DTU Management
Institut for Planlægning, Innovation og Ledelse

# Building Commissioning

## Advantages and disadvantages of the process and how it has been applied in Denmark

*Master thesis in Civil Engineering at the Department of Management Engineering*
*Technical University of Denmark*
*June 15, 2010*

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**Abstract:**
This thesis goes into what commissioning is, what objectives, requirements and documents have to be fulfilled and made during the building process and then identifies and the advantages and disadvantages of the commissioning process and how the advantages have affected the financial aspect of the building project as well as looking into how commissioning has been applied in Denmark.

**Keywords:**
Building Commissioning, advantages and disadvantages of the process, Cost-effectiveness, commissioning Case study comparison.

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# Abstract

Building commissioning can be defined in a general way as a quality assurance process with the aim to ensure that the building and its system meets the owner's needs and requirements. The reason why the need for commissioning in the building industry originally originated can be linked to the dissatisfaction among owners regarding how the buildings were when they were handed over from the contractor.

The commissioning process is not an additional phase to the building process rather it runs in parallel with the existing phases in the building process. There are numerous objectives and responsibilities that the commissioning team has to fulfil during the commissioning process an example of these responsibilities is the making of several documents that form the base for a successful commissioning process. One of the most important documents is the owner's project requirement where the owner's needs and requirements are stated and a measurable acceptance criterion for each one defined.

There are numerous advantages of commissioning and they are in most cases divided into two categories, energy and non-energy benefits, based on if they have an effect on energy consumption or not. Most of the advantages of commissioning will benefit the owner in added value of the building and the occupants of the building due to improved design of in-door air quality and thermal comfort. But the design professionals and contractors can also benefit from the commissioning process if they work in good co-operation with the commissioning team towards a well designed and constructed building.

The United States are among the leading nations in being successful in implementing commissioning as "business as usual". There have been numerous researches into what the benefits of commissioning are and their financial values. The key findings from the most comprehensive research into benefits of commissioning with a financial aspect showed a median energy savings in existing buildings was 16% and in new constructions 13% while the cost of commissioning was \$3,23 p. $m^2$ for existing buildings and \$12,48 p. $m^2$ for new construction. But when the financial impact of non-energy benefits, were it was possible, were taken into the calculation of cost of commissioning in new construction the cost reduced to \$6,24 p. $m^2$. This same research showed that due to the energy savings alone the median payback time for the commissioning process for existing buildings was around one year and four years in new construction.

Grontmij|Carl Bro has been offering a commissioning service for ten years and during that time they have continuously developed their commissioning process. Their commissioning process has used common commissioning guidelines such as ASHRAE 0-2005 as a reference but due to the type of projects they have participated in and how the Danish market has responded to the commissioning process there are few key details that have not been implemented.

To see if the commissioning process in Denmark was achieving similar results as have been documented in USA a comparison was made on two buildings were the main difference

was that during the building process in one of the building a commissioning process was used. The results of this comparison showed what was expected that the commissioned building had less energy consumption while having similar operational and maintenance cost (where cost of energy is not included). To further implement commissioning in Denmark the author finds the ideal route to be a similar route as was used in USA which is a mix of a forced and un-forced implementation where the use and advantages of commissioning are first showed before laws and regulations are updated.

Building commissioning is on a cross road were the options are weather commissioning becomes “business as usual” or not. But if commissioning becomes “business as usual” the future is bright for owners, occupants of buildings and the environment since it has been showed that properly applied commissioning can add value to the building while using less energy.

# Preface

This report is written as a master thesis in Civil Engineering at the Department of Management Engineering at the Technical University of Denmark.

I would like to thank all the good people that have helped me with my research throughout this thesis. I especially want to thank my supervisor Per Anker Jensen for all his help and guidance when needed, all the good people at Grontmij|Carl Bro for their help and interesting discussions that have shaped parts of this report. Of the good people at Grontmij|Carl Bro I would especially like to thank Ole Teisen that was always willing to explain and discuss issues relating to my thesis and Svend Åge Carlsen for accepting my offer to do my thesis in co-operation with Grontmij|Carl Bro.

The work of this thesis was done over five months and during that time there have been hundreds of hours in literature research, data analysing, writing and experiencing firsthand how commissioning is applied. To finish the thesis on time has taken tremendous self discipline and determination and I would like to thank my family and my girlfriend for the support, encouragement and mental support, to make the journey from the starting line to the end an easier and smoother journey.

Finally I would like to thank my father for all the help and support he has given me with this thesis and throughout my student years.

The work on this thesis corresponds to 30 ECTS credits at the Technical University of Denmark. The work began in February 2010 and finished in June 2010.

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Rúnar Örn Ágústsson
Lyngby, June 15th 2010

# Motivation

When I started thinking about what I would like to write about in my master thesis I quickly realised that I would like to look into how the building process can be improved to limit cost overruns and time delays while at the same time increasing the quality of the building. The main reason why such a topic was the most interesting for me is due to my previous work experience in Iceland. There I have been involved in the project management part of two large building projects and through that I experienced and witnessed numerous problems that caused time delays, change orders and deviation from the original design.

At first I did not know what building commissioning was so it was not until I met Per Anker Jensen, my supervisor, and told him what I was interested in doing a thesis about that then he told me about building commissioning and from there I started doing necessary background reading about building commissioning. After reading numerous articles, research reports and guidelines I realised that building commissioning could be the answer to my general thesis idea.

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# 1 Introduction

Commissioning has been used for many years and is therefore far from being a new term or concept. It has been "business as usual" in offshore projects and in the airline and ship building industries for years. But within the building industry the usage of commissioning has still not reached the point of being perceived as "business as usual", despite the many proven benefits of using commissioning in large projects.

## Problem description:

The problem definition of this thesis is:

What is building commissioning, how can it be applied in the building process and how can it improve the overall building performance? This is further broken down into the following three key points.

- What are the advantages and disadvantages of commissioning and using it in the building process?
- What can commissioning do and cannot do as well as what it is and is not?
- What kind of benefits can be achieved by using commissioning and what affects do the benefits have on the overall building performance and operational costs?

The thesis will therefore examine and explain what building commissioning is and is not as well as what it can do and what not. It will also clearly show how the commissioning process is applied throughout the building process from the pre-design phase and into the operational phase.

The thesis will identify, categorize and evaluate the major advantages and disadvantages of using commissioning throughout the building process as well as investigating and evaluating both energy and non-energy benefits due to commissioning, and how these benefits affect the total project cost and total cost of commissioning. The thesis will also look into how Grontmij|Carl Bro uses the methodology of commissioning in practice and compare that with current guidelines to identify where possible improvements to the process can be found and how they could be implemented.

## Methodology:

The author's methodology to find answer to these questions will be as following:

- Use literature research to gain further knowledge of the commissioning process and to identify relevant case studies and researches for this thesis.
- Examine and evaluate case studies and researches attained through literature research to identify the major advantages and disadvantages that can be linked to commissioning and through interviews with personnel from Grontmij | Carl Bro see what advantages and disadvantages commissioning has in practice.
- Compare two similar buildings projects where the main difference is that commissioning was used in one but not the other. Comparing the results (energy consumption and operational and maintenance costs) to identify/categorize if/how the use of the commissioning process had an effect on the building process, performance of the building systems and the building itself and furthermore what if any the non-energy benefits are.
- Follow an ongoing building project at Grontmij|Carl Bro where commissioning is being applied to gain deeper understanding of how the methodology is used in practice and if there is a difference between the methodology and the practice due to the years of experience Grontmij|Carl Bro has with commissioning.

## Expected results:

Being able to explain how building commissioning runs parallel to the building process. Answer what building commissioning can do and cannot do as well as what it is and is not. Being able to identify major advantages and disadvantages as well as identify and evaluate energy and non-energy benefits and how these benefits affect the total project cost. Show how Grontmij | Carl Bro uses the methodology in practice and compare that with current guidelines and try to come up with ideas for possible improvements in their process

## List of key activities with Grontmij|Carl Bro:

- Attended meetings where commissioning activities were the agenda.
- On site inspection with Ole Teisen at Friis in Aalborg.
- Constant dialogue between author and Ole Teisen regarding commissioning and this thesis.
- Presentation at a Danvak meeting regarding commissioning.
- Meetings with Ole Teisen and Christian Lundstrøm to review the authors analyses of Bryggen and Bruuns Galleri data.
- Interview with Christian Tolstrup about the future and disadvantages of commissioning

# 2 Introduction to Building Commissioning

Before it can be discussed how the commissioning process is and what is done in each building phase it is necessary to know where commissioning comes from and its background. From there will the definition of building commissioning be presented and how the evolution has been for commissioning in America which is among the nations were commissioning is used the most.

Finally before going into the commissioning process and analysis of what commissioning has done for buildings and the building process will the following questions be answered what commissioning can do and cannot do as well as what commissioning is and what it is not.

## *2.1 Background*

The premise that the usual quality assurance processes needed further development was derived mainly from the dissatisfaction of building owners resulting from the fact that their buildings rarely fulfilled their initial requirements or operational needs and the time it took to work out the faults that were overlooked in the building process (Grondzik, 2009). Commissioning is, and has been, a part of the production process in most high technology production industries to ensure a high standard of quality due to the high cost of products being called in to fix failure or flaws created during the assembly period. The general ideology behind the commissioning process has been around for decades and can be traced back to the early years of ship building where ships equipment and systems were tested in a controlled environment to verify they worked as intended before they were taken on actual journeys.

Commissioning, as it is defined today, is not a new term or concept. It can be said to have developed with the increasing project complexity. Commissioning has been used for decades in ship building industries (Wikimedia Foundation, 2010) . One of the reasons it may have been easier to sell the idea that commissioning should be an essential part of the ship building process is due to the high risk of life lost if systems or equipment fail. Therefore it is extremely important that no flaw is overlooked and the cost of commissioning is therefore quite small compared to the cost if a flaw is discovered in a production after it has been produced and complete productions have to be recalled.

When a ship has been commissioned it is declared ready for usage. Before that can be done it has to pass several commissioning milestones. Installed systems and equipment are tested, problems are identified and corrected and the crew of the ship is thoroughly

trained to be able to maintain and use the ship. So if a ship passes a commissioning process it has been ensured that the equipment, systems and personal have successfully completed a thorough quality assurance process and the ship is ready to be used (California Commissioning Collaborative, 2006).

The building commissioning takes the same approach on new buildings as done on ships. It begins in the pre-design phase and goes through design, construction and occupancy and an operation phase and ensures through intensive quality assurance processes that requirements and needs defined by the owner are met.

The building process today is not a continuous process. As a result numerous problems can arise during and between the design, construction or occupancy and operations phase. These can for example be linked to a flaw in the design, lack of communication or unclear responsibilities. These flaws are clearly visible in high numbers of request for information, change orders or in problems reported by the occupants of the building after handover. All these examples are contributory causes of cost overruns, time delays and owners project requirement (OPR) not being completely fulfilled. Because the OPR is not fulfilled the performance of the building is often not maximized and greater energy costs due to lack of efficiency and flaws in building design are experienced. This in the end decreases the value of the building and reduces the cost effectiveness of the project for the owner.

In today's building industries it has become common that building projects experience high number of request for information and change orders throughout the construction phase which can be linked to the increasing complexity of buildings and while buildings are getting more complex the design professionals and contractors are not keeping up in design and constructing the buildings without added cost and time delays. The main reasons for why buildings are getting more complex are:

- Increased requirements on energy efficiency.
- Increased requirements on secure employee surroundings.
- Increased requirements on indoor air-quality and comfort control.
- Technology developments of office and IT equipment.
- Increasing variations of operational needs for buildings.

These points each on its own do increase the complexity but combined they even further increase it because of how they contradict each other for example with the increased usage of computers and other electrical equipment in offices contributes to heating up the office space which forces the ventilation system to supply more cooling which uses more energy and therefore has the system to be more efficient to fulfill the energy requirements.

Building management software's help to solve some of these points but the software's also add complexity which can be overcome with proper training of the operations and maintenance (O&M) personnel. Because buildings are getting more complex it is necessary for owners of the buildings to take action to ensure their requirements and needs for their buildings are met and the trend has been to use building commissioning to help them achieve their "ideal" buildings.

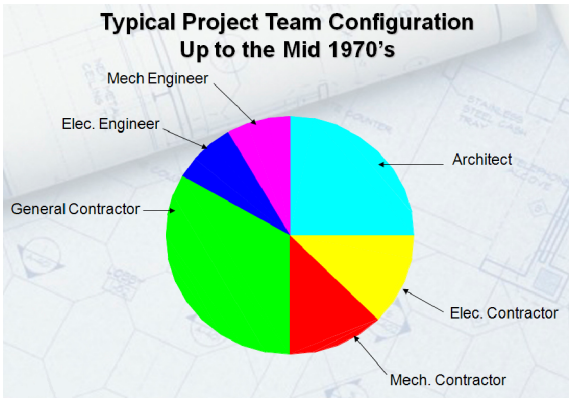


**Figure1: Shows a typical project team configuration up to the mid 1970's (Building Commissioning Association, 2010).**

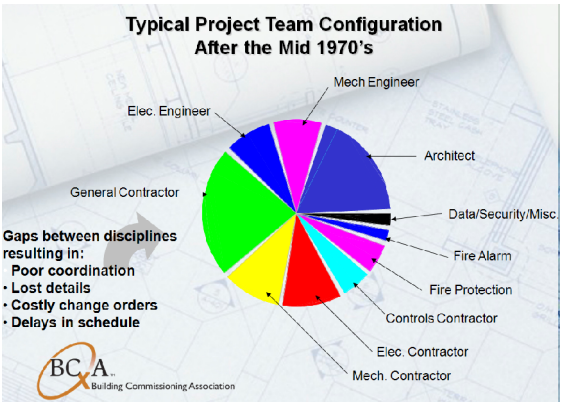


**Figure 2: Shows a typical project team configuration after the mid 1970's (Building Commissioning Association, 2010).**

Before and up to the mid 1970's the project team consisted of only 6 different parties and buildings were not as complex as today, mostly because the emphasizes on performance level and energy efficiency were not as high. After the mid 1970's the number of parties involved in the project team configuration were increased to 10 because the complexity and requirements for buildings increased partly due to the energy crisis. The results from the increase of project team size and complexity resulted in poor coordination between project team members, lost details due to poor coordination and increased complexity and size of projects, costly change orders and delays of projects schedule (Building Commissioning Association, 2010).

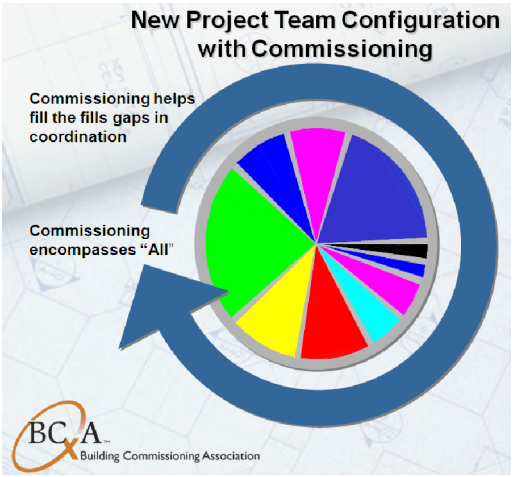


**Figure 3: Shows how commissioning can bridge the gap between project team members (Building Commissioning Association, 2010).**

One of the reason why commissioning has been gaining momentum in the building industry is that owners have started to realize how building commissioning can bridge the gap between the project team members by encouraging increased communication, documentation and co-operation. This with other commissioning activities results in a smooth start-up, health and safety requirements being met and less energy consumption (Building Commissioning Association, 2010).

