the space, which eventually ended up in high humidity and high cooling load demand. The fan control sequence was not configured properly, as exhaust fans in the AHUs continued to run even if the supply fan was turned OFF. This subjected the building to negative pressure and unconditioned outdoor air was introduced to the building through various gaps and cracks in the envelope. Communication delays between the humidistat and the control system resulted in very high data density in the communication backbone of the building, which intensified the oversaturation in the spaces, along with other reasons like infiltration, sensor errors and control sequence errors. The sensors of a number of humidistats and thermostats were out of calibration and resulted in reduced indoor environmental comfort, which is clear from the temperature log and humidity log of the building. On the other hand, the control valve of one of the air handling units was not interacting with the central control system. This caused simultaneous heating and cooling in the system, which ultimately resulted in energy wastage. Field measurements revealed considerable air leakage from the exhaust to air intake at the heat recovery wheel. This is a major reason for reduced indoor air quality.

Apart from issues in the HVAC, this building experienced a lot of issues in the electrical lighting system and plumbing system. This building is designed to employ a dimmable lighting control system with presence detectors, timers and photo sensors. However, presence sensors in most of the lighting zones were not capable of detecting occupant presence and turned OFF abruptly, which caused distraction of the everyday function of the institution. On the other hand, control through photo sensors does not dim the artificial lights, to harvest the natural light. This ended up in more energy use, glare and solar heat gain, which in turn is a reason of high cooling load. The control sequence of the external lighting had a serious bug, which demanded a lot of energy, as lights were programmed to run for the whole night at 100% output. Lights other than emergency lights shall be turned OFF after a pre-set time to save energy and to reduce light pollution (USGBC, 2013). Installed light fixtures too contributed a lot to light pollution, as most of them where throwing light upward to the sky. Full cut-off fixtures would have minimised light pollution. Condensate water is not recycled in this project, but it is discharged to the drainage system. At the same time, leaking water fixtures wasted a lot of water. Operation and maintenance of this building was in trouble, as most of the documents, including operations and maintenance manuals and record drawings were missing or incomplete. Operators were incapable of finding proper service of equipment and systems instructions, which caused a heavy overhead to the owner of the building.

Key Performance Assessment

Energy use was very high in this building as shown in the annual energy consumption graph given in figure 4.10. Exhaust duct static pressure drops, supply duct air leakage, simulations heating and cooling, solar heat gain, inability to harvest natural light and water leakage were the reasons behind high energy usage. So the project could not achieve the performance indicator for energy reduction, as explained in Table 4.9. At the same time, this project is not pursuing any sort of onsite energy generation and depends solely on grids for utility supply, even during the period of maximum demand. The cooling load of this building is very high because of air leakage in the building envelope and in supply ducts. In addition, control sequence errors of air handling units contributed to high cooling load demand. The domestic water supply performance indicator is not achieved, and water demand is very high as a result of leaking fixtures and inability to recycle water. Sick building syndrome is persistent in this building, as a result of reduced indoor air quality. This prevented achieving the performance indicator of socio-economic return. At the same time, the operational cost indicator is not achieved, as operations and maintenance information and accessibility are limited. Indoor air quality is reduced due to mould growth as a result of high humidity levels and air leakage in the heat recovery wheel. Duct air leakage led to uncomfortable indoor thermal conditions in this building, so the building could not achieve this performance indicator. Concurrently, indoor lighting quality is very poor due to distracting sensors and glare. The building service log was not updated frequently and it shows inefficiency in attending defects and user feedback.

Table 4.9: Building-4 Key Performance Indicators

Building -4					
Environmental KPIs		**Service Level KPIs**		**Economic KPIs**	
KPI	**Remarks**	**KPI**	**Remarks**	**KPI**	**Remarks**
Electrical Energy Reduction	Not Achieved	Time to take actions on reported defects	Not Achieved	Return on Investment (ROI)	Not Achieved
On site electrical energy production	Not Achieved	Time to respond to end user feedback	Not Achieved	Socio-Economic Return	Not Achieved
Electrical Energy Peak Demand Reduction	Not Achieved	Acceptable Indoor Air Quality	Not Achieved	Reduction of First Cost	Not Achieved
Cooling Savings	Not Achieved	Acceptable Indoor Light Quality	Not Achieved	Reduction of operating Cost	Not Achieved
Hot Water Savings	Not Achieved	Acceptable Indoor Thermal Quality	Not Achieved	Reduction of operating Cost	Not Achieved
On site hot water production from renewable energy.	Not Achieved	Acceptable Indoor Humidity Level	Not Achieved		
Water re-use	Not Achieved				
Cold water saving	Not Achieved				
Cold water saving	Not Achieved				

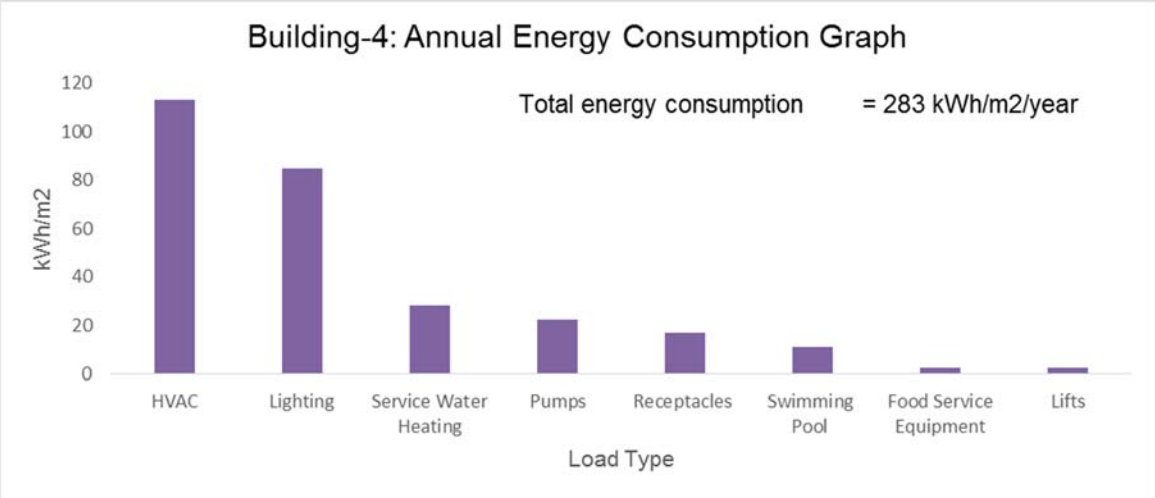

Figure 4.10: Building-4 Annual Energy Consumption Graph

4.3. Phase II: Qualitative Analysis of Expert Opinions

In phase II, qualitative analysis of expert opinions, a Delphi study is performed on various commissioning service methods. The Delphi study focuses mainly on the non-measurable benefits of the commissioning process. As stated in the literature review, ASHRAE (2013a) identifies communication, collaboration, verification and documentation as four key performance indicators. Different commissioning service methods are assessed against these performance indicators through the Delphi study. A three staged Delphi study was performed for this research. Interviewees were selected based on a strict selection procedure followed in stage-1 of the survey, by assessing the experience, educational level and their roles in the industry. Responses from 33 professionals were received in stage-1, but based on the selection criterion, 15 experts were selected for the following stages. The interviewees can be broadly classified into five groups and there are three members in each group, as explained in Table 4.10. In each stage of the study, an electronic questionnaire was forwarded to each interviewee to provide descriptive response on various aspects of the key performance indicators of different commissioning service methods. Responses were collected and refined in each stage to produce the questionnaire for the next stage. In the first stage, interviewees were encouraged to propose non-measurable key performance indicators to assess commissioning service method and to rank the recognized indicators. Participants were instructed to provide educational institution project based statements to support their opinions. First stage responses are collected and processed to produce the second stage questionnaire. During the second stage, participants were provided with the final set of performance indicators and were asked to provide their descriptive responses on the potential of each commissioning service method in achieving the selected indicators. The participants were recommended to provide their judgments based on a cost-benefit assessment and not on an advantages-disadvantages basis. Then the third stage was an opportunity for each participant to further refine the previous responses by considering other responses. However, extreme care was taken to keep the anonymity of the responses to avoid social influence and pressure from peers. Figure 4.11 shows different stages undergone in this Delphi study. To assess the commissioning service methods, responses were qualitatively analysed based on the reported project events.

Table 4.10: Delphi Study Participants' Details

Group Number	Groups Details	Number of participants
1	Sustainability Consultants	3
2	Architect/Engineers	3
3	Designers	3
4	Commissioning Authorities	3
5	Facility Managers	3

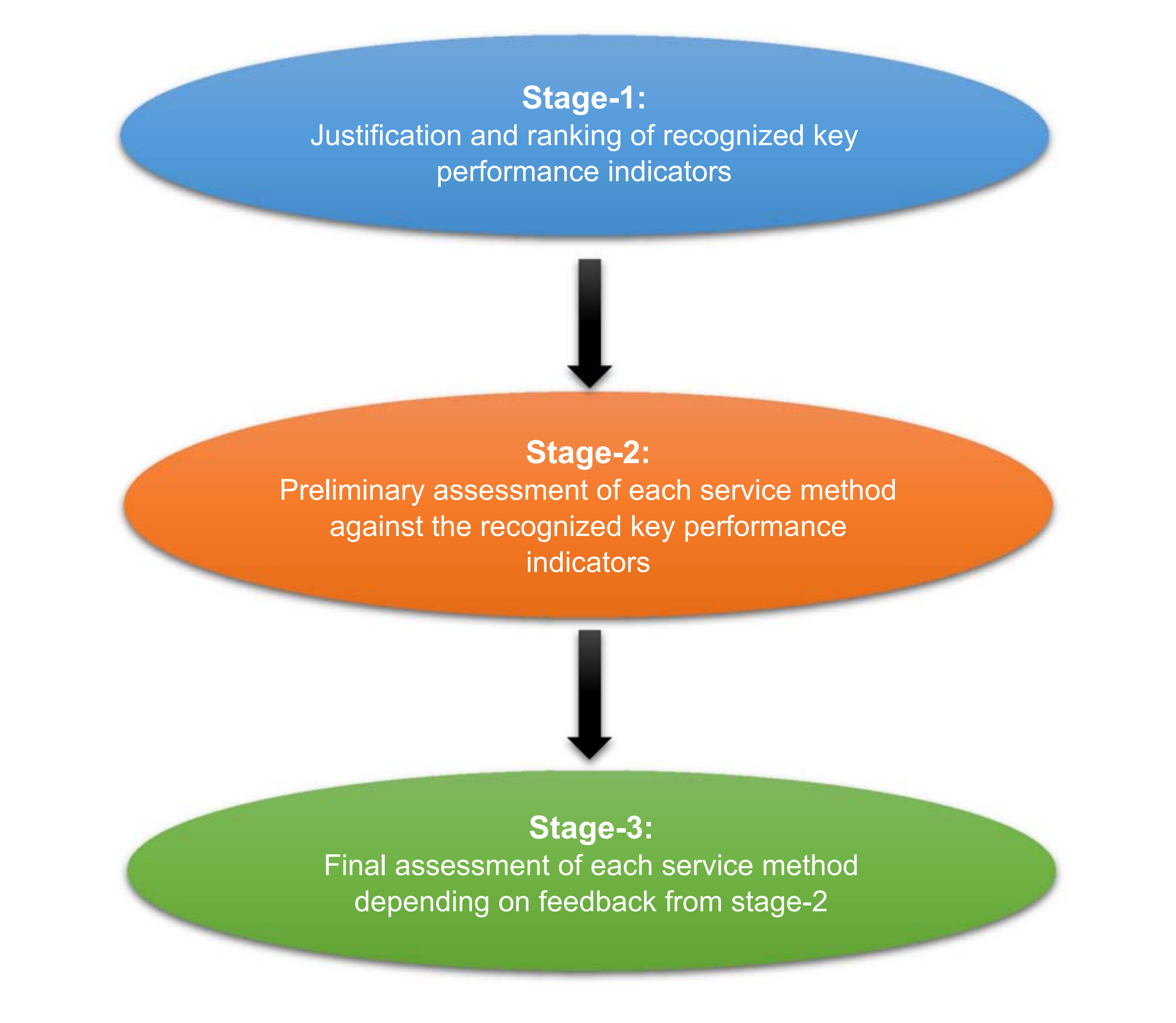

Figure 4.11: Delphi Study Stages

4.3.1. Delphi Study Stage-1

The responses of 15 qualified experts were selected for the stage-1 Delphi study analysis. Most of them agreed on the relevance of the four selected indicators. In addition to that, seven participants proposed other performance indicators, such as authority, responsibility and availability for service. These new indicators are already included within the selected performance indicators. Figure 4.12 shows the participant's ranking of selected key performance indicators. For each KPI, participants had an opportunity to provide three statements to support their opinions. Analysis of responses and statements shows that among four indicators, documentation is considered as the most important performance indicator. Communication follows next and then collaboration and verification. Ten participants believe that proper documentation is a must for efficient operation of facilities through good performance of equipment on site. At the same time, eight participants believe documentation helps to earn building rating system credits. Twelve participants stated that documentation reduces a number of conflicts, change orders and RFIs, thereby the project can meet the scheduled programme and it reduces legal risks. At the same time, nine participants think that implementation of lessons learned in one project is the key for the success of upcoming projects and this can be achieved only through proper communication and documentation. According to the opinion of seven experts, barrier-less communication has more reach and helps to educate various specialists in the project about the sustainability goals of the project. Six participants have confidence in improved communication to minimise conflicts and to reduce risks. Collaboration is considered as the best solution for scheduling tracking and on-time completion of projects, by nine participants. Seven participants treat collaboration as a tool for better system performance. On the other hand, eight participants treat verification as the best methodology for system performance. Five of them think that verification can offer good overall indoor environmental quality. Concurrently, verification can utilize the full life expectancy of the equipment, system and building, as per the opinion of four participants. These are the major findings in this stage of the Delphi study. The stage-2 questionnaire is prepared based on the analysis of these findings.

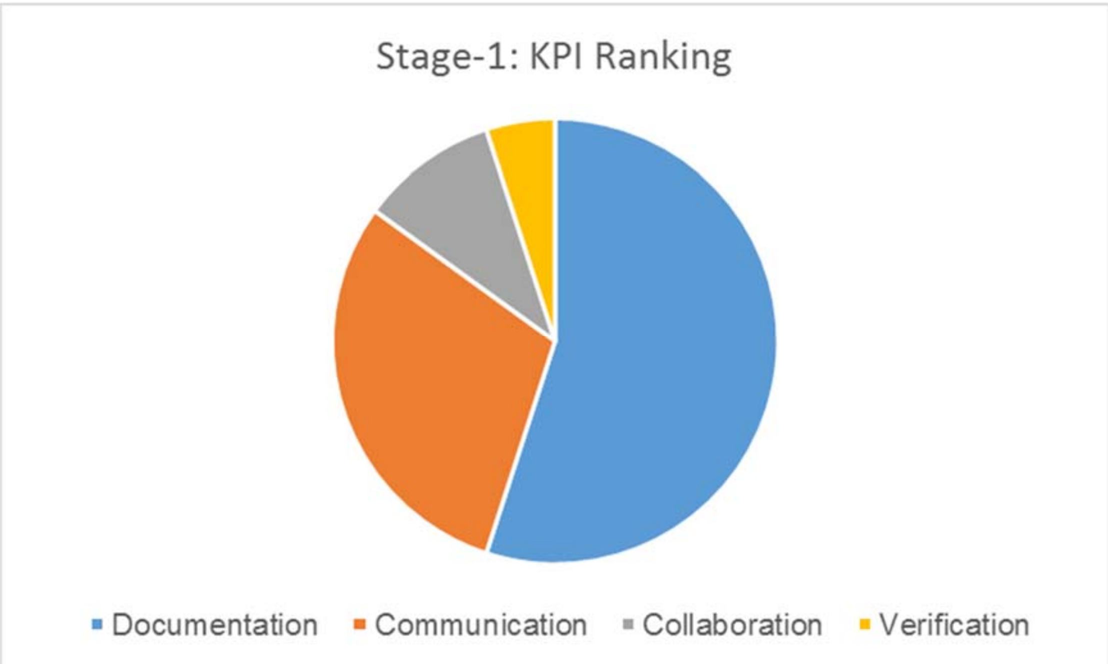

Figure 4.12: KPI Ranking Based on Stage-1 Delphi study

All qualified experts have more than ten years postgraduate experience in their respective fields with a minimum track record of ten projects in the emirate of Abu Dhabi, mostly in educational building construction. Figure 4.13 provides a summary of the project experience of the participants. Two participants have more than 25 years' experience in the construction industry and five participants have 20-25 years of experience. At the same time, three participants have 15-20 years of experience and another five participants have more than 10 years of experience. On the other hand, two participants are experienced in more than 25 projects, while five other participants have experience from more than 20 projects. Two participants fall under the classification of 15-20 projects and the remaining six participants have more than ten projects in their experience list.