The commissioning process is not a constant workload throughout the projects lifetime. A typical commissioning process activity graph can be seen in figure 4 which shows the number of commissioning activities for the shopping mall Bryggen in Denmark. As can be seen from the graph, the commissioning activities increase with the projects development and peaks at the end of construction phase. The graph does not show commissioning activities into the operation and maintenance phase but the peak level is maintained into the occupancy and operations phase and after that starts' decreasing until it reaches minimum number of commissioning activities to maintain continuous commissioning. It can though be expected that with time and increased experience that the commissioning activity graph will be smoother with less sudden increase in activities.

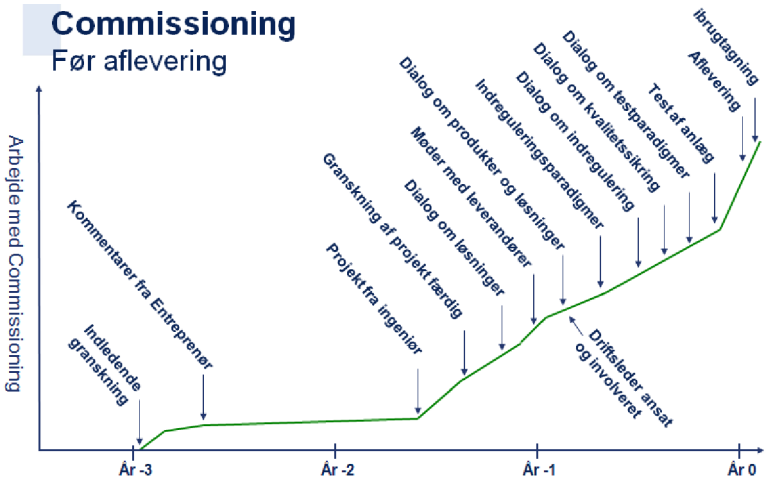


**Figure 4: Shows how the number of commissioning activities increases with projects development and peak at handover from contractor to owner (Grontmij|Carl Bro, 2010).**

To achieve the potential optimum benefits of commissioning it is important that commissioning begins in the pre-design phase. This is however not very common in today's building industry and therefore the projects that are using commissioning only experience a part of the potential benefits that commissioning has to offer, if applied to the whole building process.

If commissioning starts late in the design phase or in the construction phase some of the commissioning activities that should have been finished earlier in the building process have to be done when the commissioning team begins their work (ASHRAE, 2005). This results in that the commissioning team is playing catch up in the beginning of the commissioning process and therefore not able to identify possible errors or flaws that are not in accordance with the OPR.

When the commissioning process is included late in the building process it is often too late to make changes or it is too expensive and therefore needs the OPR to be changed to reflect the changes made to the project (ASHRAE, 2005). With such working methods the owner is not getting the building initially described in the OPR while he is paying the same or even higher price.

If commissioning is properly developed and applied throughout the building project it is the optimum quality assurance program for all phases. Why? Because instead of assuming that systems and equipment work as intended, building commissioning looks into key

design decisions, systems, equipment and operations and scrutinises them to verify that they meet the owner's needs and expectations (Heinz & Casault, APPA, 203).

## *2.2 Definition*

As always with a definition of a concept there are numerous different definitions. However most of them carry a quite similar message. In general most of these definitions refer to commissioning as a process that ensures that buildings systems performance meets the intended requirements and needs defined by the owner.

The definition presented at the summary report from the 1993 National Conference on Building Commissioning is a good example of what the definition of building commissioning is:

> *"Commissioning is a systematic process of assuring that building performs in accordance with the design intent and the owners operations needs."*

The commissioning process is defined in more detail in the ASHRAE Guideline 0-2005 and there the definition is:

> *"A quality focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that the facility and all of its systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet the Owner's Project Requirements."*

Although the definitions have it in common to state that commissioning ensures that building performance is in accordance with the design intent and the owners operations need, it should be stated that no quality assurance process, including commissioning, is that good that it does not oversee any mistakes or problems. Time has proved that most of the quality assurance processes used in today's building industry discovers most of the problems at last but the timing is often as bad as it gets, and often it is too late to correct the problems and/or the solutions are too expensive and therefore changes are made to work around the problems. By doing that the owner will not be able to achieve his requirements and operational needs for the building.

One of the things that commissioning has over other quality assurance processes is that it forces discoveries of mistakes and problems to be revealed as early as possible, under controlled conditions and at time when massive consequences are least likely to occur.

## *2.3 Evolution of building commissioning in America*

Commissioning is closest to becoming "business as usual" in America and therefore will this chapter look into how the evolution has been and what were the key decisions in implementing commissioning.

As stated earlier that commissioning is not a new concept and neither is building commissioning. Many of the components that make building commissioning of what it is today have been around and used for some time all over the world.

In the late 1960's and early 1970's were environmental consciousness movements beginning their lobbyism to try to change public's attitudes regarding energy consumption and the idea got more momentum with the energy crisis in the 1970's. The answer to this change of public's attitude towards energy consumption was answered with action to reduce energy consumption by increasing the efficiency of lighting and heating/air conditioning. So at this time the focus of the commissioning process was mainly on conservation of energy. When the awareness as to what the effect of the pollution of non-sustainable energy resources had on the climate, the focus of commissioning widened from conservation of energy to include operational and management focus and increase the energy savings through increased efficiency. Most of the complaints from occupants of buildings at this time were related to poor performance of HVAC systems in the building which still today plays an important role to sustain a good indoor air quality (National Energy Management Institute, 2001). Because of this was the initial focus of commissioning

1977:
- Public works Canada begins to use commissioning in its project delivery system

1981:
- Disney includes commissioning in the design construction and start up of Expo Center

1984:
- University of Wisconsin begins to offer commissioning courses
- ASHRAE HVAC commission guideline committee formed

1988:
- ASHRAE publishes HVAC commissioning guide

1989:
- Montgomery County, Maryland institutes commissioning program

1991:
- Electric utilities begin to require commissioning on energy installation

1993:
- NEBB develops commissioning providers certification program
- 1st NCBC hosted by SMUD, held annually from this point.

1994:
- LADWP launches commissioning program
- Executive order 12902 requires a commissioning program for federal buildings.
- ASHRAE commissioning seried offered via proffessinal Development seminars
- ACEEE summer study devotes a full panel of presentations to commissioning and O and M
- LBNL focus on building performance assurance through metrics, commissioning operations

1995:
- US EOPA and DOE conduct commissioning demonstrations of 5 existing buildings
- State of Washington requires commissioning

1996:
- ASHRAE publishes guideline 1-1996: The HVAC commissioning process
- International Measurements and verification (NREL) protocols recommends commissioning in all projects
- US DOE/FEMP conducts commissioning workshop for federal agency project managers
- US GSA/FEMP conduct existing building demonstration in Seattle, WA

mainly on HVAC systems to respond to occupant's complaints and increased requirements for increased efficiency of building systems. Due to the main focus being on HVAC systems it was natural that the first guideline on commissioning was a HVAC commissioning guide that was published 1988 by ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers).

After that was a fast development where Montgomery County in Maryland took the initiative and instituted a commissioning program in 1989. Only two years after that the electric utility companies started to require commissioning process on energy installations.

The first certification program of the commissioning process was established in 1993 by the National Environmental Building Bureau (NEBB) and the same year was the first time when the National Conference on Building Commissioning was held and due to its success it was decided it should be an annual event.

1994 is one of the most important years in the evolution of building commissioning in the America and building commissioning development gained more momentum, more acceptance and awareness of its potential benefits. The reason for this is the executive order no 12902 that was approved and signed by the president of the United States of America which declared that all federal buildings were required to utilise a commissioning program. Due to this executive order seminars and presentations were held to introduce further what commissioning is and what benefit's it can have for operational and maintenance part of a

1997:
- Sprint commissioning world headquarters in Kansas
- Commissioning articles begin to be published in trade press regularly
- NEEA conducts commissioning base line and market research study

1998:
- US DOE sponsors national strategy for Building commissioning
- BCA incorporated as a not-for-profit trade association
- USGBC LEED includes commissioning

1999:
- State of Tennessee begins new construction commissioning initiative
- Benner award were fist presented (annually)

2000:
- BCA develops technical training
- Xcel Energy launches retro commissioning program for customers in Colorado and Minnesota

2001:
- CERL produces commissioning-pedia CD-Rom
- First international conference on enhanced building operation held in Austin Texas
- PIER project investigades persistance of commissioning

2003:
- CCC develops outline library of commissioning related research, articles, brochures and guidelines

2004:
- Commissioning included in a executive order by the California governor
- CCC incorperated as a non-profit organization
- BCA launches certification program
- LBNL releases the cost effectiveness of commissioning a national study of commissioning and benefits

2005:
- ASHRAE publishes Guideline 0:2005 The commissioning process
- California energy efficiency standards include acceptance testing requirements for non-residential new construction
- NEMI publishes a national study of market potentials for new building commissioning

2007:
- N-Caroline includes commissioning in a bill to increase energy efficiency in state buildings.

building. The same year the Los Angeles Department of Water and Power (LADWP) lunched its commissioning program and the state of Washington a year later began to require commissioning programs in specific building projects.

2008:
- BCA membership increases more that 30%
- USGBC increases points available for commissioning in LEED-EB
- **Source:** (Portland Energy Conservation, Inc, 2010)

Over the years 1995 and 1996 the government of USA conducted commissioning demonstrations on existing buildings as well as hosting a commissioning workshop for federal project managers.

In the year 1997 articles on commissioning first begin to be published on a regular basis in trade press. The reason why at this time articles on commissioning process started to be published on a regular basis, may be due to the executive order and from the commissioning demonstrations conducted by the US government to showcase how and what the benefits are that can be achieved with building commissioning.

In 1998 the US department of energy (DoE) sponsored the process to develop a national strategy for building commissioning and the same year a large step for building commissioning was achieved when the USGBC[1] includes commissioning in the LEED[2] certification process.

From 1999 and to 2004 was the main progress period for building commissioning in the form of publication of documents to help and guide newcomers within the building commissioning. How to apply it on different projects, see what has to be done to maintain the benefits achieved with commissioning and organizations were starting library for building commissioning related research, articles, brochures and guidelines. In 1999 was the first time the Benner award was awarded. The Benner award is awarded to a person or organization that has showed outstanding achievement in making building commissioning business as usual (Portland Energy Conservation, Inc, 2008).

In 2005 ASHRAE publishes the commissioning process 0-2005 guideline. Still today the 0-2005 guideline is used as a foundation for most guidelines that countries or states have developed and are following.

From 2006 and onwards the key evolvement has been in actions where commissioning is required to increase energy efficiency (Portland Energy Conservation, Inc, 2010).

When looking over how the evolvement has been the last 33 years in the US it can be said that building commissioning did not in a natural way get to be included in the building process. In fact through executive orders, energy efficiency standards and bills the building commissioning has been made a requirement in specific building types. Due to

[1] United States Green Building Council
[2] Leadership in Energy and Environmental Design

the forced usage of building commissioning the acceptance and awareness of its benefits have been accomplished and therefore has building commissioning been used more and more in projects where it is not required by executive orders, standards or bills. But like the US has shown it is not enough to pass the executive orders, standards and bills to get the benefits of building commissioning. It is also important to show and educate how building commissioning should be used, to be able to achieve the potential benefits. A deeper look into what an effect building commissioning has had on building in the USA will be discussed in chapters 4 and 5.

## *2.4 What building commissioning is and is not?*

Like stated in chapter 2.2 building commissioning can be described in general as a process that ensures that building systems performance meets the intended requirements and needs defined by the owner, with increased communication and verification process, that optimally begins as early as possible in the building process and are continuous throughout building occupancy phase. But such a description is quite a general description but to the core it summarizes what building commissioning is. Below are points that further describe what building commissioning is. The lists below are not exhaustive rather points that most commissioning process have in common. Below is a list of what building commissioning is (Grondzik, 2009) (California Commissioning Collaborative, 2006) (Heinz & Casault, The building commissioning handbook, second edition, 2004):

- Enforce co-operation between participants of the building process.
- Encourages and documents communications between owner, designers, contractor and operation and maintenance personnel.
- Document all problems/errors that contradict the owner's project requirements (OPR) and their solutions in a structural way.
- Systematic quality assurance process which through tests and verification ensures the building meets the OPR.
- Ensures that operation and maintenance personnel are provided with needed training to be able to maintain the building at owner's intended performance level.
- A process that focuses on outcome first then what equipment is used to achieve the outcome.

Below is a list of what building commissioning is not (Grondzik, 2009) (California Commissioning Collaborative, 2006):

- Not a replacement for the existing quality inspection process, it is an addition to that process.
- Not an additional phase to the existing pre-design, design, construct and occupancy and operations phases, it runs parallel with the building process.
- Not an isolated testing event of single equipment.
- Not a testing, adjusting and balancing tool.

Some of these points that are listed as what commissioning is not are included in the building commissioning process but the reason why they are listed as what building commissioning is not is that building commissioning is not just one of these points.

## *2.5 What building commissioning can and cannot do?*

Before going into what building commissioning can and cannot do it is necessary to assume that the commissioning process begins during pre-design phase and runs parallel with the building process and throughout the buildings life span. The reason why such an assumption is necessary is because the full potentials of building commissioning can only be achieved by using it from the pre-design phase and throughout the building life span.

By proper application of building commissioning the following points can be achieved (Grondzik, 2009) (California Commissioning Collaborative, 2006) (U.S. General Services Administration, 2005) (Heinz & Casault, The building commissioning handbook, second edition, 2004):

- Owner's needs and expectations are identified, clearly documented and an acceptance criterion for each need and requirement is defined in a measurable way in a complete OPR.
- Review the design solution and verify that it fulfils the OPR.
- Improved building occupant productivity through improved in-door air quality and thermal comfort.
- Reduced change orders due to poor communication or insufficient design documents.
- Lower O&M costs due to improved equipment life and lowered utility bills through energy savings.
- Through testing it is verified that systems, assemblies and equipment work as described in OPR and test results and procedures are documented so they can be reviewed later to look for possible improvements or to redo tests and see if performance level has changed.
- Operation and maintenance personnel are provided with needed training to be able to maintain the building performance level.
- Because of regular documentation that is summarised in a final commissioning report all key information regarding the project and building are available.

Above is what can be expected to be achieved through proper application of building commissioning. What building commissioning cannot do can be seen below but it should be stated that some of the points can be avoided if building commissioning is introduced early enough in the project.

The following is what commissioning cannot do but as with other lists it is not exhaustive (Grondzik, 2009):

- Be able to make project fulfil poorly defined and/or unrealistic project's expectations.
- Make up for insufficient and/or unrealistic project budget.
- Design and/or be responsible for a design of a building or systems.
- Be expected to be able to repair major errors with systems or assemblies without high costs.
- Operate and/or maintain a building.
- Correct problems that occurred early in the building process by involving commissioning process at the last minute of construction phase.

# 3 The Commissioning Process

The objective of this chapter is to explain what objectives and requirements the commissioning team has during the building process and what the key documents are and their purpose. To do so the chapter will be divided into four sub chapters for each building process phase. It is necessary to know the key information about how the commissioning process is, what documents are made and what information should be included in them before further discussion of what results commissioning has had and can have.

An overview of the four typical building process phases and the commissioning process activities for the commissioning team in each phase can be seen in figure 5.

Before going into each phase there are few terms that have to be defined to increase the understanding of the following sections (ASHRAE, 2005).