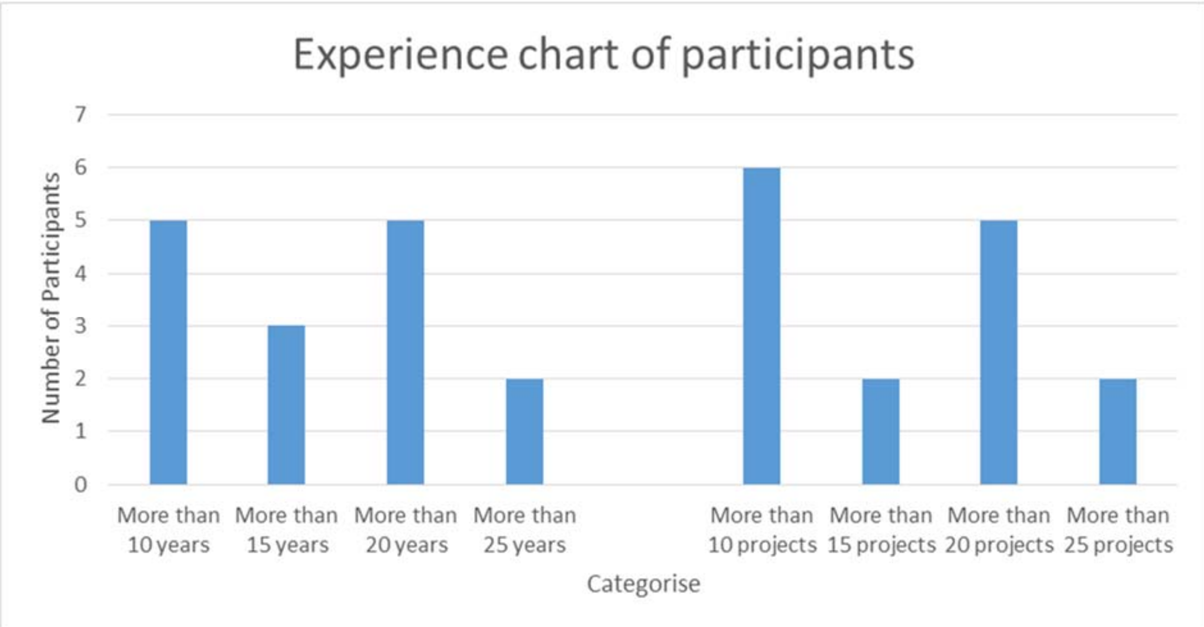

Figure 4.13: Project Experience of Delphi Study Participants

4.3.2. Delphi Study stage-2

This stage was exclusive for selected 15 experts. All 15 participants responded to all questions within the stipulated time. Based on stage-1, four participants recognized that non-measurable performance indicators are used to assess the performance of the four commissioning service methods under research. Unlike stage-1, participant responses varied widely in this stage. Figure 4.14 gives a summary of stage-2 of the Delphi study. The third party directed commissioning service method obtained the highest ranking in this stage of the Delphi study, with the highest rating for verification and documentation. However, its rating for communication and collaboration are below average. For third party directed commissioning firms, commissioning is their only business, so most of them have the resource and experience in documentation and verification. Modern cloud based documentation management applications are used by most of the commissioning firms for proper and controlled circulation of documents and to prevent the loss of documentation. At the same time, proper design verification and on-site verification of performances is a speciality of third party directed commissioning services, without which they cannot survive. However, in most cases, other stakeholders in the projects believe that, third parties are unnecessary additions to the project. Although communication is a major function of the commissioning authority, this research shows that third party commissioning consultants fail in achieving this indicator. The primary reason behind this is, as stated by most of the interviewees, that the authority of commissioning consultants is not well defined in the construction projects in this geographic region. Commissioning consultants have no authority to stop work or payment, if any non-conformance is found. This affects both the communication indicator and collaboration indicator of the project. Communication and collaboration are mutually related, if there is no proper communication, then proper collaboration between different stakeholders is not possible and vice versa. At the same time, priority of communication depends on the authority of the communication originator; responsibility without authority will never succeed.

Owner directed commissioning ranked next with the highest rating in communication and collaboration, while documentation and verification are rated very poor. Documentation is very poor primarily because professionals in this organisation are responsible for a lot of other project related matters and due to a lack of resources to manage documentation. The same can be said for verification, either they do not have resources for verifications or they do not know the importance of performance verification. On the other hand, as the owner is the financier of the project, they have the authority over others and communication from the owner’s organisation is treated as a high priority.

Similarly, the owner's representative can improve collaboration between all stakeholders supported with the highest priority communication and authority.

Engineer directed commissioning was ranked third with the highest rating for verification, as shown in the figure 4.14. A closer look reveals that in engineer directed commissioning, the performance indicator of documentation ranked lowest among other indicators. The participants stated that the conventional paper based documentation method followed by most of the engineers is the reason behind this. At the time of project hand-over, most of the documents were either lost or damaged. On the other hand, the indicator of verification managed to achieve an above average performance rating in this service method, as this is a major contractual obligation of engineers. Communication and collaboration in the engineer directed service method received an average rating only. As stated by the participants, communication in this case is almost unilateral because of the authoritative approach of the engineering firms. They fail in collecting and processing responses from other parties and to act accordingly.

The ranking of designer directed commissioning is the lowest among the four service methods and verification is considered as the best performance indicator in this service method. However, design verification is a major function of any designer. Changes in the design phase of the project have much lower cost impact than in the construction phase. As a result of this, the designer directed commissioning service achieved a considerable rating for verification, even though the on-site performance verifications are not conducted in most cases. On the other hand, proper documentation is not executed in a number of projects as stated by the participants, which is supported by the fact that handover documents and maintenance documents are not available in most cases. A lack of operation and maintenance data ends up in improper operations and underperforming buildings. Simultaneously, reduced collaboration results in the failure to achieve project schedules, which is a major commercial overhead to the owner. Communication is also very poor in this service method, as per the stage-2 Delphi study result.

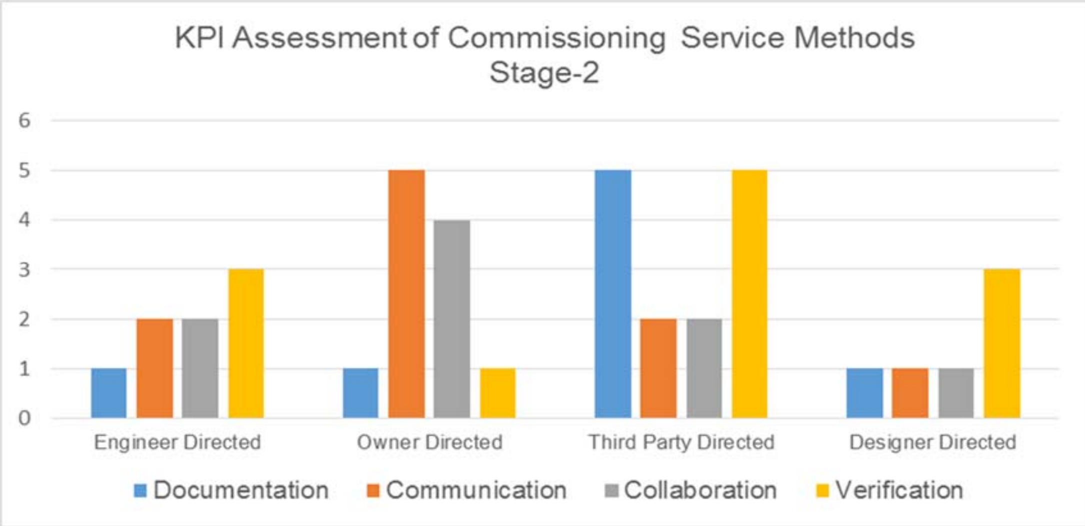

Figure 4.14: Stage-2 Delphi Study Summary

4.3.3. Delphi Study Stage-3

In this stage of the Delphi study, the responses of the interviewees in the previous stages are processed and findings are consolidated for the re-consideration of the participants, however, this added nothing new. Results shows no major difference from the previous stage. Third party directed commissioning still achieved the highest ranking and owner directed commissioning succeeded, with further increases in the collaboration indicator to the maximum level. For the designer directed commissioning and engineer directed commissioning performance assessment is almost similar to the previous stage. Figure 4.15 shows the outcome of stage-3.