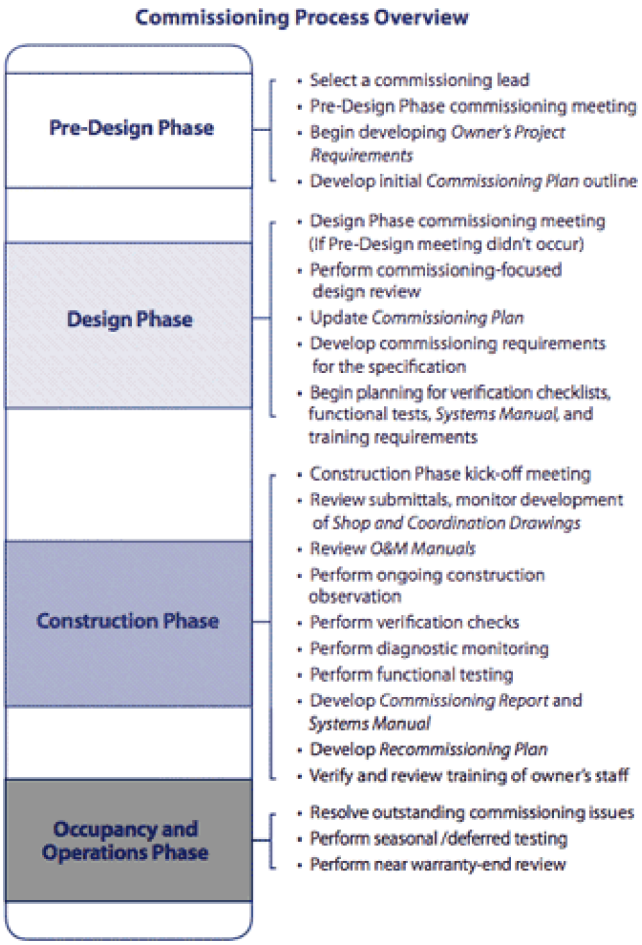


**Figure 5: Shows an overview for the most significant commissioning activities that are done in each phase (Berkeley Lab, 2010).**

### *Design professional*

The design professionals are the architects and the engineers responsible for the design and making the construction documents.

### *Design team*

All the design professionals that participate in the design of a project form the design team.

### *Commissioning Authority (CxA)*

That is the person, company or agency that leads, plans, schedules and coordinates the commissioning team to implement the commissioning process. The CxA reports directly to the owner or the owner's representative and is responsible for the commissioning process and for the review and approval of all commissioning activities.

### *Commissioning team*

All the professionals that participate and through coordinated actions are responsible for implementing the commissioning process whether they are employees of the commissioning provider or other professionals that are brought in because of their expert knowledge on particular issue form the commissioning team.

The information in this chapter is drawn from the following references:


- ASHRAE. (2005). *ASHRAE Guideline 0-2005.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc
- Grondzik, W. T. (2009). *Principles of Building Commissioning.* New Jersay: John Wiley & Sons, Inc
- Heinz, J. A., & Casault, R. B. (2004). *The building commissioning handbook, second edition.* Washington: Building Commissioning Association and APPA
- California Commissioning Collaborative. (2006). California Commissioning Guide: New Building. California, United States of America
- U.S. General Services Administration. (2005). *The Building Commissioning Guide.* U.S. General Services Administration

## 3.1 Communication lines in a building process

The commissioning authority handles all of the communication for the commissioning team to the owner unless he has deligated some of the direct communication to fellow members of the commissioning team. Figure 6 shows a simplified version of a communication structure for a project that choose to use the tendering method design and build. If the owner would choose to use a commissioning process as the quality assurance process for such a project figure 7 shows where the commissioning authority would come into the communication tree.

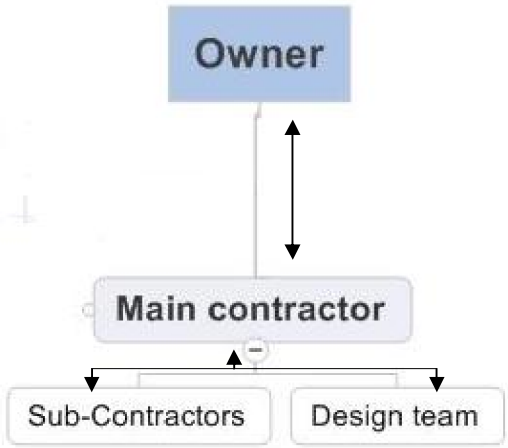


**Figure 6: Shows the communication lines in a typical design and build project.**

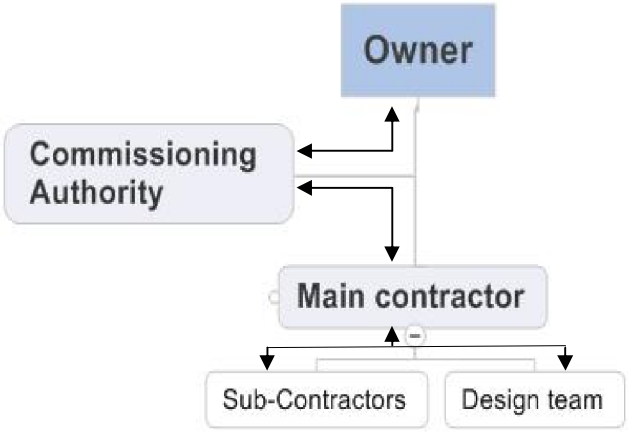


**Figure 7: Shows communication lines in a typical design and build project where commissioning is used.**

The commissioning process comes into the communication line to the owner and reviews all relevent documents and information before it is brought to the owner. But regardless of choosen tendering procedure the commissioning authority and the commissioning team do always connect with the normal communication structure like shown in figure 7.

## 3.2 Pre-design phase

The pre-design phase in the typical building process can vary in how detailed the work done in the phase is due to how much funds are available. However it is important to invest in a good and well developed OPR due to it is the foundation for all decisions made in design and construction phases. During the pre-design phase, studies are done to analyze space requirement issues, the constraints and opportunities of the proposed site, and the cost analysis to determine a budget. Like stated earlier the amount of funding available in the pre-design phase varies and therefore is it critical to determine which studies have a higher priority. Funds should though always be able to cover the development of a complete OPR and if that has been secured then investment in investigation of certain technical issues in order to determine scope, budget, or project schedule in more detail can be made (University of California, 2010).

In the following sub chapters the responsibilities and objectives that the commissioning team has during the pre-design phase and three key documents that are created during the pre-design phase will be explained.

### 3.2.1 Responsibilities and objectives of the commissioning team

The main objectives of the commissioning team during the pre-design phase are developing and completing the OPR, as well as developing the commissioning plan for the project (ASHRAE, 2005). Although there are other objectives that the commissioning team has during this phase they however do not have as much affect on later phases and the project in whole as these two.

The main responsibilities for the commissioning team during the pre-design phase are (ASHRAE, 2005):

- Develop, document and complete the OPR,
- Develop the scope and budget for the commissioning process, if possible assign budget between commissioning activities.
- Ensure that all requirements of commissioning work are stated in contracts.
- Ensure that commissioning schedule fits and runs parallel with the project schedule and major commissioning milestones are included in the project schedule.
- Make and update the commissioning plan and issue log throughout the project.

As well as with the objectives there are other responsibilities that the commissioning team has but the one mentioned above are essential for effective and successful commissioning process. Additional objectives and responsibilities of the commissioning team can be seen in ASHREA guideline 0-2005.

The objectives and the responsibilities that the commissioning team has in each building process phase are often closely related. The difference between the two categorise can be seen as the objective shows the main goals for the commissioning team while the responsibilities show what has to be done to achieve the main goals and therefore defined in more detail.

### 3.2.2 Determining the scope and budget for the commissioning process

As stated in chapter 3.2.1 two of the responsibilities for the commissioning team are to identify the scope and budget for the commissioning process. The goal of identifying the scope of the commissioning process is to find out which parts of the project will be commissioned and in what way to be able to make the commissioning schedule for the commissioning plan.

The most effective way to determine the scope is to do a risk analysis of the project were systems and assemblies are analyzed with respects to possible errors and their likelihood to decrease energy efficiency, increase operation costs, construction cost over runs and/or time delays. Along with such a risk analysis the owners should be asked where he has in previous projects experienced the most fatal errors that resulted in decrease energy efficiency, increase operation costs, construction cost over runs and/or time delays. The interview should be compared to the risk analysis to see if there are common items that

have a high risk profile but the interview should rarely outweigh the risk analysis but should also not be overlooked.

When a main systems and/or assemblies have been chosen to be commissioned with respect to the risk analysis and the interview a greater identification into what within the system and assembly concerned will be commissioned and what will be the key items to look into. In the pre-design phase the system and assembly has not been designed so therefore it is not possible to go in great detail in specific equipment and systems but what will be commissioned, how it will be commissioned and what to look out for is recommended as initial plan.

The main focus of the commissioning process should be the outcome instead of focusing simply on commissioning of equipment and assemblies. The reason for that is the owner is not concerned of the type of systems or equipment used if it fulfils the OPR and consideration is made to the whole life cycle cost.

The commissioning process budget can be made after the scope for the commissioning process has been decided. It is important that the budget is realistic, as accurate as possible and documented how it is allocated between commissioning activities. By fulfilling these three requirements the owner can know an estimated cost and trust that the budget will unlikely exceed initial budget so he can put aside funds to cover the cost for commissioning process. It is as well as important that the owner does not dip into marked funds for the commissioning process to cover cost over runs in other parts of the projects.

### *3.2.3 Issue log*

The issue log is a document where all problems that the commissioning team identifies are documented and when they have been solved their solution is as well documented. The problems that are documented in the issue log do all have in common that they contradict the OPR in some way.

It is common that the issue log and a punch list, which is already used in the normal building process, are compared and some find them serving the same purpose. However these two documents should not be confused since they serve two very different purposes. Punch list verifies that equipment has been delivered unharmed and installed correctly but the issue log documents findings that affect the way equipment operates and systems interact. On top of having different purposes they are as well developed differently since the punch list is usually made during walk-though which usually occurs close to the end of construction phase while the issue log is developed throughout the commissioning process.

The issue log is one of the key documents of the commissioning process due to how it can decreases the risk of problems being forgotten and therefore unsolved which can lead to performance levels and OPR not being fulfilled.

### 3.2.4 Owner's project requirements (OPR)

The owner's project requirement (OPR) is made by the owner or a person appointed by the owner and often in co-operation with specialists that capture and document the needs and expectations for a proposed building. The OPR should include all requirements that the owner expects the building to fulfil physically and functionally and it should state clearly what the performance level and acceptance criteria for each system and assembly is. Due to how specific the OPR should be it is a critical first step for the commissioning process that the OPR is carefully thought out and has been reviewed by specialists in related fields to make sure it is well developed and completed.

One of the reasons why such emphasises should be put on the OPR is all decisions have to be in accordance with the OPR. However it is important that the OPR does not make suggestions to design methods or solutions it only has the purpose of setting the requirements in terms of quality and quantity that the design of a system or assembly has to fulfil.

In most countries there is already a document similar to OPR called "building program". It is made during the pre-design phase and has similar purpose as the OPR that is set to document all requirements that the owner expects from the building. However those documents only touch upon the surface of what the OPR goes into and in most cases do not go in great detail what performance level and acceptance criteria the owner has to each system or assembly and often make suggestions to what design methods or solutions should be used. By doing so the document limits the possible design solutions and can prevent usage of new technology.

Because of how little information the building program contains regarding quantity and quality it is to indecisive and incomplete to serve as a useful reference document for the commissioning process.

An optimal OPR will contain all of the information in a form that can be handed to the design team, commissioning team and the main contractor (the OPR is only for informational purpose for the contractor since he is not bound by contract to fulfil the OPR only the design documents) with limited explanation needed to understand the requirements and needs the owner has to the building.

The detail level of the OPR can vary and often it is related to the size and complexity of the project. However each OPR should include at minimum the expectation and requirements the owners has for the building and for each item listed in the OPR the performance level and acceptance criteria should be defined in a measurable way.

### 3.2.5 Commissioning plan

The commissioning plan is a document that outlines and defines the commissioning process over the building process for a specific project. It serves as a guideline for commissioning team members because the process that will be undertaken, the schedule

for activities, the roles and responsibilities of commissioning team members and commissioning budget are documented in the commissioning plan.

The commissioning plan is not completed in the pre-design phase instead it is constantly being updated as the project progresses and goes between phases. The most emphasises is mainly on the commissioning activities that will be carried out in the next phase, who is responsible for each part, when and how they will be performed. The commissioning plan is updated in each phase with respect to these emphasises. The owner or owner's representative is expected to review the commissioning plan at certain milestones such as between project phases.

The commissioning authority is responsible for making the format for the commissioning plan and that the plan is up to date. It is however made by the commissioning team in co-operation with appropriate design specialists and contractors.

## *3.3 Design phase*

In the following sub chapters the responsibilities and objectives that the commissioning team has during the design phase, the key documents that are created during the design phase, Basis of Design (BoD) and Construction documents, and how the commissioning plan is updated will be explained. Figure 8 shows the main commissioning activities that are performed during the design phase by the commissioning team.

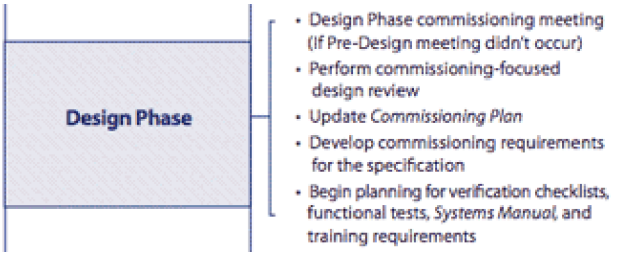


**Figure 8: Shows the main commissioning activities to be performed by the commissioning team during design phase (Berkeley Lab, 2010).**

The difference between the normal design phase and a design phase with commissioning is not that much. The main difference is between these two types of design phases is throughout the design phase with commissioning the design is regularly reviewed by the commissioning team and compared with the OPR and the design team has the OPR which defines the requirements and needs in a more structural and clearer way then the usual building program.

### *3.3.1 Responsibilities and objectives of the commissioning team*

The main goal for the commissioning team during the design phase can be described in a very general way as ensuring that the construction documents are according to and meet all requirements regarding listed in the OPR.

To achieve that goal there are several objectives that the commissioning team has to fulfil during the design phase. Those objectives are (ASHRAE, 2005):

- Review the construction documents to ensure that they are according to the OPR.
- Verify that the basis of design is according to the OPR.

- Update the commissioning plan to include construction phase commissioning activities and outlines for operation and maintenance phases commissioning process activities.
- Develop a construction checklist in co-operation with relevant designer.
- Update the scope of the system manual.
- Defining how training of operation and maintenance personnel will be performed and what requirements are regarding material provided and how it will be verified.
- Ensure that all requirements regarding commissioning works done by other then the commissioning team are included in their contracts.

The main responsibilities of the commissioning team during the design phase are (ASHRAE, 2005):

- Ensure that construction documents and basis of design are according to OPR.
- Ensure that commissioning works are clearly stated in all relevant contracts.
- Further develop the scope and budget for the commissioning process so scope and budget for each commissioning activities is defined.
- Update the commissioning plan to include who is responsible for the commissioning activities of a specific system and assembly.
- Assure that the commissioning schedule and the project schedule can run parallel and integrate the major milestone of the commissioning process into the project schedule.
- Continue updating the Issue log of problems that contradict the OPR.
- Develop training requirements for operation and maintenance personal.
- Update the OPR if requirements that are defined in it can no longer be meet and notify all relevant personal of the changes made to the OPR.
- Ensure that the construction checklist is developed.
- Further develop the test requirements for systems and assemblies to be performed during the construction and operation and maintenance phase.

The lists above are not exhaustive and only list the key objectives and responsibilities of the commissioning team. Additional objectives and responsibilities of the commissioning team can be seen in ASHREA guideline 0-2005.

### *3.3.2 Basis of Design*

The basis of design (BoD) is a document made by the design team and the head designer is responsible for the document. The basis of design is made with the purpose of capturing the thought and reasons behind the design that makes the construction document. The basis of design should include all key assumptions made during the design phase, calculations and methods, products selected to meet the OPR and a description of the system and how it should work. The basis of design will be used by most of the parties that work with the construction document to get a deeper understanding of the building systems. Therefore it is important that it is setup up in a structural way with the thought of a wide variety of eyes viewing the document.

The basis of design is set out to bridge the gap between the OPR and the construction documents. As the main purpose with the construction documents is to illustrate what the contractor should do but the reason why it should be done like that is seldom readable from the construction documents and that is where the basis of design comes in.

For the commissioning team to be able to ensure that the construction documents meet the OPR and are according to current regulations, standards and guidelines the basis of design plays an important role. Some might see the basis of design as a document to put the blame on the designer if something goes wrong but that is in fact not the purpose with this document. Instead the goal is to give the designers a chance to explain and justify why the design is as it is in a document. By doing so the commissioning team can use the basis of design to see what thoughts and assumptions the designers have behind the construction document instead of being forced to constantly ask the designers to explain their design or assume designers were aware of a particular high risk issues.

The basis of design can also become quite valuable for the design engineer if there have to be made changes to the building because then he can know the details behind the design instead of being forced to make assumptions.

### *3.3.3 Construction documents*

Construction documents can be defined as a document that includes all the building plans, drawings, specification, supporting documents and contracts used during the completion of a construction project. These documents serve several purposes. They help translate the needs and requirements specified in the OPR into a buildable format that can be understood throughout the construction industry. They allow the owner to put the project out for bid, obtain permits from local authorities and a key purpose is it provides a comprehensive instructions to the contractor as to how the project should be constructed.

It is quite important that all commissioning work that has to be done by the contractors is identified and clearly stated in their relevant contract. The reason for this is to avoid possible change orders due to the contractor claiming he was not aware of a commissioning activity that he is supposed to execute.

It is as important to include what the performance level and acceptance criteria of systems and assemblies are and how tests will be conducted. In the construction documents it should be clearly stated for each system and assembly who is responsible for doing the test procedures. The contractor or the commissioning team can either be responsible for doing the testing procedures. It should also be clearly defined how each test for each system and assembly should be done and how. Test and system verification procedures will be explained in more detail in section 3.4.2.

If the contractors that are going to bid for the project are unfamiliar or have little experience with commissioning it is recommended to invite the contractors to a pre-bid meeting and introduce them to how commissioning runs parallel to the building process

and what is expected from them as well as handout examples and guidelines of how all documents and commissioning work is expected to be done. By holding such a meeting and handing out examples and guidelines the possibilities of misunderstanding and change orders after contracts have been signed are limited.

### *3.3.4 Updating the Commissioning plan*

The commissioning plan is further developed during the design phase with the main focus on the construction phase. Commissioning activities that will be performed during the construction phase are developed and a schedule that shows when each activity will be performed is made. The commissioning plan is updated to include additional information developed during the design phase. The main items that will be added to the commissioning plan are:

- What systems and assemblies will be verified and tested.
- Commissioning schedule for the construction phase and an outline for occupancy and operations phase.
- Roles and responsibilities of existing and new commissioning team members.
- Communication protocols during the construction and occupancy and operations phase are updated.

On top of developing a complete commissioning schedule for the construction phase the initial draft of commissioning activities to be performed during the operation and maintenance phase are outlined.

## *3.4 Construction phase*

In the following sub chapters the responsibilities and objectives that the commissioning team has during the construction phase, how equipment and system verification should be performed, how and why training of operational and maintenance staff is important, the system manual and how the commissioning plan is updated will be explained. Figure 9 shows the main commissioning activities performed during the construction phase by the commissioning team.

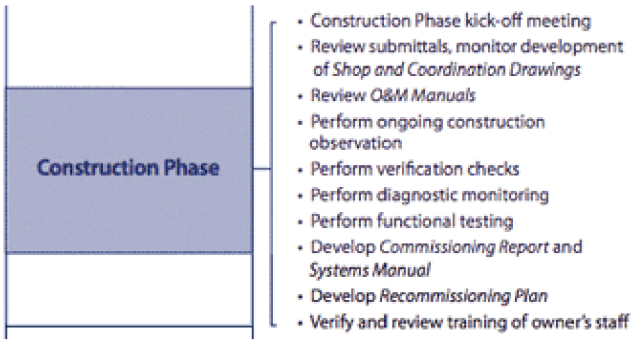


**Figure 9: Shows the main commissioning activities to be performed by the commissioning team during the construction phase (Berkeley Lab, 2010).**

Like stated in chapter 2.1 and showed in figure 4 the number of activities done by the commissioning team peaks during the construction phase due to most of the system and equipment testing and verification will be performed during the construction phase on top of most documents made by the commissioning team have to be finished before the

building is handed over to the owner from the contractor and the occupancy and operations phase begins.

### 3.4.1 Responsibilities and objectives of the commissioning team

The objectives for the commissioning team during the construction phase are (ASHRAE, 2005):

- Verify that systems, assemblies and equipments fulfil the OPR.
- Develop further the test procedures and data forms for the verification process for systems and equipments.
- See to that the system manual is finished and is according to specification in the OPR before the owner accepts the building.
- Verify that operation and maintenance personal have gotten the appropriate training to be able to at minimum maintain the intended performance level of the building.

The main responsibilities for the commissioning team during the construction phase are (ASHRAE, 2005):

- Participate in the pre-bid meeting and introduce the commissioning process activities.
- Update the commissioning plan with new responsibilities for current and new commissioning team members as well for specialists that are not part of the commissioning team.
- Update the OPR if requirements that are defined in it can no longer be meet due to decisions made during the bidding and construction phase and notify all relevant personal of the changes made to the OPR.
- Integrate the project schedule and the commissioning schedule and keep the joined schedule up to date.
- Develop and document detailed test procedures and data forms.
- Verify that all systems and assemblies meet the OPR and through site visits monitor their installation process from arrival to complete installation.
- Verify training of operation and maintenance personnel.
- Verify system manual before it is handed over to the owner with the building.

To be able to fulfil all these responsibilities the commissioning team is forced to use quality-based sampling as is described in section 3.4.2.

The lists above are not exhaustive and only list the key objectives and responsibilities of the commissioning team. Additional objectives and responsibilities of the commissioning team can be seen in ASHREA guideline 0-2005.

### 3.4.2 Equipment and system verification

As the commissioning process is today the equipment and system verification is still one of the most important parts of the commissioning process due to the great focus on

increasing efficiency of systems to achieve lower energy consumption and lack of whole building commissioning projects. How detailed the verification process is can vary from one project to another but a complete and comprehensive process should be like (Grondzik, 2009):

1. Verify that correct equipment has been delivered on site.
2. Verify that equipment has been installed correctly.
3. Verify that equipment works as intended individually.
4. Verify that equipment works as intended within the whole system it is a part of.
5. Verify that the whole system the equipment is part of works properly with other systems.

To verify these steps a balance between cost and quality of the verification has to be found. To do so it is recommended to take a sample of 5-10% and test if that meets requirements defined in the OPR. If so then the equipment in whole is assumed to meet the OPR. If the equipment fails the test the test should be done again with a new sample and if that sample fails as well the equipment should be rejected with comments regarding why it is rejected (ASHRAE, 2005).

It is not recommended to do a 100% testing of each system or assembly due to it not being cost effective instead do sample testing as described above. The sample can be either chosen randomly or parts that are most critical to be working properly.

It is not recommended to skip steps in the process since equipment that is not working properly could cause the whole system to fail its test and then it has to be done again when the cause has been found which can take longer time, delay the project and cost more than following the five steps above from the beginning.

### *3.4.3 Training of operation and maintenance personals*

Training of operation and maintenance personals is a key part of the commissioning process. Because if the personnel responsible for maintaining the performance level of the building throughout the lifetime of the building are not capable of maintaining the intended performance level the investment in commissioning work may not be cost effective due to energy savings not being maintained. Training of operation and maintenance personal should be conducted by the party most suitable for that task which often is the provider of the particular system or equipment. The requirements and scope for the training are stated and documented in the construction documents and it is the commissioning team that is responsible for that it is included in the construction documents.

Even though training of operation and maintenance personals is one of the keys to persistent commissioning benefits this thesis will not go in more detail what should be included in training due to each system is special. For further requirements and how training of operation and maintenance personals should be performed the author refers the reader to the ASHRAE Guideline 0-2005.

### 3.4.4 System manual

The system manual should provide the information needed to understand, operate and maintain the building systems and equipment. Also to inform those that were not involved in the design and construction process how the system and equipment work. The System manual consists of operation and maintenance documents and all the information that is gathered during the commissioning process. The operation and maintenance document is not a new document and is already existing in today's building processes were commissioning is not used but what commissioning adds to the operation and maintenance document is it expands the scope of the traditional document as well as setting requirements regarding what has to be included and how it should be documented in the operation and maintenance document.

The following documents should be included in all system manuals but the content of these documents can vary from one to the other (ASHRAE, 2005).

- Short description of what information and what documents can be found in the system manual.
- The owner's project requirement.
- Basis of design.
- Construction record documents.
- Operation and maintenance manuals.
- Training materials that are used in training of operation and maintenance personal.
- Commissioning process report which should include recommendation for ongoing optimisation.

### 3.4.5 Updating Commissioning plan

During the construction phase the commissioning plan will be updated to include, if there are any, changes to the project because of approved changes to the OPR, change orders and system and/or equipment test failure. The commissioning plan is also updated to include new responsibilities for current and new commissioning team members as well for specialists that are not part of the commissioning team during the construction phase and further details on commissioning activities that will be performed during the occupancy and operations phase.

## 3.5 Occupancy and operations phase

Before going into the sub-chapters for this chapter it is necessary to define for how long the commissioning process goes into the occupancy and operations phase. If commissioning is used during the building process that normally includes the warranty

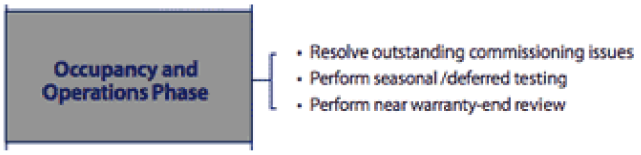


**Figure 10: Shows the main commissioning activities to be performed by the commissioning team during the operation phase (Berkeley Lab, 2010).**

period of the operation phase. That is the time when contractor, system and equipment providers are still responsible for the building systems and/or equipments.

In the following sub chapters the responsibilities and objectives that the commissioning team has during the operation phase, the commissioning report, continuous commissioning and monitor based commissioning (MBCx) will be explained. Figure 10 shows the main commissioning activities performed during the operation phase by the commissioning team.

### *3.5.1 Responsibilities and objectives of the commissioning team*

The main objectives for the commissioning team during the operation phase are (ASHRAE, 2005):

- Limit the contractors call back's[3] by using the knowledge of the commissioning team.
- Guide the operation and maintenance personal if they are not capable of maintaining the OPR on their own.
- Make sure that test that were supposed to be done in the construction phase but were not possible and the test that are to be made in the operation phase are performed.
- Document the lesson learned from this project.

The main responsibilities that the commissioning team has are (ASHRAE, 2005):

- Coordinate necessary contactor call back's.
- Make sure required seasonal and postponed test's are performed and verified.
- Verify operation and maintenance personal training.
- Verify system and assemblies meet the OPR.
- Verify the system manual to be in accordance with the OPR.
- Complete the final commissioning report.

The lists above are not exhaustive and only list the key objectives and responsibilities of the commissioning team. Additional objectives and responsibilities of the commissioning team can be seen in ASHREA guideline 0-2005.

### *3.5.2 Commissioning Process Report*

At the end of each phase a commissioning process report (commissioning report) should be published due to these reports being key part of the documentation part of the commissioning process. These reports should provide the commissioning team members with a current picture of the ongoing commissioning process status by displaying the evolution and status of commissioning activities in a clear and organized way. These

[3] *Call Back:* is used as a term over when a contractor has to be call backed on site to fix a problem or error.

reports should focus on being concise rather than verbose and make references to other commissioning documents when needed to avoid repeating information that has been documented in other commissioning documents. The commissioning authority is responsible for preparation, distributing and archiving of the commissioning process reports.

As described above during the course of a project, usually at the end of each project phase, commissioning progress reports are prepared and distributed to interested parties. At the end of a project a Final Commissioning Process Report is prepared that summarises the complete commissioning process. The commissioning process report including the final version can be viewed as a summary for all commissioning efforts and evaluates whether each piece of commissioned design, equipment and system meets the specification in the OPR and states key information from other commissioning documents and then references these documents for further information. (Grondzik, 2009) (California Commissioning Collaborative, 2006)

### *3.5.3 Ongoing commissioning / continuous commissioning*

The term continuous commissioning is used when referring to a commissioning process that is used after the warranty period is expired and often throughout the buildings life cycle. Some of the tasks that the commissioning team is responsible for are (ASHRAE, 2005):

- Maintain the OPR to include all changes requirements and needs due to changes in use and operation of the facility.
- Maintain the BoD to include all changes made to the system or assemblies due to renovation or changes in OPR.
- Verify that OPR is still being fulfilled by doing benchmarks and compare to previous benchmarks.
- Maintain the system manual to include all changes made to the OPR and BoD.
- Keep operation and maintenance personal up to date with ongoing training.
- Look for possible improvements to increase energy savings and lower operational costs.

To sum up the task the commissioning team is responsible for after the warranty period and throughout the buildings lifetime is to keep the documents made during the building process up to date with all changes that are made during the operation phase and look for possible improvements that result in increased energy savings and lower operational costs.

To be able to maintain the performance level of the building throughout the lifetime it is important that benchmarks are made and documented so comparison is possible to see how building performance has developed over time.

### *3.5.4 Monitoring Based Commissioning*

Monitoring-based commissioning (MBCx) combines existing building energy system monitoring with a retro commissioning process with the objective of providing increasing and persistent energy savings throughout the life cycle of the building. There are three main reasons for how additional energy savings have been achieved due to MBCx. These three points are (Mills & Mathew, 2009):

- Added energy savings because of more persistent benefits due to advanced metering technology and analyzing of data encourages early identification of upcoming problems.
- Added energy savings due to problems identified through metering and trending during the initial commissioning process.
- Because there is continuous monitoring of building systems it encourages continual identification of new measures that can improve efficiency and performance of the systems and therefore increases energy savings.

Figure 11 shows how energy use over time can be expected for a typical building. The yellow area is possible energy savings due to either new construction commissioning or retro commissioning process (depends on the building). The green and two types of purple show then the possible gain in energy savings due to monitored based commissioning.