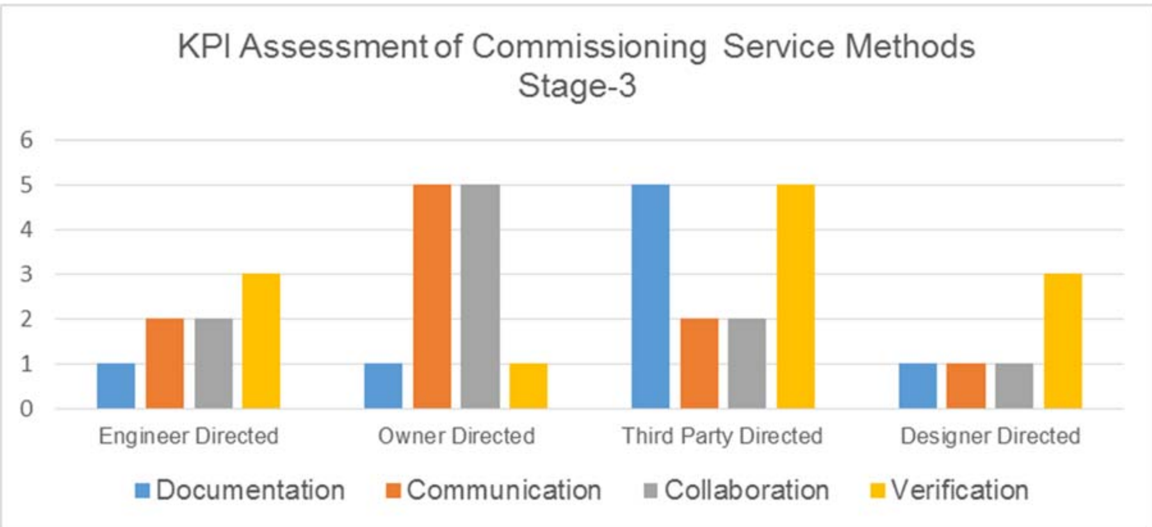

Figure 4.15: Stage-3 Delphi Study Summary

4.4. Phase III: Selection of the Best Service Method

Based on this research analysis, a combination of third party directed commissioning and owner directed commissioning can yield the best in the construction of educational institutions in the emirate of Abu Dhabi. Third party consultants offer the best in the technical side of the commissioning, however, their limitations in communication and collaboration due to restrictions in authority hinders them in the performance of the management side of building commissioning process (Ágústsson & Jensen, 2012). With proper integration of owner directed commissioning and third party directed commissioning, both process commissioning aspects and technical commissioning aspects can be achieved. Quantitative analysis also reveals the same, in projects where owner directed commissioning is selected, technical errors were significant for example, oversized equipment and major control sequence errors. While, communication and collaboration were very good to finish the projects on time and to stick to the budget. On the other hand, quantitative analysis of buildings that were subject to third party commissioning, shows better energy performance and indoor environment performance as a result of the best technical solutions and proper documentation.

A combination of third party directed commissioning and owner directed commissioning is the best solution, as stated previously. However, the extent of combination and depth of combination makes the difference. From figures 4.14 and 4.15, it is clear that the owner directed commissioning is the best in communication and collaboration. On the other hand, third party directed commissioning is the best in documentation and verification. If the project communications of the third party consultant can be channelled through the owner of the project, it can achieve all four KPIs. Turner (2012) states that if the owner is the main communication channel between the commissioning authority and other stakeholders in the project, it will increase the effect of the commissioning process. This statement is proved through this research. Communication from the owner is more authoritative than any other party, as the owner is the finance provider of the project. Concurrently, collaboration of projects shall be through a combined effort of the owner and the third party consultant.

The owner has the authority to integrate all parties involved in the project for the well-being of the project. Properly documented and structured commissioning meetings will help the commissioning authority to achieve this. A well-structured and controlled communication hierarchy helps in proper project collaboration.

Concurrently, this research shows that owner directed commissioning is very poor in documentation and verification. So, a combination of third party-owner commissioning can find a solution for documentation issues and verification can be improved. From the quantitative analysis, the building commissioned by the third party (building-3) achieved good energy savings and operational cost savings by using proper operational strategies. This is a result of good handing-over documentation, proper end user training, design verification and onsite verifications. However, in the case of the building which was commissioned by the owner (building-2), energy performance, operational cost and indoor environmental quality are very poor.

Designer directed commissioning and engineer directed commissioning show below average performance in both qualitative and quantitative analysis. Indicators of documentation, communication and collaboration showed poor performance in designer commissioning and engineer commissioning. On the other hand, the verification indicator shows above average performance. However, this alone cannot support these service methods. As stated already, verification is a contractual obligation of engineers and designers in their respective fields, so this does not have much significance.

In short, the best solution for the commissioning of educational institutional buildings in the emirate of Abu Dhabi can be found through a combination of owner-third party directed commissioning, which is properly structured to achieve maximum performances indicators. The third party commissioning consultant must have the lead role and the owner's organization shall have the supporting role in achieving the communication and collaboration performance indicators. In light of these findings, the third party-owner combined commissioning service method is implemented on an educational building (building-5) in Abu Dhabi.

Quantitative analysis of this building is performed and is made available in the next section.

4.5. Phase IV: Evaluation of Selected Commissioning Service Method

Overview

This is a confidential school building in Khalifa City, Abu Dhabi. A thumbnail of the plans of this building is given in figure 4.16 and figure 4.17. This building has undergone comprehensive commissioning of all systems and assemblies led by a third party commissioning consultant supported by the owner of the project. Documentation and verification of the project in each phase including design and construction was performed by the third party consultant and leads the communication and collaboration, with the support of the owner's organization. In essence all communications related to the commissioning process are initiated by the third party organization, but channelled through the owner of the building. The third party chaired and the owner attended all commissioning meetings and coordination meetings. This building has been operational since February 2015. All relevant data required for this research are readily available for the researcher's reference. Table 4.11 provides key details about the building.

Table-4.11: Building-5 Details

(Estimated by the author No external reference available)

Location	Khalifa City, Abu Dhabi
Building Type	School
Area	19,250 square meters (207,205 square feet)
Number of Storey	Two Storey
Construction Period	June 2014 to February 2015
Commissioning Service Method	Third party-Owner combination.