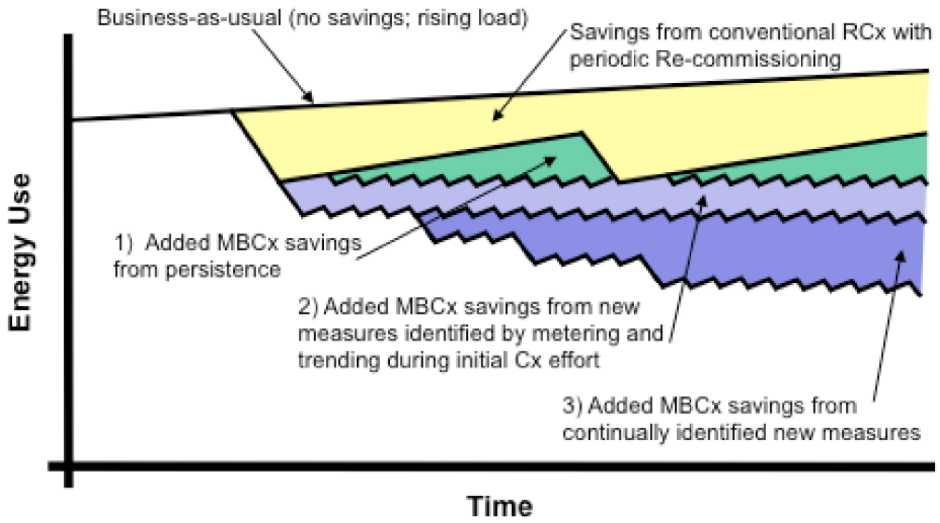


**Figure 11: Shows how MBCx can improve energy savings and make them more persistent (Mills E. P., 2010).**

As has been mentioned before that part of the training of O&M personnel should be to make them able to gather data on building systems through Building Management Software (BMS) programs and analyze them to be able to identify possible problems as early as possible. However as building commissioning is still gaining momentum the optimum training programs have not yet been included in today's commissioning process. Therefore exists the demand for outsourcing the process of monitoring and analyzing data of building systems but hopefully with further development of building commissioning will

better and improved O&M personnel training plans be included that makes monitoring and data analyzing part of the O&M personnel tasks.

Continuous commissioning, re-commissioning or retro-commissioning will not in the near future be part of the O&M personnel tasks but by including monitoring and data analyzing of building systems as O&M personnel tasks could be the first step to involve the O&M staff more in increasing energy savings of buildings.

As has been put forward in this chapter there are numerous objectives, requirements and documents that the commissioning team has to fulfil and make so the commissioning process can be successful. In the following chapters the aim is to analyse what has been achieved in commissioning projects with regard to energy and non-energy benefits and how cost effective the process is as well as looking into what can be done to improve the results that the commissioning process achieves.

# 4 Benefits of commissioning from literature

The benefits of a well developed and executed building commissioning program span a wide range. The benefits are often divided into two categories, energy benefits and non-energy benefits, to further distinguish them. When looking at the whole picture and from there identifying what the benefits of commissioning are it is clear that it is not just the owner that can benefit from the commissioning process it is also the design team and contractors. What each participant can benefit from the commissioning process is quite different therefore will the benefits of commissioning be divided into three categories and the main benefits for each participant identified.

The overall benefit of building commissioning is that it is a process that serves as the overall quality assurance process for the functional success of the project. Due to its role the commissioning process decreases the likelihood of construction time delays and cost overrun while fulfilling the OPR.

In the following sub chapters the benefits for the owner, design team and contractors will be identified and after benefits for all participants have been listed a deeper analyses into key benefits will be discussed.

## *4.1 Benefits for the Owner*

Most of the benefits of commissioning are linked to the owner and the persons that will use the building. The benefits that the owner can expect to experience during the building process and after handover from the contractor are (California Commissioning Collaborative, 2006) (Heinz & Casault, The building commissioning handbook, second edition, 2004):

- The needs and requirements the owner has to the building are clearly documented in the OPR with references to what performance level and acceptance criteria each item has.
- All building systems will function as described in the OPR. This includes the often complex interaction between systems that often do not get tested or looked at due to the high level of complexity and little knowledge of how to optimize the interaction between the systems.
- A safe, healthy, comfortable environment will be assured before handover from contractor to the owner. The results for good in-door air quality can be seen in productivity of workers inside the building. This can be achieved because building

commissioning forces flaws to be discovered as early as possible and can therefore be corrected during design or construction phase.

- All building systems will be achieving at the minimum the performance level and efficiency standard described in acceptance criteria in the OPR. Resulting in at minimum estimated annual energy savings.
- The opportunity to monitor building performance and O&M personnel that are capable of analyzing the data and perform benchmarks.
- Increased equipment life because of less wear and tear due to optimized building systems.
- Well trained O&M personnel are capable of maintaining the efficiency and performance level of the building.
- All key information of the building are documented which can be vital for the O&M personnel to be able to maintain and operate the building and also in later years when renovation of the building is being planed the design consultant will not be forced to make assumptions regarding what thoughts were behind the design due to the extensive documentation because of the building commissioning process.

The benefits that are listed for the owner do all contribute to increased probability of the project being on schedule, within budget, operational cost being as low as possible due to optimized operating systems and fulfilling the OPR.

## *4.2 Benefits for the Design team*

It is not just the owner that can benefit from a commissioning process. The following are benefits that the design team can expect to experience by participating in a commissioning process (Heinz & Casault, The building commissioning handbook, second edition, 2004):

- The building commissioning team in co-operation with the design team improves the building design by bringing an operation engineer and a construction expert to review design concepts and ideas regularly throughout the design phase as well as it opens a communication line between the design team and the operation engineer and the construction experts.
- Through regular commissioning-oriented review the number of design errors is reduced and with thorough functional performance testing of building systems during the construction phase the post construction call back's for the design team are reduced drastically.
- Design team's profit is not diminished because if they work in good relationship with the building commissioning team during the design phase the amount of time the design team spends at their own cost resolving design problems that are causing construction problems is minimized.
- By being part of the building commissioning process the design team gains experience and expertise and will therefore be more qualified for future projects were building commissioning will be part of the project.

The benefits for the design team can be summed up to be that the design of the building is improved in co-operation with the commissioning team which decreases the likelihood of call back's and the design team gains experience for future projects were commissioning will be used.

The benefits for the design team occur indirectly due to the building commissioning process being included in the project. Therefore are these benefits often overlooked or not even recognized as being part of the benefits of the commissioning process. The reason why can perhaps be that since the owner of the building being built is not interested in these benefits or what other participants of the building process gain from the commissioning process.

## *4.3 Benefits for the contractor*

The same goes for the contractor as for the design team that if the contractor works in good co-operation with the commissioning team there are benefits that he can enjoy and the main benefits are(Heinz & Casault, The building commissioning handbook, second edition, 2004):

- There is increased attention to scheduling and coordination due to commissioning which leads to smoother installation and fewer conflicts between sub-contractors for installation positions. The reason for increased attention to scheduling and coordination is because of about one third of the way into the construction phase the commissioning team starts testing systems and assemblies and to be able to do so they have to be aware how the project is going to know when tests should and can be performed.
- When flaws and/or errors are discovered during the construction phase the solution are achieved faster due to the commissioning team has identified in the commissioning plan who is responsible for what part of the project and therefore is no time wasted in figuring out who should be contacted. As a result the likelihood of the project being completed on schedule and within budget is not decreased.
- Contractors profit is not diminished because if they work in good relationship with the building commissioning team during the construction phase the amount of time spend at their own cost resolving construction errors after construction phase that did not have to occur is minimized.
- By being part of the building commissioning process the contractor gains experience and expertise and will therefore be more qualified for future projects were building commissioning will be part of the project.
- Post construction call backs are minimized due to thorough quality assurance process during the construction phase.

After reading that every participant to the building process can gain from the building commissioning process some might wonder why building commissioning has not been included in the normal building process. One of the reasons why is also one of the main

obstacles building commissioning is trying to overcome which is members of the design team and contractors seem to think that the building commissioning team has the main purpose to make them reliable for any future problems or errors that might happen rather than looking at the commissioning team as extra set of eyes that can discover flaws that they might have overlooked and work with them towards a successful building project.

Due to such a state of mind the members of the design team and/or the contractor are often working against the commissioning team and are threatened to show their work until it is fully designed and at that time many hours have gone into the design and often it is too late to change instead of working with the commissioning team throughout the building process and in co-operation working towards a well developed design and constructed building.

## *4.4 Increased efficiency and higher performance levels*

A study done by Evan Mills, Ph.D. (2009) for the California Energy Commission and Public Interest Energy Research (PIER) is the most extensive research with respect to sample size that looked into how much energy savings have been achieved with building commissioning, how cost effective building commissioning is and how important one-time non-energy benefits are to deciding if a building commissioning process is cost effective. Before the results of the study will be showed and analysed, a short introduction to the study will be presented first.

Key information regarding the sample size for the study are:

- 332 commissioning projects on existing buildings
- 77 commissioning projects on new construction buildings
- These buildings span 26 states.
- The total square meter size ($m^2$) of these buildings is around 9.2 million $m^2$.
- The total commissioning cost for all these projects is about $43 million.

To be able to compare all these different buildings from all over the US all energy prices were normalized to a US standard for average commercial sector energy price for the year 2009. As well since the weather conditions are quite different between places in the US the energy use and energy savings were weather normalized.

Median value is used to find out the middle value of the distribution of results being analyzed. The reason why is by using the median value extreme boundaries in either direction do not affect the middle value as they would do if average value would be used.

Like stated in sub chapter 2.3, building commissioning started as a process to ensure mechanical systems, such as HVAC systems, within the building worked as intended. Even after more than 20 years the main focus of building commissioning is still on the mechanical part of the building. In the study previously mentioned as well as analyzing energy savings and non-energy impacts on the projects. The study gathered all the issue logs and categorized each item into a relevant group based on systems. Figure 12 shows

the results from this categorization and it shows clearly that the main focus of building commissioning is still on the mechanical systems on the buildings. The reason for such a low number of identified and reported flaws within simpler systems such as building envelopes and plug loads may be due to how simpler these systems are compared to heating or cooling systems and also due to how few projects include a whole building commissioning process or focus on these systems.

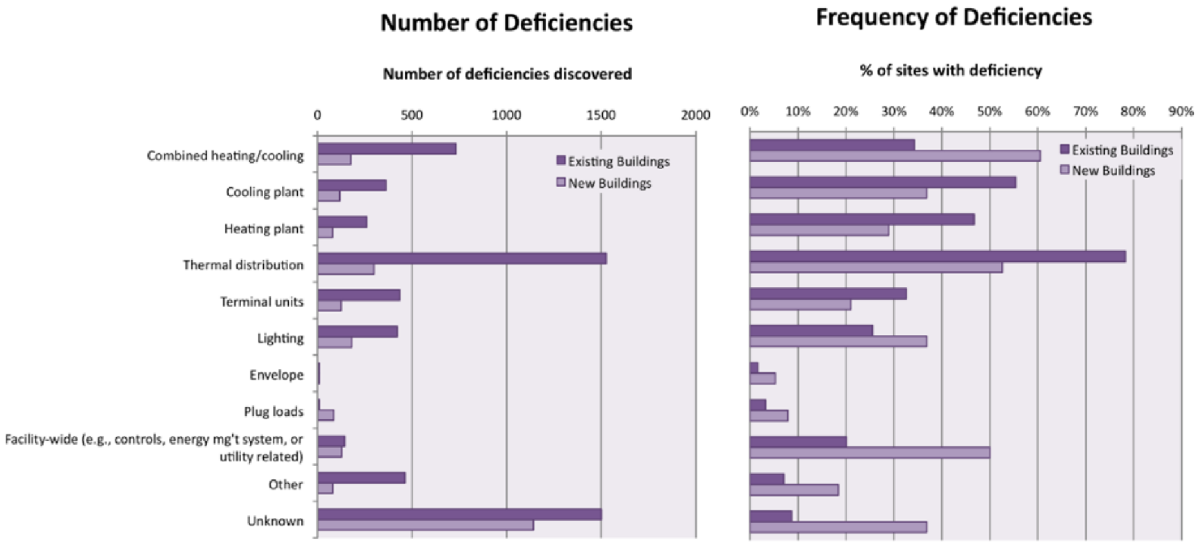


**Figure 12: Shows how deficiencies are divided between systems (Mills E. P., 2010).**

The majority of the building commissioning projects that were analyzed in this study were not a whole building commissioning process instead a building commissioning process with focus on specific areas therefore if more focus was put into for example building envelopes the number of flaws identified would be larger. But if it gives the same payback time as mechanical system focus has yet to be analyzed.

The study divided the buildings into categorise based on their operation type and then looked into how much energy savings were experienced in each building type and what the payback time was. When calculating the payback time the first cost savings were included where data was available to calculate that. First cost savings are savings that are experienced only during construction and an example of a first cost savings is if a system is over designed and by fixing that difference between construction cost of these two solutions is a first cost saving. Table 1 shows the results for each building type.

**Table 1: Results on energy savings and payback time by types of building (Mills E. P., 2010).**

| Type of building | Energy savings (%) | Simple payback time (years) | Sample size |
|---|---|---|---|
| **Higher education (non-lab)** | 11% | 1,5 | 165 |
| **Food sales** | 12% | 0,3 | 10 |
| **Healthcare inpatient** | 15% | 0,6 | 15 |
| **Healthcare outpatient** | 12% | 0,1 | 13 |
| **Laboratory** | 14% | 0,5 | 50 |
| **Lodging** | 12% | 1,5 | 38 |
| **Office** | 22% | 1,1 | 145 |
| **Public order and safety** | 16% | 3,2 | 15 |

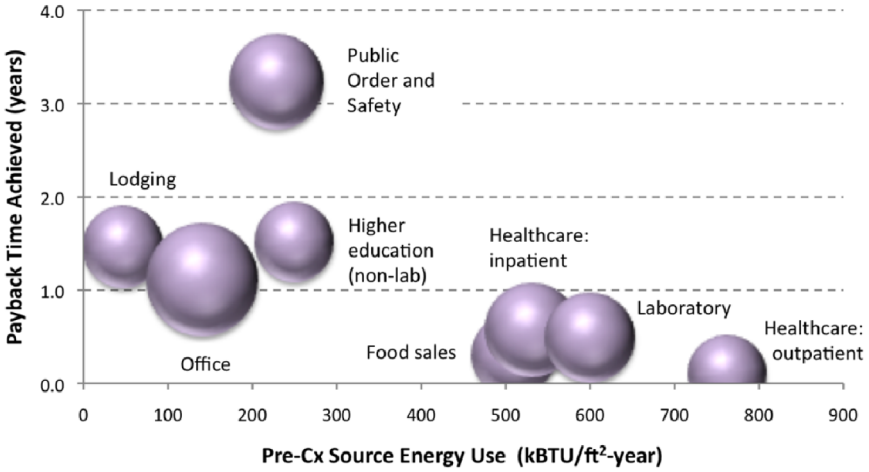


**Figure 13: Shows the values in table 1 in a graph (Mills E. P., 2010).**

What is especially interesting about the results in table 1 and figure 13 is that relatively simple buildings like offices are returning the highest whole-building energy savings and a payback time just over a one year. This shows that building commissioning is not only a valuable tool for buildings with great complexity but also a commercial buildings were large building systems will be installed and therefore a great opportunity for energy savings exists through high performance level and efficiency. For more complex buildings the payback time is less than zero years in some cases which shows that in those cases the first cost savings because of non-energy benefits were greater than the total cost of the commissioning process. This shows what can be achieved when a good co-operation is between the design phase and the commissioning team during the design phase and the mind set is total economy.

The median whole building energy savings for all building types was found to be 16% in existing building and 13% for new constructions. Figure 14 shows how the distribution of energy savings for existing buildings and new constructions and were the median value lies in the distribution.

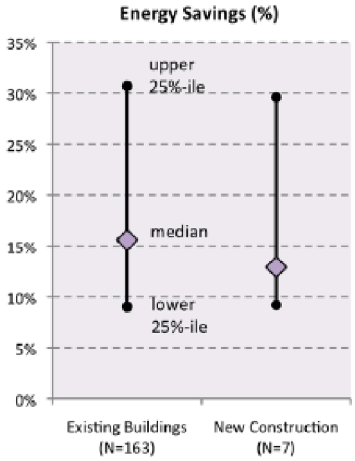


**Figure 14: Energy savings in existing buildings and new construction (Mills E. P., 2010).**

In the study as stated earlier the total building commissioning cost was around $43 million. The cost of commissioning in the study is not just the fee that the commissioning provider charges it includes the fees every party of the commissioning process charges.