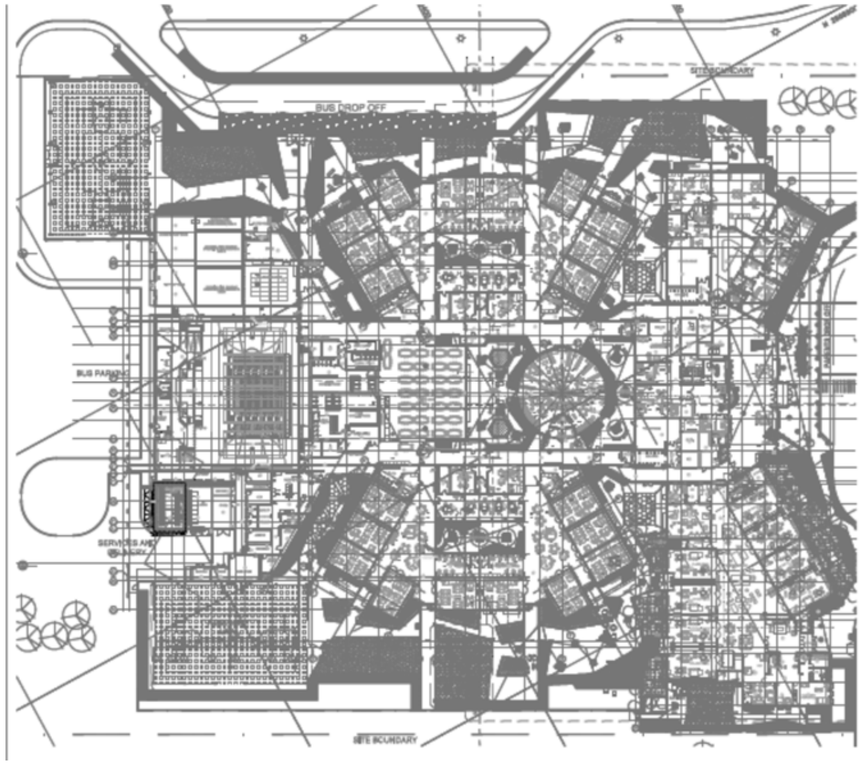

Figure 4.16: Ground Floor Plan Thumbnail of Building-5

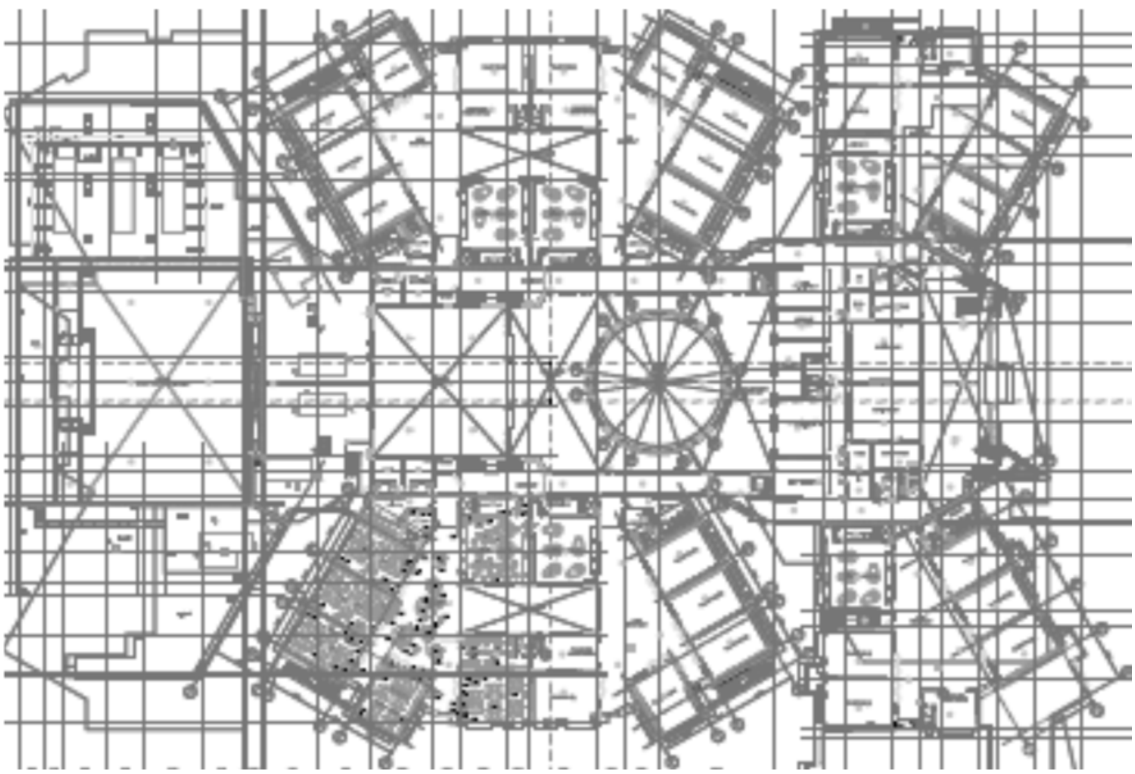

Figure 4.17: First Floor Plan Thumbnail of Building-5

Quantitative Analysis

This building saves a lot of energy, especially in cooling through proper control sequence optimisation and performance optimisation, as shown in the annual energy consumption graph of building-5, provided in figure 4.18. The equipment is selected at full load, as the efficiency of mechanical equipment is maximum near full load conditions. Another major action towards energy saving is the controlled ventilation. Air infiltration and exfiltration through cracks and gaps are energy intensive. The building envelope leak test shows the best results with very minimum leakage. At the same time, indoor air quality tests show acceptable levels in volatile organic compound (VOC) levels, carbon dioxide levels and other parameters. This too is related to building envelope integrity and ventilation. As per NEBB (2013), a tight envelope and proper ventilation minimise contamination and helps to dilute pollutants in the breathing zone as stated by Ahmed, Kurnitski and Sormunen (2015). Hygrostat logs prove the same results. Furthermore, humidity levels in the space were under control and occupant comfort was achieved.

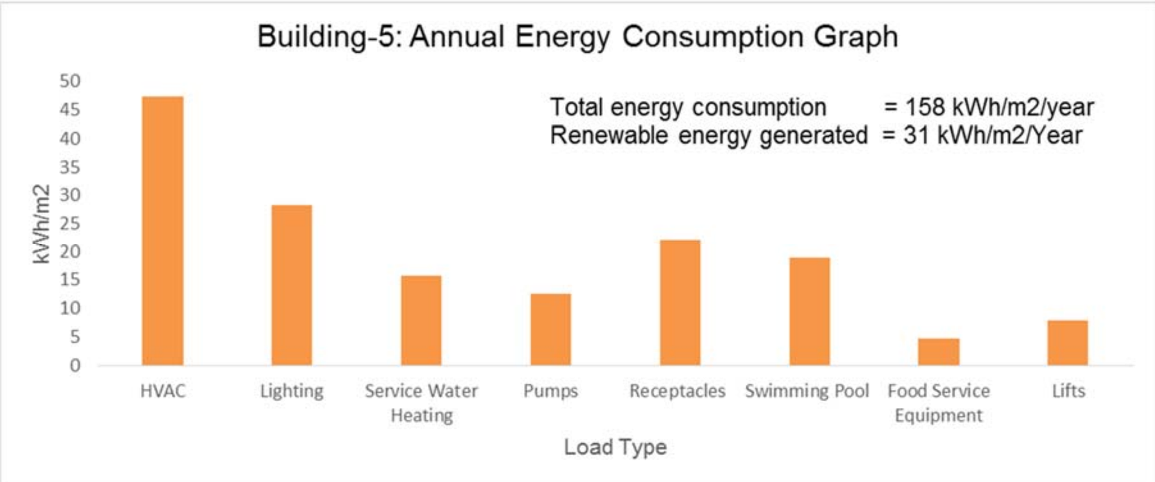

Figure 4.18: Building-5 Annual Energy Consumption Graph

Compared to other buildings, energy consumption is very low as shown in figure 4.19. Again, on-site energy generation through solar photovoltaic, solar thermal and biogas plants further reduces the net energy consumption of this building. Figure 4.20 compares the net energy consumption of all five buildings. The renewable energy generation of building-5 contributes to about 20% of annual energy use. This is a significant figure compared to other buildings. Polycrystalline solar PV modules generate energy during the day time and are connected to the main supply to the building. Electrical energy generated on site is neither stored nor connected to the grid, but directly used as an auxiliary power supply to the building, during day time. Hot water generated by the solar hot water system serves all domestic areas and feeds heated water to the swimming pool. Food waste from the kitchen is used to supply the bio-gas plant employing anaerobic digestion. Fuel generated by the plant is used for food preparation in the main kitchen.

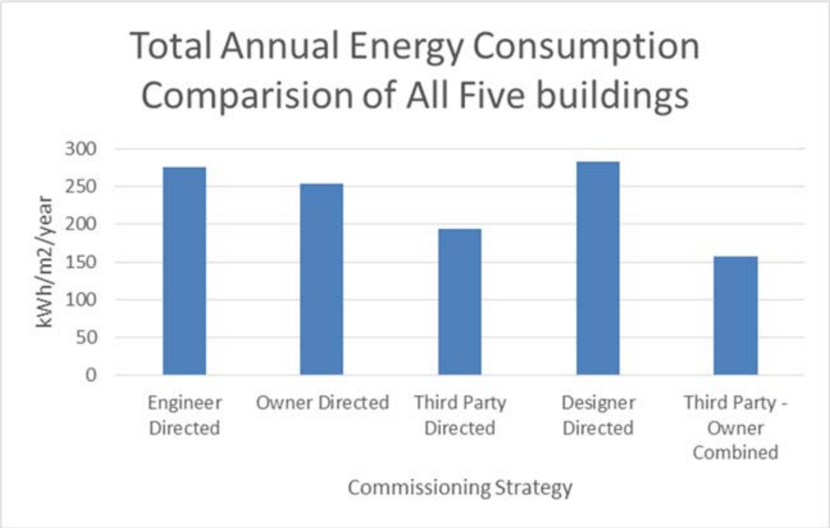

Figure 4.19: Annual Energy Consumption Comparison of All Five Buildings

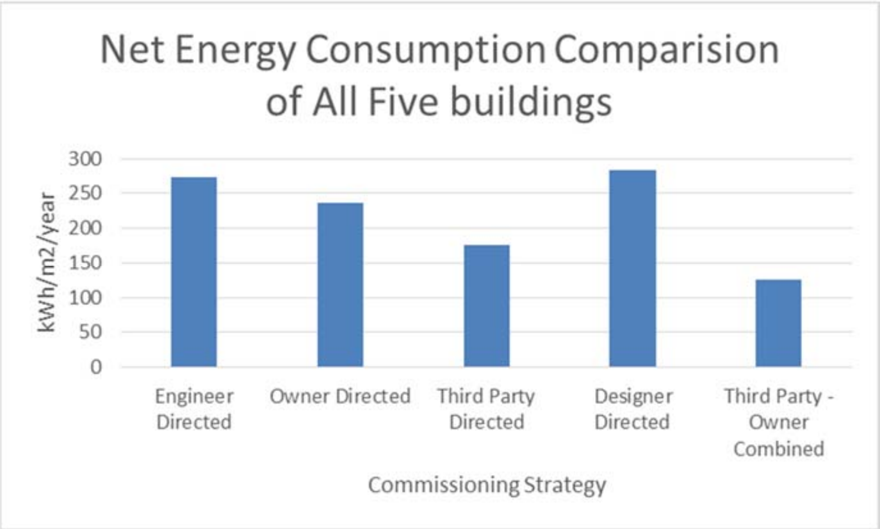

Figure 4.20: Net Energy Consumption Comparison of All Five Buildings

A facility established to monitor and compare the energy and water use of this building aids in energy savings and (or) identifies energy wastage. Energy and water usages are monitored at central monitoring stations and compared continuously against a calibrated baseline. Users will be alerted in case of over usage of utilities. Proper access for maintenance and repair is given the utmost importance in this building. This is very significant in the maintenance of good indoor air quality. Air side filters are cleaned and maintained frequently based on a pre-set maintenance schedule.

At the same time, this building's lighting control system is a state of the art technology to improve the energy performance through proper time scheduling and dimming. Then again, proper glare control through automated blinds, dimming and scene selection through a combination of lamp colour temperatures contributes to good indoor environmental comfort. Both internal and external lights are controlled through optimum sensitive sensors to optimise energy performance and comfort. Re-calibration of all sensors in this building is performed regularly as per the manufacturer's recommendation, which is well documented and is available in the operations and maintenance manual. Operations and maintenance manuals are compiled in electronic searchable format and integrated into the computerised maintenance management system, which is eventually integrated into the building management system. Therefore, from the main operating station, the operator can access the operational data of the building to find the deficiencies reported through the automation system. Furthermore, the operator can easily find solutions through the computerised operations and maintenance manual.

Another major achievement of this building is in conveying the sustainability messages to the inhabitants through on-screen messages. Efficient LED screens are installed at various locations in the building explaining the benefits of sustainable building in general and the operational strategy of this building, by illustrating savings it makes in terms of carbon emission reduction and water savings. This makes the occupants aware of the needs of sustainable development and to operate this building sustainably. A study conducted by

Smith (2015) demonstrates that proper conveyance of sustainable operations has a psychological effect on end users, encouraging them to use buildings sustainably.

Key Performance Assessment

This building is a good example among educational buildings in Abu Dhabi for the perfect utilization of resources available on-site. Table 4.12 shows the key performance indicators assessment of this building. Solar energy is abundantly available and biological food waste from the canteen and restaurants located in the campus are utilized to produce energy on site with the help of a biogas treatment plant. This helped the project in achieving renewable energy indicator criteria in the environmental section of the KPIs. Energy use reduction is achieved through renewable energy, optimised equipment selection, proper operation, maintenance and reduced cooling load. Commissioning had a significant impact in achieving these environmental indicators through proper communication, documentation, verification and collaboration. Reduced water use in the building with the help of proper sanitary fixtures, water re-use and leak detection system helps in achieving other indicators in the environmental section. All KPIs set in the service level section are achieved in the building. Indoor air quality and light quality shows more significant improvement than any other building considered for this research. The humidity level indicator is achieved as envelope air leakage is well below the acceptable maximum level. Proper training and documentation helped in prompt responses to service calls and user feedback. All project documents are available at their fingertips, electronically, which is easily navigable and updatable. Other non-measurable KPIs of the building like documentation, communication collaboration and verification are also achieved. As energy use is reduced, the operating cost is reduced considerably. This achieves best return on investment. The initial cost is reduced considerably as the design reviews helped in optimising equipment sizes.

Conversely, this project experienced a major issue. As all commissioning based communications were channelled through the owner, the owner's organization has become overloaded with information transmittals. The next phase of the research is to find a practical solution for this problem.

Table 4.12: Building-5 Key Performance Indicators

Building -5- combination					
Environmental KPIs		**Service Level KPIs**		**Economic KPIs**	
KPI	**Remarks**	**KPI**	**Remarks**	**KPI**	**Remarks**
Electrical Energy Reduction	Achieved	Time to take actions on reported defects	Achieved	Return on Investment (ROI)	Achieved
On site electrical energy production	Achieved	Time to respond to end user feedback	Achieved	Socio-Economic Return	Achieved
Electrical Energy Peak Demand Reduction	Achieved	Acceptable Indoor Air Quality	Achieved	Reduction of First Cost	Achieved
Cooling Savings	Achieved	Acceptable Indoor Light Quality	Achieved	Reduction of operating Cost	Achieved
Hot Water Savings	Achieved	Acceptable Indoor Thermal Quality	Achieved		
On site hot water production from renewable energy.	Achieved	Acceptable Indoor Humidity Level	Achieved		
Water re-use	Achieved	Communication	Achieved		
Cold water saving	Achieved	Collaboration	Achieved		
		Verification	Achieved		
		Documentation	Achieved		

4.6. Phase V: Refine the Service Method to Reflect the Lessons Learned

Phase IV of this research helped to validate the findings in the previous phases of the research. Real-life implementation of the findings in Phase I to Phase III of the research was performed in Phase IV. Performance indicators considered until then are achieved with the proposed commissioning service method. On the other hand, this exposed another issue, as the owner hires all other entities to help him in performing construction activities, but if day-to-day project communications becomes the owner's responsibility, it works against the owner's interest. During the execution of the project in Phase IV, the project team experienced a similar situation and this had an impact on the project schedule. Based on ASHRAE (2013a), a communication structure is developed, as shown in Table 4.13, to manage information handling. Minor issues are reported and coordinated directly by the third party consultant but other issues are channelled through the owner of the building at stipulated development stages or milestones. Furthermore, critical issues are reported to both owner and other concerned parties immediately. The communication structure shown in Table 4.13, shall be configured for each project as per the project requirements. The priority of issues will vary project by project and economic or time criterions can be set at the beginning of each project to define the priorities. This communication structure will help to minimise transmittals to the owner. At the same time, it has the capability to communicate effectively for the success of the project and this authoritative approach has the potential to solve issues efficiently.

Table 4.13: Commissioning Service Communication Strategy
(ASHRAE, 2013a and GSFIC, 2010)

Minor design or construction issues in all phases of the project.	Conveyed directly by the commissioning authority to the stakeholders responsible for the resolution.
Major issues in the pre-design phase	Conveyed directly to the owner by the commissioning authority immediately after identification of the issue.
Major issues in the design phase.	Conveyed to the designer, through the owner of the project. At the end of the schematic design stage, the first review report shall be forwarded compiling all issues found.
	A second review report shall be forwarded to the designer through the owner, at the end of the detailed design stage. This is to make sure that all previous issues are integrated in the detailed design and to report new issues, if any.

Major issues in construction phase.	The first review report shall be forwarded to the contractor through the owner before the procurement of major equipment. This report will be based on the material submittals, shop drawings and method statements. So a minimum 90% of the submittals must be made by this milestone. This strategy helps the commissioning authority to make sure that the project is following the schedule.
	A second report shall be forwarded to the contractor through the owner at the end of the functional performance tests at the equipment level and system level. Performance deficiencies can be identified at this stage and required changes can be made.
	The construction stage final review report will be produced and forwarded to the contractor through the owner at the end of the integrated testing of all systems. This will help to optimise the control sequence of equipment and to optimise the energy saving potential of systems.
Major issues in operation phase.	A review report will be transmitted to the facility manager and the maintenance contractor at the end of the first year of service. This is to fine tune the building based on a yearlong performance of equipment and systems.
	The second review report will be transmitted to the concerned parties towards the end of the warranty period. This is to guarantee the performance of the building even after the warranty period. This is also for the owner to consider extending the warranty or replacing equipment.
Critical issues in all phases.	Critical issues are issues that will have great impact on the schedule and (or) budget of the project. This will be reported immediately to the owner and a copy will be forwarded to concerned party.

Chapter – 5: Conclusions and Recommendations for Future Research

5.1. Introduction

This chapter summarises the ultimate findings of the research. Research studies in building commissioning have a great potential to make dynamic changes in the sustainable building construction sector. Therefore, recommendations for future research are also provided in this chapter. To date, the construction and operation of sustainable buildings has been considered as uneconomical. However, this research supports that, with a proper selection of the commissioning service method, less carbon emission is economical than emitting more.

Results of the research revealed that a well-defined, third party-owner combined commissioning can achieve the performance KPI's of educational buildings in Abu-Dhabi. Phase I demonstrates that measurable key performance indicators of the building that was subject to third party directed commissioning has considerably better performance over other buildings, in terms of environmental performance, economic performance and service level performance. Most of the issues in buildings could be resolved easily, through minor control sequence resetting or set point adjustments. This highlights the benefits of proper building commissioning. The HVAC system had the highest number of issues and lighting systems also had a lot of deficiencies. The total energy use reduction of the third party directed commissioning is better than any other building. Indoor environmental quality in most of the buildings was very poor. Indoor air qualities did not meet the standard requirements, mostly due to the high humidity level in the space and envelope air leakage. Indoor lighting quality was compromised in most buildings as a result of high glare and non-matching colour rendering index combinations. Thermal qualities in the building were affected by control sequence errors and imbalanced supplies. At the same time, reduced thermal comfort ended up in increased electrical energy use in buildings. Oversized equipment, control sequence errors, air leakage and water leakage were other factors behind escalated energy bills. Water leakage in the hot water and cold water systems were persistent in most of the buildings, which ultimately ended up in high water demand.

On the other hand, limitations of current commissioning service methods to achieve the non-measurable indicators are revealed in phase II. Analysis shows that, third party commissioning achieved the top rating in documentation and verification indicators. However, the communication indicator and collaboration indicators were comparatively poor. On the other hand, communication and collaboration in owner directed commissioning was reasonable. The Delphi study result shows that engineer directed commissioning and designer directed commissioning are under performing in terms of all indicators except verification.

Third party-owner combined commissioning strategy has the potential to overcome the limitations of current service methods. In phase III of the research, this combined commissioning is selected as the best service method, as it balances each component to attain a good overall performance. The idea is to channel all commissioning related communications and collaborations through the owner of the project, while the third party leads the process. This method can achieve all four non-measureable performance indicators along with all measurable performance indicators. Third party-owner combined commissioning service was implemented on an educational building, in Phase IV of this research and the performance of the building was assessed quantitatively against KPIs. Results of the assessment show considerable achievement of performance indicators over other commissioning service methods. The energy use and water use of the building were reduced considerably and indoor environmental conditions were improved. Environmental, social and service level indicators are achieved in this building as a result of the implementation of the selected commissioning service method.