For existing buildings the median normalized commissioning cost was $0,3/square foot ($ft^2$) ($3,23/square meter ($m^2$)) and for new constructions the cost was $1,16/$ft^2$ ($12,48/$m^2$) as can be seen in figure 15. These numbers do not include non-energy benefits which in some cases can be quantifiable in economic terms. The study found out that the price for commissioning in existing did incline with the size of the building but however for new constructions the study confirmed what has been used as a rule of thumb for cost of new construction commissioning, 0,5-1,5% of constructions cost (U.S. department of energy), that the cost is less dependent on the size of the building rather a percentage value of the building construction cost. Therefore is it a more common metric for new building commissioning projects to define the cost as a percentage of total building construction cost. The study found that the median direct cost percentage for new buildings to be 0,4%, but if first-cost savings were taken into the calculations the percentage dropped by half to 0,2%.

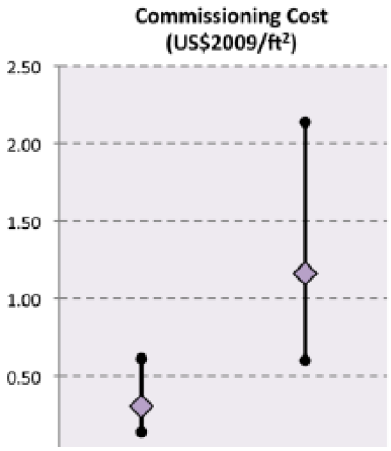


**Figure 15: Commissioning cost for existing buildings and new constructions (Mills E. P., 2010).**

Figure 16 shows the distribution of new construction projects cost and how much impact non-energy benefits of commissioning that result in first-cost savings can have on the net cost of commissioning. Even though the sample size for net cost for new construction commissioning projects is not as large as the direct cost sample it should though be big enough to give a clear picture on how important it is to include non-energy first-cost savings and how it much it affects the net commissioning cost.

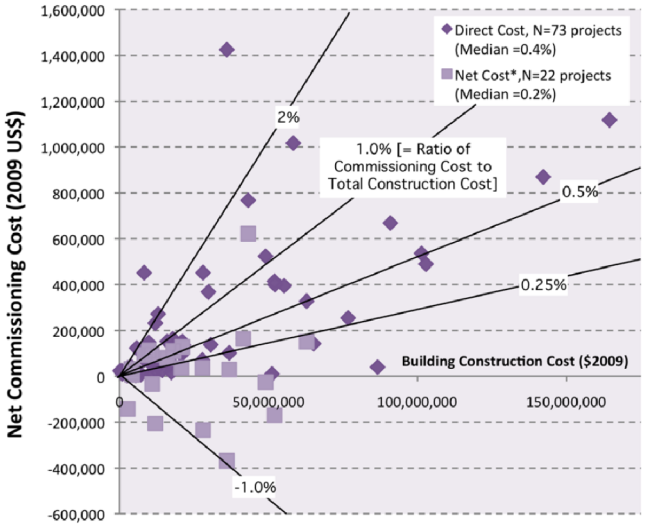


**Figure 16: Shows the direct cost and net cost of commissioning as percentage of total building cost (Mills E. P., 2010).**

To keep track of cost savings[4] is as important as keeping track of the cost of commissioning due to cost savings are used to determine how cost effective the commissioning process was by calculating the payback time. The study found the median cost savings for existing buildings to be \$0,29/ft$^2$-year (\$3,12/m$^2$-year) and for new constructions \$0,18/ft$^2$-year (1,93/m$^2$-year). Figure 17 shows the distribution of the cost savings for existing buildings and new constructions and were the median value is within the distribution.

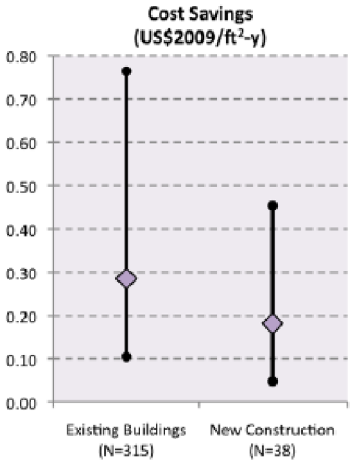


**Figure 17: Cost savings for existing buildings and new constructions (Mills E. P., 2010).**

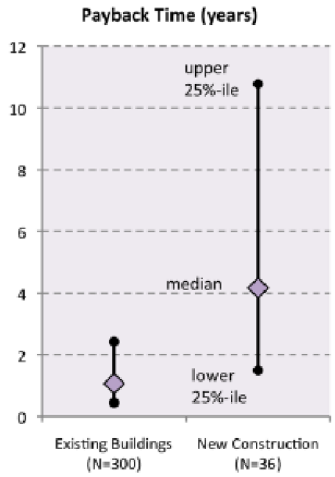


**Figure 18: Payback time in years for existing buildings and new constructions (Mills E. P., 2010).**

[4] Cost savings are savings that are achieved through lower annual O&M cost. First cost savings are not included in cost savings becuase they are not annual savings.

The payback time is calculated by dividing the project cost with the first-year cost savings. For existing buildings the median payback time was 1,1 years and for new constructions the median payback time was 4,2 years. Figure 18 shows the distribution of payback times for existing buildings and new constructions and were the median value is within the distribution.

The benefit-cost ratio takes the sum of projects benefits over the assumed expected lifetime and divides it with the project cost. If the ratio is greater than 1 the project can be considered cost effective. For existing buildings the median benefit-cost ratio was 4,5 and for new constructions it was 1,1. Figure 19 shows the results metaphorically.

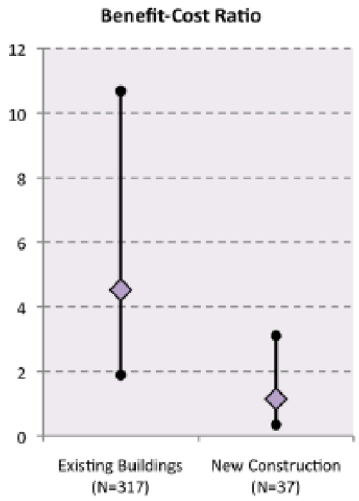


**Figure 19: Shows results for benefit-cost ratio calculations for existing buildings and new constructions (Mills E. P., 2010).**

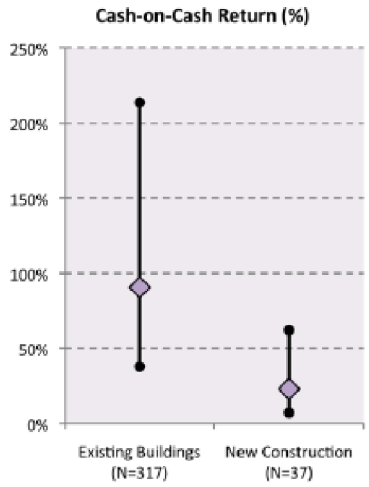


**Figure 20: Shows results for cash-on-cash return calculations for existing buildings and new construction (Mills E. P., 2010).**

Cash-on-Cash return is a ratio of the first-year cost savings from the project divided by the project cost. The ratio is presented as a percentage return (if there is 10% percentage return and $100 were invested in a commissioning process the buyer can expect $10 in first-year cost savings). Cash-on-cash return ratios are widely used in the real estate industry and beside that it can give a clearer picture on how the return on investment is with commissioning in existing buildings and new constructions. For existing buildings the median cash-on-cash return ratio was 91% and for new constructions 23%. Figure 20 shows the distribution of the cash-on-cash return for existing buildings and new constructions and where the median value is within the distribution.

The results from this research on the impact of energy benefits economically can be summarised as the median energy saving both in existing buildings and new constructions is high enough to make the commissioning process cost-effective regardless of the impact of non-energy benefits. This can clearly be seen in the median payback time as well as the benefit cost ratio.

## *4.5 Impact of non-energy benefits from commissioning*

Building commissioning had its main focus in the beginning on mechanical systems, especially HVAC systems, and improving their efficiency to save energy as stated in sub chapter 2.3. Over time the focus had broadened and today non-energy benefits of commissioning are gaining more and more momentum in being the main reason for building commissioning process being a part of a building project. However the recognition of non-energy benefits of commissioning has not yet gotten to the same level as energy benefits. Numerous studies have been made to research and quantify the energy benefits of commissioning however it is not the same for non-energy benefits. One of the reasons why could be how difficult it can be to quantify and put a price on some of the non-energy benefits of building commissioning and some non-energy benefits can be quite subjective. There have been studies on single projects to illustrate how building commissioning process with great focus maximizing non-energy benefits have been successful but studies with large sample size that look into how cost effective non-energy benefits are lacking.

The study done by Mills (2009) mentioned in section 4.4 looked into, besides energy savings and cost effectiveness, what was the main reason for deciding to include building commissioning in the building project, what were the main non-energy benefits that were experienced in these projects and how one-time non-energy cost savings affected the net project cost.

The study gathered data on reasons for commissioning from 178 existing building projects and 36 new-construction projects (Mills E. P., 2010). The results from the analysis for reasons for commissioning shows that still even 30 years later the main reason for including building commissioning in existing buildings is still to obtain energy savings as it is the main focus in around 90% of cases the good news are though that non-energy reasons are gaining momentum and today benefits like ensured or improved thermal comfort and ensuring adequate in-door air quality are a closing in on energy savings (Mills E. P., 2010). For new construction the picture is a bit different and there has non-energy benefits caught up with energy savings and in some cases exceeded it. Ensuring equipment performance and ensuring adequate in-door air quality are often the main reason for including building commissioning rather than energy savings (Mills E. P., 2010). The complete results from the analysis of reasons for commissioning for both existing buildings and new constructions can be seen in figure 18.

The study looked into what of the non-energy benefits were most experienced. The study gathered data from 68 existing building commissioning projects and 44 new-construction commissioning projects and the total number of identified non-energy benefits among these projects were in total 480. For existing building the main non-energy benefits that were experienced were (Mills E. P., 2010):

- Improved or ensured thermal comfort
- First-cost savings
- Improved equipment life
- Improved or ensured indoor air quality

For new-construction projects the main non-energy benefits that were experienced were (Mills E. P., 2010):

- Reduced change orders and warranty claims
- Improved team function
- Improved or ensured thermal comfort
- Improved or ensured in-door air quality
- Improved or ensured productivity of workers and safety
- Improved equipment life

The complete results from the analysis of non-energy benefits experienced due to commissioning can be seen in figure 22.

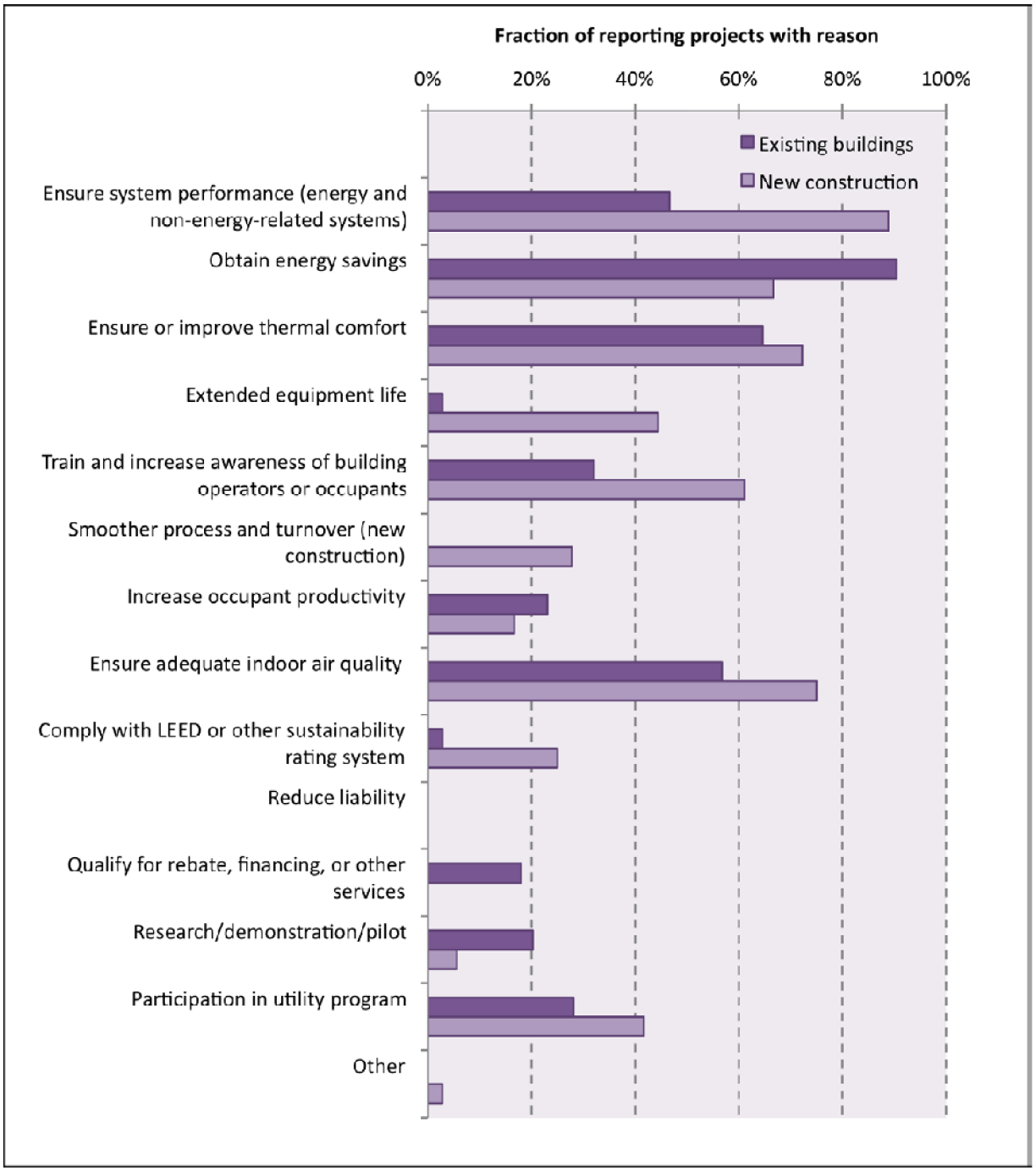


**Figure 21: Shows the distribution of reasons for why commissioning was included in the building process (Mills E. P., 2010).**