Phase V of the research further refined the selected commissioning service method to improve the communication process. A communication structure is developed to avoid improper communications and excessive notifications. Practicing this communication strategy will help to efficiently manage resources and to solve issues. Notifications will be classified based on the priority and bundled together at each stage of the construction process. This helps in proper management and controlled circulation of information. At the same time, communication and collaboration will be authoritative as it is channelled through the owner

5.2. Conclusion

This research assesses the ability of various commissioning service methods, including third party directed commissioning, owner directed commissioning, engineer directed commissioning and designer directed commissioning to achieve the performance KPIs of educational buildings in Abu Dhabi. The research progressed through a literature review, quantitative analysis of building performance and qualitative analysis of expert opinions. The outcome of the research shows that, third party commissioning and owner directed commissioning yields better results than other commissioning service methods. At the same time, these service methods also have limitations, although a combination of these services can provide the optimum solution, if the boundaries of the combination are well defined. This conclusion is based on the real-life application of this combined service method on an educational building and the assessment of the performance of this building. Again, the selected service method is further refined to eliminate issues identified in the communication strategy. This research will help to develop energy and water benchmark for buildings in Abu Dhabi and to establish key performance indicators for educational buildings. The result of this research can be used to select the commissioning service method suitable for educational buildings in Abu Dhabi.

5.3. Recommendations for Future Research

As stated earlier, research studies on building energy management and building commissioning are very limited in this region. There are a lot of research opportunities available for future researchers in this field, which are capable of finding solutions to a number of energy related and non-energy related issues in new and existing buildings. This research can be treated as a pilot research in establishing regional energy and water usage benchmarking for buildings. Further research can be performed in this stream to develop an extensive database to collect and process building trend logs and to establish energy and water benchmarks. Utility benchmarks depend a lot on the climatic, social and cultural conditions of the region. Assessing building performance based on benchmarks developed for an extremely different climatic zone, such as the USA, will have a severe impact on the energy and water use of buildings in Abu Dhabi. Therefore, developing and establishing a comprehensive regional benchmark is a good research recommendation. On the other hand, this will have to overcome a lot of hindrances, as the owners and operators of most of the buildings in this region are typically not interested in disclosing information for any purpose, even for research. At the same time, developing a tool to process this collected information is also a tedious task, as the amount of information needed to develop benchmarks is very large and must be processed accurately. To develop a benchmark, data must be collected from a number of sub-meters and sensor and data collection intervals must be short, as stated by Wang et al. (2013). Therefore, collecting and processing building data is a tiresome job, but it will certainly help professionals and researchers to perfectly analyse the behaviour of buildings in the selected region.

A research on the avoided cost of commissioning, focusing on the climatic and economic circumstances of this region is recommended, in order to understand the significance of various commissioning service methods. The research shall focus more on the commercial side of commissioning service methods rather than the technical side. As stated by Altwies and Mcintosh (2011), cost savings from commissioning cannot be calculated, as the commissioning process helps to eliminate deficiencies in construction projects. Thus, the calculation must be performed as if the deficiencies are not identified, and the monetary loss due to those deficiencies shall be estimated. This is treated as avoided cost, since the cost associated with this is avoided by the commissioning process. Avoided cost will be different for each commissioning service method, a research study on this can determine avoided costs in each service method. This will allow building developers to select the optimum commissioning service based on the avoided cost. This research needs a lot of information including the cost of services and cost of parts. Collecting and processing these data using quantitative methods will help to identify the costs avoided due to commissioning.

At the same time, research to improve the communication indicator in the commissioning process, as well as the overall construction process is an opportunity for future research. This research proposed a communication strategy for the commissioning service, but its effectiveness is yet to be validated. A project based research on the effects of communication strategies will help to fine tune the strategy proposed in this research. At the same time, a research on the communication effectiveness of modern cloud based project management applications and networking applications on construction projects is a good research proposal to optimise the communication process in the construction industry.

Another opening is to execute similar research on other types of buildings. This research, focuses only on educational buildings. Future researchers can conduct research on commercial, residential or office buildings to extend the reach of the research outcomes. At the same time, results of similar research can be consolidated together to establish a general guideline for the selection of commissioning service methods in Abu Dhabi, for various types of buildings.

Tools for monitoring based continuous commissioning and automated fault detection have already been developed in the industry for the real time analysis of building performance. These tools depend on data from the building simulation model, building information model (BIM) and trend logs. The building information model will provide all required building physics information and energy simulation will give information about energy and water estimates. At the same time, the trend log provides actual conditions in the building. A research to coordinate these three processes through building management system can produce more accurate results, with minimum errors and minimum efforts. At the same time, it will be user friendly, as all calculations and comparisons will be done at the back end and results will be available at the front end through BMS. This could minimise the service of building information modellers, simulation modellers and commissioning professionals. An optimum algorithm for the process can perform continuous automatic commissioning and fault detection in an efficient manner and on a regular basis.

Further research can be performed on the KPIs of buildings, to rate them based on the social and cultural effects of the region. A qualitative research to find the significance of each KPI against different types of buildings will help to refine KPIs for advanced studies. This in turn, will help to fine tune the commissioning process, to meet the requirements of each building type. Research performed on different types of buildings can be compiled together to establish a general guideline in setting up the project's KPIs.

References

Abd, H., Ali, E.M., Al-Sulaihi, I.A. & Al-Gahtani, K.S. (2013). Indicators for measuring performance of building construction companies in kingdom of Saudi Arabia. *Journal of King Saud University - Engineering Sciences*, vol. 25, pp. 125–134.

Ahmed, K., Kurnitski, J. & Sormunen, P. (2015). Demand controlled ventilation indoor climate and energy performance in a high performance building with air flow rate controlled chilled beams. *Energy and Buildings*, vol. 109, pp. 115–126, in Espoo:Elsevier.

Altwies, J.E. & Mcintosh, I.B.D. (2011). Quantifying the Cost Benefits of Commissioning. *National Conference on Building Commissioning*. 18 May. Atlanta.

ALwaer, H. & Clements-Croome, D.J. (2010). Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings. *Building and Environment*, vol. 45 (4), pp. 799–807, in Elsevier.

ASHRAE. (2013a). *ASHRAE 202-2013: Commissioning Process for Buildings and Systems*. Atlanta:ASHRAE.

ASHRAE. (2013b). *ASHRAE 90.1-2013: Energy standard for building except low rise residential buildings*. Atlanta:ASHRAE.

ASHRAE. (2013c). *HVAC design manual for hospitals and clinics*. Atlanta:ASHRAE.

ASHRAE. (2016). *ASHRAE 62.1-2016: Ventilation for Acceptable indoor Air Quality*. Atlanta:ASHRAE.

Baechler, M. & Farley, J. (2011). *A guide to Building Commissioning*. Washington, USA:U.S. Department of Energy.

Chan, D.W.M. & Chan, J.H.L. (2012). Developing a performance measurement index (PMI) for target cost contracts in construction: A Delphi study. *Construction Law Journal (CLJ)*, vol. 28 (8), pp. 590–613, in London:LexisNexis.

Enck, H.J. (2010). Commissioning High Performance Buildings. *ASHRAE Journal*, vol. 52 (1), pp. 12–18, in Atlanta:ASHRAE.

Eriksson, E. & Westerberg, M. (2010). Effects of cooperative procurement procedures on construction project performance: A conceptual framework. *International Journal of Project Management*, vol. 29, pp. 197–208.

Friedman, H., Claridge, D., Choinière, D. & Toole, C. (2010). *ECBCS annex 47 Commissioning cost benefit and Persistence of Savings*. Canada:International Energy Agency.

Goldstein, D.B. & Eley, C. (2014). A classification of building energy performance indices. *Energy Efficiency*, vol. 7 (2), pp. 353–375, in Springer Science and Business Media.

GSFIC. (2010). *GSFIC Commissioning Guide*. Georgia:Georgia State financing and investment commission.

Gudnason, G., Balaras, C.A., Guruz, R., Dascalaki, E.G., Kontoyiannidis, S., Droutsa, P., Gudnason, G., Droutsa, K.G. & Guruz, R. (2015). Energy and other key performance indicators for Buildings– examples for Hellenic buildings. *Global Journal of Energy Technology Research Updates*, vol. 34 (1), pp. 71–89, in Athens:ResearchGate.

Gultekin, P., Mollaoglu-Korkmaz, S., Riley, D.R. & Leicht, R.M. (2013). Process indicators to track effectiveness of high-performance green building projects. *Journal of Construction Engineering and Management*, vol. 139 (12), p. A4013005, in Virginia:American Society of Civil Engineers (ASCE).

Jeptepkeny, P. (2015). Effects of Procurement Procedures On Project Performance: A Case Study Of Light Construction Projects At Kenya Ports

Authority, Mombasa. *European Journal of Logistics Purchasing and Supply Chain Management*, vol. 3 (1), pp. 1–11, in Kent.

Kantola, M. & Saari, A. (2014). Commissioning for nearly zero-energy building projects. *Construction Innovation*, vol. 14 (3), in ResearchGate.

Kats, G. (2013). *Greening our built world: Costs, benefits, and strategies*. Island Press.

Khullar, R., Agarwal, A. & Kumar, B.R. (2010). Real Estate and Construction Sector in the UAE: Growth Strategies.

Langston, C. (2013). Development of generic key performance indicators for PMBOK® using a 3D project integration model. *Construction Economics and Building*, vol. 13 (4), pp. 78–91.