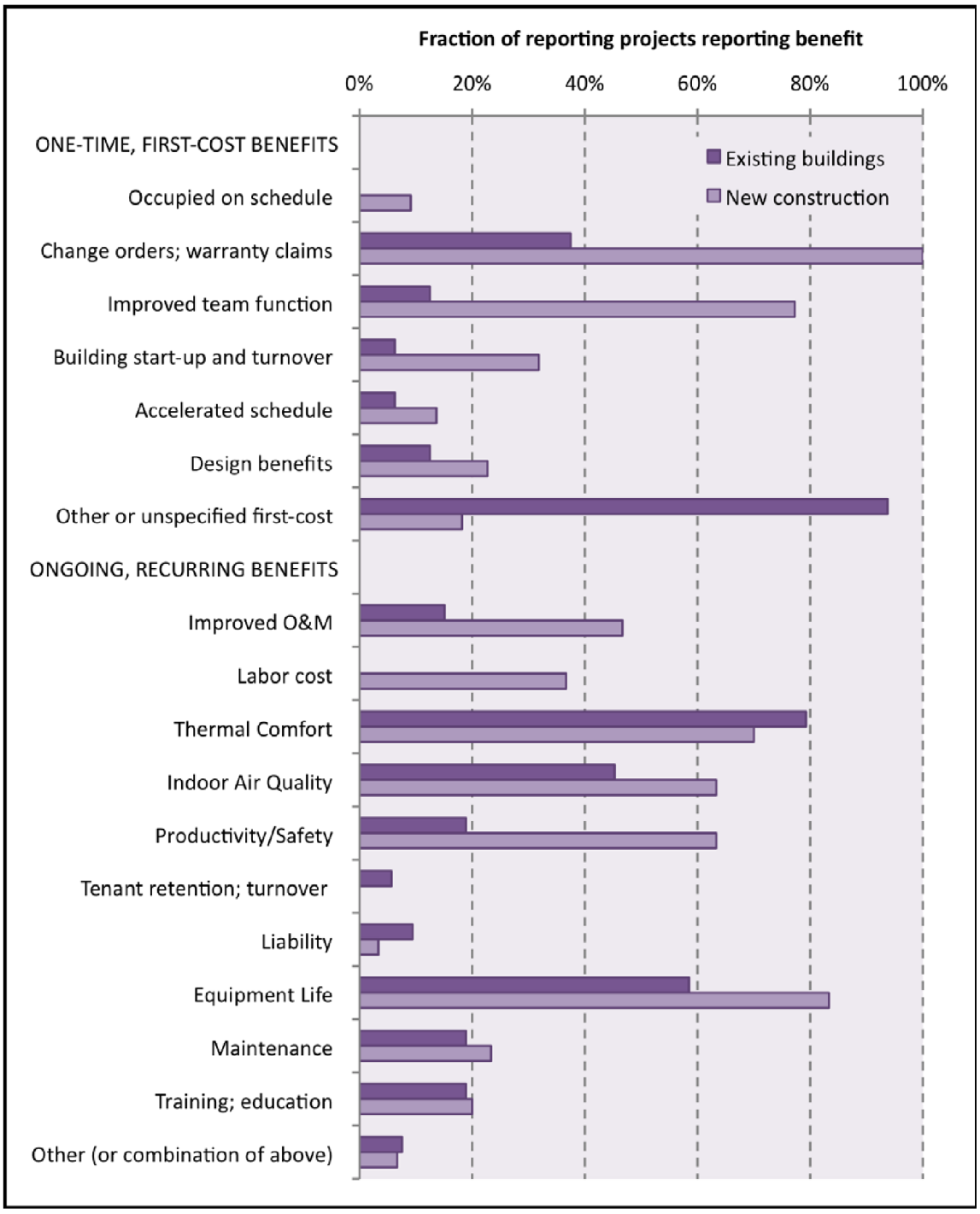


**Figure 22: Shows the number of projects following non-energy benefits were experienced in percentages (Mills E. P., 2010).**

A research done in Texas by The Texas State Energy Conservation Office (2007) about the viability of commissioning in new school construction in the area supports the results that commissioning can reduce change orders, request for information and warranty claims. On top of identifying that commissioning can reduce these issues the research also identified that the change orders, request for information and warranty claims that did occur were not as costly as if not commissioned.

Due to non-energy benefits being overlooked the cost of commissioning is often overestimated. A more accurate cost of commissioning is net cost of commissioning that is the total cost of commissioning minus the one-time non-energy cost savings benefits. As before the study done by Mills (2009) looked into how one-time non-energy cost savings affected the net project cost and in 38 cases could non-energy benefits be quantified. As figure 23 shows, the one-time non-energy cost savings have a significant effect on the direct cost of commissioning. The median value for how much cost reduction was experienced in these 38 cases was 49%. The darker columns in figure 23 that are showing net project cost less than zero are cases where the amount of one-time cost savings were larger than the total commissioning cost.

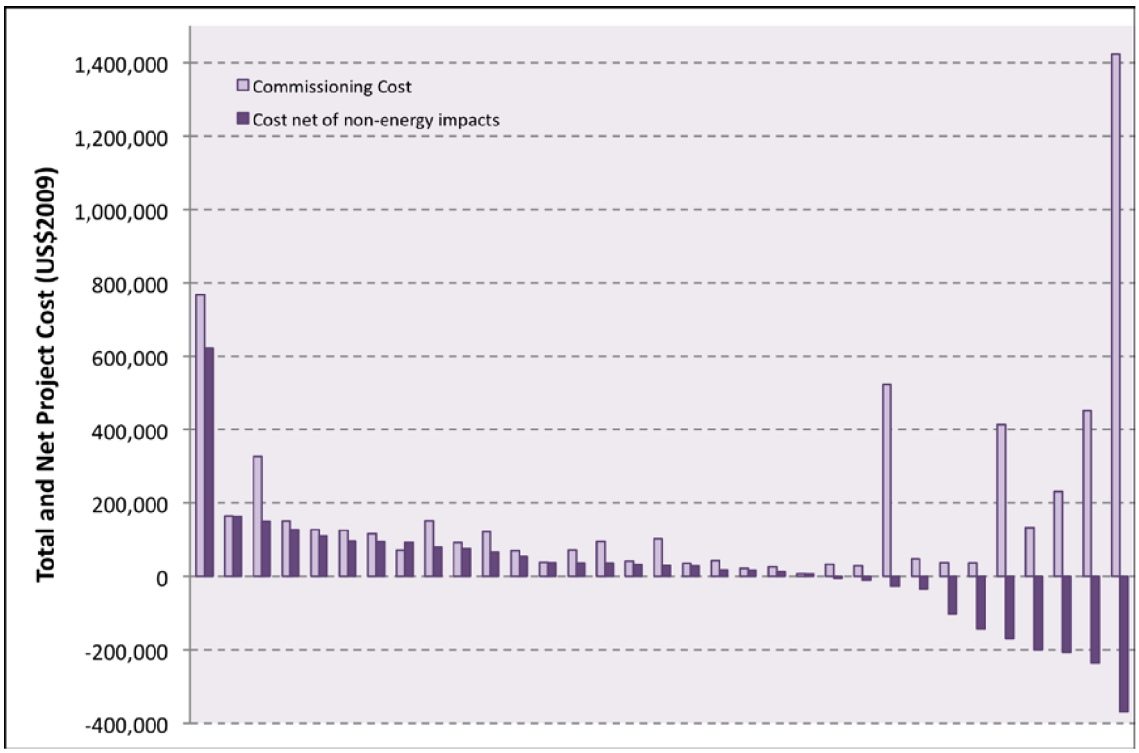


**Figure 23: Shows how one-time non-energy benefits affect the net commissioning project cost.**

As has been stated earlier that what the building commissioning process identifies are often problems that will be identified at some time over the buildings life time. A study done by Della Barba (2005) took on the task to examine the commissioning issue log for two buildings to see what the issues documented impacted. The study used 5 categorise that were energy, productivity, repair and maintenance, equipment life, and other. The

research for these two buildings showed that 62% (building 1) and 46% (building 2) of documented issues had impact on repair and maintenance of the buildings. Figure 25 and 26 below show how the issues documented in the issue log impacted each category.

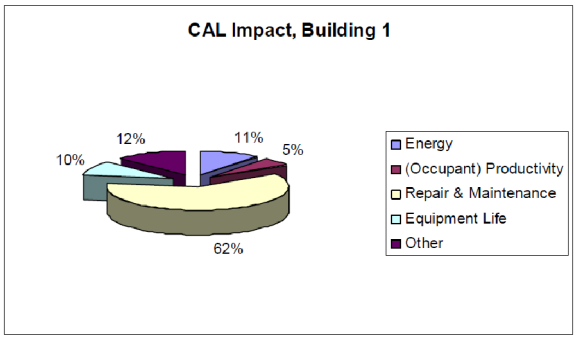


**Figure 24: Shows the commissioning action list (issue log) impact on energy, productivity, repair and maintenance, and equipment life building 1 (Della Barba, 2005).**

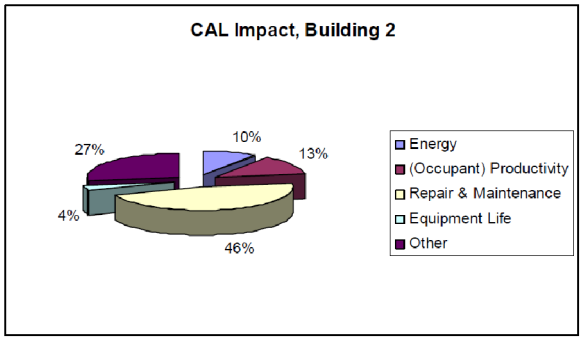


**Figure 25: Shows the commissioning action list (issue log) impact on energy, productivity, repair and maintenance, and equipment life for building 2 (Della Barba, 2005).**

Although this is only one study that just looked at two buildings it shows that most of the issued identified by the commissioning team affect other issues than energy savings which is often the main focus for the commissioning process.

This also supports the idea that what is discovered during the commissioning process are flaws or problems that are bound to be discovered later in the buildings life cycle when they can have caused damages and/or decreased the buildings performance level. Therefore the thought of not commissioning or not solving the issues identified by the commissioning team can be viewed as just kicking the ball further ahead in that sense what will be or was discovered during the commissioning process would have caused problems later. By postponing dealing with the problems the risk of increased repair and maintenance cost increases.

# 5 Persistence of benefits from New Building Commissioning

At the end of the commissioning process the building's systems should have been tuned to maximum efficiency and all requirements of the OPR fulfilled. But with time the usage and expectations to the building will change more and more from the initial design intent and often does performance level of the building decrease due to these changes.

However the main reasons for the declining performance of building system's over time can be divided into two different categories:

- System repairs with a "band-aid" approach.
- Hardware failure, lack of maintenance or regular wear and tear.

When system repairs are made and a "band-aid" approach is chosen the goal is only to fix the problem so the system can keep running and no thoughts or time is put into how that will affect the efficiency of the system or if the efficiency of the system has already decreased and what can be done to reach the initial performance level. A solution to the "band aid" approach would be to spend more time and resources to find the root of the problem and its solution. By doing so the building system would be error free and the efficiency would be higher than by just fixing it to keep it running and the efficiency could reach its initial performance level. Making the system error free might cost more in repair costs than the "band aid" approach however by looking at the total economy and taking into the calculations of costs the energy consumption for both efficiency levels it is highly likely that the error free approach would be more cost effective over time then the "band aid " approach.

Hardware failure, lack of maintenance and regular wear and tear can be hidden problems that may not be discovered if there is no regular observation to if the system is running as designed. And problems that fall under this category often decrease the equipment life time which increases the O&M costs. Such problems can go on and on over a long period of time, even get worse and at the same time decreasing the efficiency. But such problems are often not severe enough to effect a system breakdown but decrease efficiency and thereby energy costs increase. But if there is building management system that has the ability to constantly monitor the performance of the building systems a well trained O&M personnel could identify from that if the performance level is decreasing and step in and repair the error in the system.

The “band-aid” approach can also be the cause for more hardware failure and increased wear and tear due to systems not running smoothly which results in decreased equipment life time.

Even if the main reason for declining performance is broken down to two categories they are closely related and can affect each other.

## *5.1 Do the benefits of building commissioning last?*

For the owner to be able to justify the extra cost of including a commissioning process in the building process he has to be sure that the possible benefits that commissioning can have on the building will persist over time to increase the cost effectiveness of the commissioning process to ensure it is a good investment instead of only being short term benefits.

The available researches on the subject are not many. Two of the researches that have been made will be used to show how persistence the energy savings due to commissioning are and in general how persistence benefits of commissioning are.

In a research done by Hannah Friedmann, Amanda Potter and Tudi Hassal (2003) as part of the PIER High Performance Commercial Building System program was looking into how persistence the benefits of new buildings commissioning are. The research only looked at 10 different projects and therefore cannot be looked as a clear cross section of how persistence the benefits of building commissioning are numerically. However it still shows what in these cases resulted in persistence benefits and what can be done to prevent a short term life span of benefits.

In new buildings the research showed that most of the problems that the commissioning team identified and were fixed during the commissioning process were still few years later showing benefits. The benefits that were the most persistent and long lasting can be divided into two groups:

- Modification to equipment that did not require further adjustment.
- Building management system (BMS) programming changes that are not easily accessed through the workstation user interface.

Like has been mentioned before that building commissioning cannot be expected to be able to identify all possible problems and as well are not all the solutions to the problems that are identified always long lasting. The solutions that did not last long were often control strategies such as schedule and set points that could easily be modified using the workstation interface. In other words the solutions that should be avoided are solutions that O&M personnel can easily change through there user interface in their BMS software or elsewhere. But with proper training and education of the O&M personnel they can be taught in great detail what each setting does in the BMS and therefore limiting the risk of personnel un-tuning the system subconsciously.

The study found in two buildings component failures that did not affect the comfort level of the building but it increased the energy consumption by $150,000 per year and in few buildings the control parameters were changed which resulted in increased energy consumption around $50,000 per year but these buildings had already reduced energy consumption by about $1,000,000 per year (Friedman, Potter, Haasl, & Claridge, 2003). So a 5% decrease in savings per year cannot be viewed as a benefit of commissioning that did not persist.

The study done by Mills (2009) analysed energy savings data from 36 buildings were data was available for more than two years to be able to determine how persistence the energy savings were. Figures 26 and 27 show the results from the analysis where each gray line corresponds to results from one building and the read lines show the median value for each category.

It is noticeable that savings in many cases increase in the second year. The reasons for that could be refinements of the solutions from the commissioning process or some of the recommendation by the commissioning team did not get implanted in the first year. Increase in energy use is common in most cases after the second year and that should be expected due to factors that with time tend to bring a building “out of tune”. These factors also make the need for building commissioning.

For the sample as a whole the tendency is towards increased savings over time. This reverse outcome for the 36 projects, that energy savings increased over time, may be explained with the fact that a complete building commissioning process includes a comprehensive training of O&M staff, documentation and installation of permanent metering and feedback systems. These improvements if properly utilized can maintain and even result in increased savings.

As can be seen in the figures 26 and 27 that the total energy savings decrease a little after the second year but one of the reasons for that are most of the projects showing the best results did not have data for more than two years. Therefore should presumptions for years 3 and 4 be made with fact in mind that due to the small sample size the results may not be showing accurate tendency of energy savings in commissioning projects overall.

This data does though emphasize the importance of benchmarking performance over time and the need to commission buildings regularly.