Light, E., Bailey, J. & Meetre, R. (2015). Controlling Summer Mold Growth in Schools. *ASHRAE Journal*, vol. 57 (12), pp. 52–56.

Lohne, J., Shirkavand, I., Firing, M., Schneider, K. & Lædre, O. (2015). Ethics in commissioning in construction. *Procedia Economics and Finance*, vol. 21, pp. 256–263, in Elsevier.

McFarlane, D. (2013). Technical vs. Process commissioning. *ASHRAE Journal*, vol. 55 (6), pp. 28–34, in Atlanta:ASHRAE.

Mills, E. (2011). Capturing the potential. *ASHRAE*, vol. 3 (6), pp. 1–2.

Monno, V. & Conte, E. (2012). Beyond the building centric approach: A vision for an integrated evaluation of sustainable buildings. *Environmental Impact Assessment Review*, vol. 34 (Complete), in ResearchGate.

NEBB. (2013). *Procedural Standards for Building Enclosure Testing*. Maryland:National Environmental Balancing Bureau.

Nino, F.S. (2016). 'List of parties that signed the Paris Agreement on 22 April'. *Climate change* [online]. [Accessed 30 April 2016]. Available at: http://www.un.org/sustainabledevelopment/blog/2016/04/parisagreementsingatures/

Per, E. & Eriksson. (2009). *Effects of Procurement on Construction Project Performance*.

Raftery, P., Keane, M. & Costa, A. (2009). Calibration of a Detailed Simulation Model to Energy Monitoring System Data: A Methodology and Case Study. *11th IBPSA Conference*. Glasgow. 27 July. International Building Performance Simulation Association:Wisconsin.

Randolph, J.J. (2009). A guide to writing the Dissertation literature review. *Practical Assessment, Research & Evaluation*, vol. 14 (13), pp. 1–13, in Minnesota:Walden University.

Raynham, P., Boyce, P. & Fitzpatrick, J. (2012). *The SLL Code for Lighting*. London:The Society of Light and Lighting.

Schiendorfer, A. & Zimmermann, G. (2012). Fault diagnosis in HVAC systems based on the heat flow model. *Fifth National Conference of IBPSA*. Madison. 1 August. International Building Performance Simulation Association:Wisconsin.

Shi, X. (2011). Implementation of Integrated Commissioning, Retrofits and Control Optimization Process In A Small Commercial Building. August.

Sisinni, M. (2013). *Key performance indicators in UK and Italy*. European Commission.

Smith, A. (2015). Energy Saving Template for Campus. *ASHRAE Journal*, vol. 57 (11), pp. 58–63.

Taleb, M. & Mannsour, N. (2012). A self-controlled energy efficient office lighting system. *Journal of the Association of Arab Universities for Basic and Applied Sciences*, vol. 11 (1), pp. 9–15, in Elsevier.

Toor, S. & Ogunlana, S.O. (2010). Beyond the ‘iron triangle’: Stakeholder perception of key performance indicators (KPIs) for large-scale public sector development projects. *International Journal of Project Management*, vol. 28 (3), pp. 228–236, in ResearchGate.

Turner, S.C. (2012). Commissioning Design/Build Projects. *ASHRAE Journal*, vol. 4 (5).

UPC. (2010a). *The pearl rating system for ESTIDAMA*. Abu Dhabi:Urban Planning Council.

UPC. (2010b). *Abu Dhabi real estate market forecasts*. Abu Dhabi:Abu Dhabi Municipality.

USGBC. (2013). Vol. 4. *LEED reference guide for building design and construction*. 1st edn. Washington:USGBC.

Vogt, G., Robinson, S. & Dashja, E. (2014). KPIs for S.M.A.R.T. Cities. *1st Workshop organised by the EEB Data Models Community ICT for Sustainable Places*. European Union:Nice, France.

Wang, L., Greenberg, S., Fiegel, J., Rubalcava, A., Earni, S., Pang, X., Yin, R., Woodworth, S. & Hernandez-Maldonado, J. (2013). Monitoring-based HVAC commissioning of an existing office building for energy efficiency. *Applied Energy*, vol. 102 (4), pp. 1382–1390, in California:Elsevier.

Ye, K.M. & Rahman, H.A. (2011). *Attentiveness of building commissioning in the Malaysian construction industry*, vol. 5 (8), pp. 968–972, in International Scholarly and Scientific Research & Innovation.

Ágústsson, R.Ö. & Jensen, P.A. (2012). Building commissioning: What can Denmark learn from the U.S. Experience? *Journal of Performance of Constructed Facilities*, vol. 26 (3), pp. 271–278, in American Society of Civil Engineers (ASCE).

Bibliography

Afshari, A. & Friedrich, L. (2016). A proposal to introduce tradable energy savings certificates in the emirate of Abu Dhabi. *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 1342–1351.

Assaf, S. & Nour, M. (2015). Potential of energy and water efficiency improvement in Abu Dhabi's building sector – analysis of Estidama pearl rating system. *Renewable Energy*, vol. 82, pp. 100–107.

Castellano, J., Ribera, A. & Ciurana, J. (2016). Integrated system approach to evaluate social, environmental and economics impacts of buildings for users of housings. *Energy and Buildings*, vol. 123, pp. 106–118.

Harmer, L.C. & Henze, G.P. (2015). Using calibrated energy models for building commissioning and load prediction. *Energy and Buildings*, vol. 92, pp. 204–215.

Jeptepkeny, P. (2015). Effects of Procurement Procedures on Project Performance: A Case Study of Light Construction Projects at Kenya Ports Authority, Mombasa. *European Journal of Logistics Purchasing and Supply Chain Management*, vol. 3 (1), pp. 1–11.

Jiménez, M.J. & Bloem, H. (2015). Energy performance assessment of buildings and building components. Guidelines for data analysis from dynamic experimental campaigns part 1: Physical aspects ☆. *Energy Procedia*, vol. 78, pp. 3306–3311.

Kylili, A., Fokaides, P.A. & Jimenez, P.A.L. (2016). Key performance indicators (KPIs) approach in buildings renovation for the sustainability of the built environment: A review. *Renewable and Sustainable Energy Reviews*, vol. 56, pp. 906–915.

Liu, H. & Lin, B. (2016). Ecological indicators for green building construction. *Ecological Indicators*, vol. 67, pp. 68–77.

Lohne, J., Shirkavand, I., Firing, M., Schneider, K. & Lædre, O. (2015). Ethics in commissioning in construction ☆. *Procedia Economics and Finance*, vol. 21, pp. 256–263.

McDonnell, R.A. (2014). Circulations and transformations of energy and water in Abu Dhabi's hydrosocial cycle. *Geoforum*, vol. 57, pp. 225–233.

Peña, M., Biscarri, F., Guerrero, J.I., Monedero, I. & León, C. (2016). Rule-based system to detect energy efficiency anomalies in smart buildings, a data mining approach. *Expert Systems with Applications*, vol. 56, pp. 242–255.

Ponzini, D. (2011). Large scale development projects and star architecture in the absence of democratic politics: The case of Abu Dhabi, UAE. *Cities*, vol. 28 (3), pp. 251–259.

Shih, H.-C. (2014). A robust occupancy detection and tracking algorithm for the automatic monitoring and commissioning of a building. *Energy and Buildings*, vol. 77, pp. 270–280.

Silva, A.S., Ghisi, E. & Lamberts, R. (2016). Performance evaluation of long-term thermal comfort indices in building simulation according to ASHRAE standard 55. *Building and Environment*, vol. 102, pp. 95–115.

Small, E.P. & Mazrooei, M.A. (2016). Evaluation of construction-specific provisions of sustainable design codes and standards in the United Arab Emirates. *Procedia Engineering*, vol. 145, pp. 1021–1028.

Srinivasan, R.S., Ingwersen, W., Trucco, C., Ries, R. & Campbell, D. (2014). Comparison of energy-based indicators used in life cycle assessment tools for buildings. *Building and Environment*, vol. 79, pp. 138–151.

Tremblay, V. & Zmeureanu, R. (2014). Benchmarking models for the ongoing commissioning of heat recovery process in a central heating and cooling plant. *Energy*, vol. 70, pp. 194–203.

Wang, Y., Almazrooei, S.A., Kapsalyamova, Z., Diabat, A. & Tsai, I.-T. (2016). Utility subsidy reform in Abu Dhabi: A review and a Computable general equilibrium analysis. *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 1352–1362.

Wang, Y., Kuckelkorn, J.M., Zhao, F.-Y., Mu, M. & Li, D. (2016). Evaluation on energy performance in a low-energy building using new energy conservation index based on monitoring measurement system with sensor network. *Energy and Buildings*, vol. 123, pp. 79–91.

Zibin, N., Zmeureanu, R. & Love, J. (2016). Automatic assisted calibration tool for coupling building automation system trend data with commissioning. *Automation in Construction*, vol. 61, pp. 124–133.

Zmeureanu, R. & Vandenbroucke, H. (2015). Use of trend data from BEMS for the ongoing commissioning of HVAC systems. *Energy Procedia*, vol. 78, pp. 2415–2420.