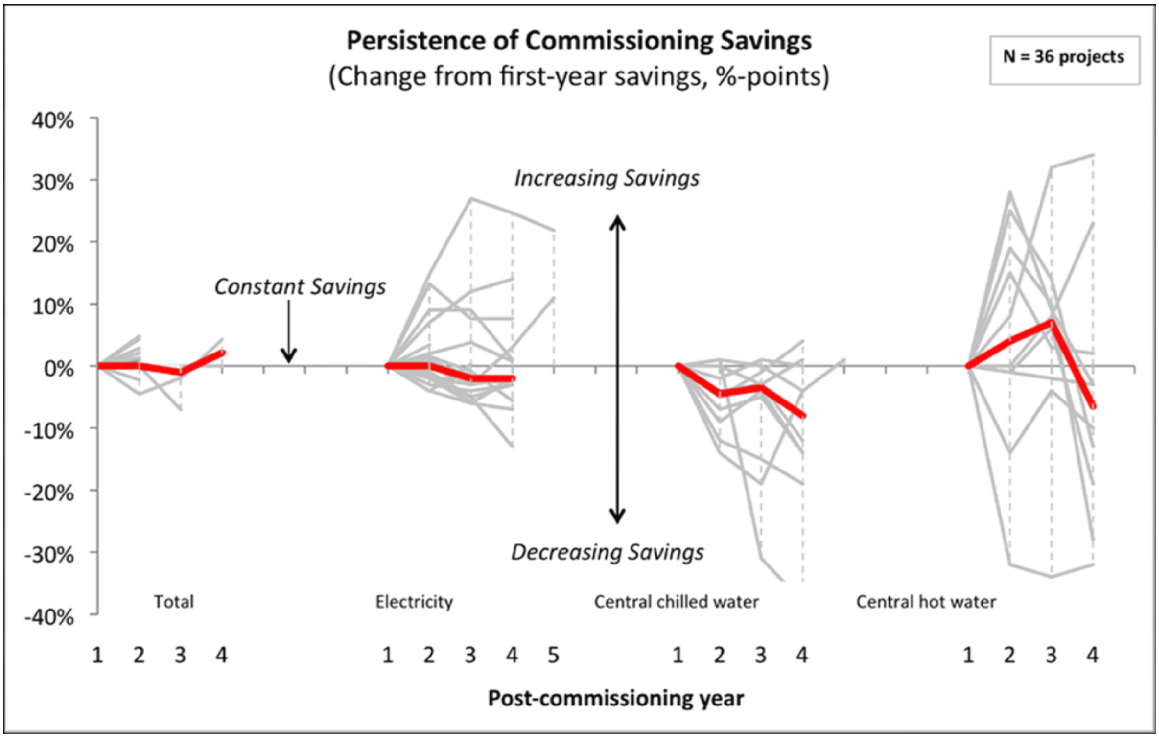


**Figure 26: Shows how achieved energy savings due to commissioning compared to initial energy savings (Mills E. P., 2010).**

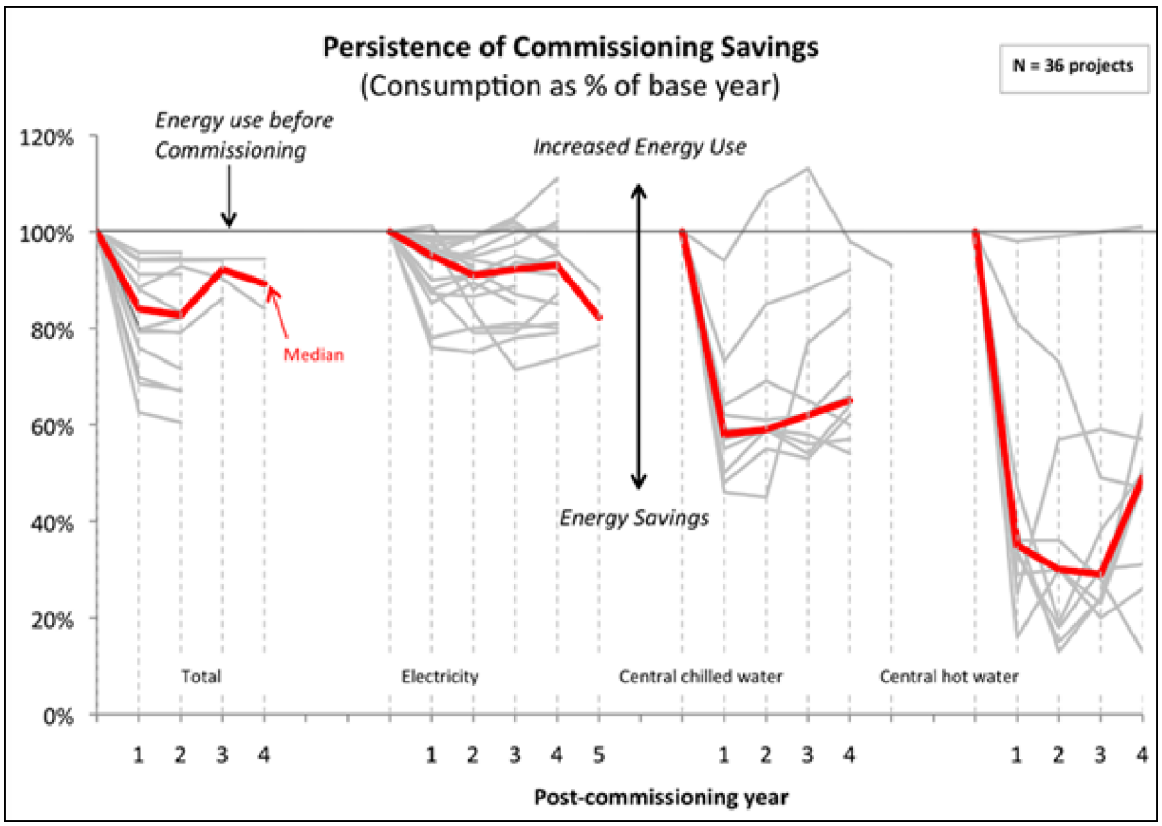


**Figure 27: Shows how persistence of energy savings compared to energy use before commissioning (Mills E. P., 2010).**

Although there has not been great emphasis on retro commissioning which is when building is commissioned after it has been built and taken into operation. A study of energy savings of buildings that went under retro commissioning showed that averaged energy savings were 41% of total energy use but over the first two years after retro commissioning the savings decreased by average by 17% (Claridge, et al., 2003).

The study by Mills (2009), which was discussed in chapter 4.3.1, showed that in existing buildings that went under retro commissioning showed a median energy savings of 16%, figure 14, but average value and median value cannot be compared. If an average value for existing buildings is read out from the graph in figure 8 the average energy savings for existing buildings would be around 20% which is still quite less than the study done by Claridge, et al., (2003). The reason for such a different findings in energy savings and their percistancy in existing buildings could be due to the following reasons:

- Different sample sizes.
- Different purposes with each study.
- The main focus and the level of size for the building commissioning process in each case.

The Mills (2009) sample size for existing buildings was 163 buildings and with the purpose to analyze how cost effective the energy and non-energy benefits of building commissioning are. While Claridge, et al., (2003) sample size was only 10 buildings and had the purpose to analyze how percistant energy benefits of commissioning are, when follow-up on commissioning should be performed and how continoues commissioning improves building performance.

As stated above the study done by Claridge, et al., (2003) showed the results that energy savings due to commissioning decreased by average of 17% while Mills (2009) study of percistancy of energy savings showed that over 36 projects the energy savings increased over time. The reason for such different findings could be due to numerous things but what is most likely the reason based on difference of the commissioning process is the O&M staff capabilities to maintain the building performance level since in both researches the cases analyzed achieved high energy savings at the start of the occupancy and operations phase but in some cases this energy savings could not be maintained.

Aside from the difference between the commissioning processes and methods of work it is quite likely that the difference is partly because of the different sample size. The affect it can have on the results is clearly visiable in the analyzes of presistence of energy savings done by Mills (2009) as can be seen in figures 27 and 28 after the second year where the tendency for increased energy savings gets reversed due to decrease in sample size.

## *5.2 Why do benefits persist in some cases and not others?*

What it all comes down to in determining how persistence the benefits are is hinged on the ability of the O&M personnel to be able to maintain the building at the same performance level as was achieved during the commissioning process. For them to be able

to achieve this they have to have a full understanding how the systems are supposed to work and if something breaks to be able to trust that they have the knowledge to troubleshoot the problem and get the systems to the original performance level.

Key factor that can make the difference between commissioning benefits that are long lasting and those that are short lived is the working environment that the O&M personnel have. A workplace that provides its O&M personnel with (Friedman, Potter, Haasl, & Claridge, 2003):

- Proper operation training on building systems on site.
- Time to be able to study and optimize the building systems.
- Management division that has focus on optimizing building performance and reducing energy costs.

is more likely to be able to maintain the building commissioning benefits and therefore the high building performance level that was achieved through the commissioning process. However there are also factors that can contribute to decline in building performance. These factors are mostly (Friedman, Potter, Haasl, & Claridge, 2003):

- Little or inadequate operation training on building systems.
- High turnover of O&M personnel.
- Lack of documentation and documents from the commissioning process.
- No performance tracking or benchmarking.

Why these four factors can have such an impact on performance level will be explained in more detail in following sub chapters.

### *5.2.1 Operation training and personnel turnover*

It is so often the case that the operation and maintenance personnel are not provided with proper education and training of the building systems and often the training does not take place on site and therefore the personnel is not getting trained on the systems he/she will operate, since each system is different. Therefore it is not fair to expect them to be able to maintain the performance level of the building.

High staff turnover can have a drastic decreasing impact on performance levels due to knowledge loss and new training of O&M personnel consisting of a one day walkthrough with the former O&M personnel. Therefore if the former operation and maintenance personnel did get proper training there is a high risk that knowledge about the building systems will be lost with him due to inadequate new personnel training. The risk of the loss of knowledge with retiring staff can be lowered with proper documentation and proper training of new operation and maintenance personnel (Friedman, Potter, Haasl, & Claridge, 2003) (Claridge, et al., 2003).

As has been stated before in this report the key to maintaining the high performance level and efficiency of buildings is to have experienced and well educated operation and maintenance personnel, who are interested in their work and share the focus with the

management division, of increased optimisation of building systems to achieve higher performance levels and efficiency.

### *5.2.2 Commissioning documentation*

Even with proper training and education the operation and maintenance personnel cannot be expected to be able to learn and memorise every detail of the building systems. Therefore is it quite important that the documentation of the commissioning process is adequate so the O&M personnel have documents that they can use to look up specific details. All information about the building and its systems should be documented in a clear and simply way so the O&M personnel can use it in a fast an efficient way to maintain the high performance level throughout the life span of the building. Proper documentation also lowers the risks that some information might get lost between the commissioning team and the O&M personnel. Proper documentation also serves as a great tool for training of new O&M personnel (Friedman, Potter, Haasl, & Claridge, 2003) (Claridge, et al., 2003).

It may sound obvious but all the documents made by the commissioning team about the building should be stored in a place that is on site and easily accessible for the O&M staff at all times and in an organized way. In today's building commissioning projects the owner often cut corners to decrease the cost of commissioning and the documentation is often sacrificed to achieve that. By doing so the owners are limiting a key tool for the commissioning team to bridge the gap between participants as described in chapter 2.1 and as well decreasing the information available for the O&M staff about the building and therefore increasing the knowledge loss between the commissioning team and the O&M staff.

### *5.2.3 Performance tracking or Benchmarking*

Performance tracking can be a great tool if used properly to discover problems before they start causing decreasing in-door air quality, higher energy cost and unexpected equipment failure. As building systems are getting more complex continuous performance tracking becomes more and more important due to how the O&M personnel can use it to discover when systems are not working as intended. In a proper operation and maintenance training program it should be part of the process to train and educate the O&M personnel how to extract and gather data from the BMS programs and how to analyze them to be able to identify in time if the system is starting to deviate from its ideal performance level. It may sound like skipping this step in the training of O&M personnel to be the last to go but that is however not the case. It is so often that top of the line BMS programs are bought and installed and the owner sees opportunity for savings in the training of O&M personnel and unfortunately is the performance tracking often the part to be cut out of the training program. With BMS programs, as with so many programs, they do not work better then the person controlling them (Friedman, Potter, Haasl, & Claridge, 2003) (Claridge, et al., 2003).

In order to be able to improve building performance and efficiency the first step is to evaluate your current operating systems and practices. To be able to evaluate the system a BMS that is capable of performance tracking must be available. When the building performance and efficiency has been evaluated it can then be compared to other similar buildings to see if the energy usage is similar or there are possibilities for improvement. This practice is called Benchmarking and is gaining more and more momentum in today's operation of buildings due to increasing energy costs and climate changes awareness (Friedman, Potter, Haasl, & Claridge, 2003) (Claridge, et al., 2003).

The ability to be able to benchmark a building's performance and use the statistical data to continually improve the performance of the building systems does not only help the O&M personnel to see if performance level has been maintained it also conduces further development of building systems towards increased efficiency and performance due to constant comparison with competitors buildings. It also gives the owner the possibility to be able to track the energy use and cost over time and see how they stack up against the competition (Friedman, Potter, Haasl, & Claridge, 2003) (Claridge, et al., 2003).

In the USA there are mainly two benchmarking tools that have gained a wide acceptance. Those are ENERGY STAR Portfolio Manager (http://www.energystar.gov/) and the Cal-Arch Building Energy Reference Tool (http://poet.lbl.gov/cal-arch/). This report will not go into detail how these benchmarking tools work or how the procedure is but further information on these tools can be found at their websites.

# 6 Comparison of Bryggen and Bruuns Gallery

To get a glimpse at how the commissioning process has affected the energy consumption and operational costs of buildings in Denmark two shopping malls will be compared. This comparison should not be viewed as demonstration of best use of practice or that it reflects the results for other building commissioning projects in Denmark but rather to show what the difference was in two similar building projects in Denmark.

The two shopping malls that will be compared are Bryggen in Vejle and Bruuns Galleri in Aarhus. Table 2 shows key information for both shopping malls such as size, opening year, what building regulation was valid at construction time and who main contractor was. All these parameters are similar for these two shopping malls except the size and if there is a movie theatre. Bruuns Galleri has a movie theatre and is about 33% larger in size. The fact that the same building regulation BR95 was used for both shopping malls makes these two shopping malls comparable without having to take into consideration changes to energy standards that were included in the BR08. Since the same main contractor was used in both shopping malls and that Bruuns Galleri was used as a building reference for Bryggen that eliminates a lot of uncertainties such as work procedures, building structure and contractors' experience.

**Table 2: Shows key information for Bryggen and Bruuns Galleri.**

| | Bryggen | Bruuns Galleri |
|---|---|---|
| Location: | Vejle, Denmark | Aarhus, Denmark |
| Size: | 56.363 $m^2$ | 85.022 $m^2$ |
| Opening year: | 2008 | 2003 |
| Stores: | 80 | 85 |
| Cafe/restaurants: | 2 | 5 |
| Movie theatre: | 0 | 1 (2.011 seats in 8 auditoriums) |
| Building regulation used: | BR95 | BR95 |
| Main Contractor | NCC | NCC |

In Bryggen building commissioning was used throughout the building process. Were the main focus of the commissioning process was to lower operational costs by decreasing energy consumption of the building and creating the basis for structured O&M. However commissioning was not used in Bruuns Galleri and have there been numerous problems

that have still not been solved and the effects they have had one the shopping mall have affected the comfort and energy consumption of the building.

Grontmij|Carl Bro served as commissioning authority in the commissioning process at Bryggen and the commissioning team consisted of employees of Grontmij|Carl Bro who initially developed the OPR together with Steen & Strøm Facilities directors, later in the process with Steen & Strøm's project manager and during the final stages with the local O&M manager.

The data available to analyze were monthly values for consumption of electricity, energy used for heating and hot water production and water consumption. Of these three measurements the commissioning process tried to have an effect on the electricity consumption and energy used for heating by increasing efficiency. Therefore the main focus of the analyses will be to try to identify if the commissioning process was successful in reducing electricity consumption and energy used for heating and the water consumption will be used to determine if the energy is used for heating or hot water production.

The data is obtained through the website www.minenergi.dk which is a website that shows energy consumption for defined meters by the customer, Steen and Strom in this case. The values for the defined meters are then updated automatically on a monthly base and the website can be configured to send alerts via email to users when consumption that is greater than the specified alarm limit of each meter, thus additional consumption is disclosed immediately and action can be taken.

The time that will be analyzed is the time that both shopping malls have been in operation which is from May 2008 to April 2010.

## *6.1 Electrical Consumption*

Electricity is the main energy source for most of the systems that are used in shopping malls and of those these systems the following systems have high consumption.

- Light systems
- Cooling systems
- Hydraulic systems
- Ventilation systems

It is important that these systems are designed properly, installed correctly and tuned to achieve high efficiency. The reason why this is important is that the main source for heat in stores in shopping malls is the lights in each store. All this extra heat requires added cooling and if these two systems are not carefully designed and tuned it can increase the electricity consumption drastically. These two systems were among points that were focused on in Bryggen by the commissioning team which will be discussed later.

It should though be noted that in both Bryggen and Bruuns Galleri Steen and Strom could not have an effect of the use of lighting.

The electricity consumption for each month for Bryggen and Bruuns Galleri for the time period May 2008 to April 2010 can be seen presented in graphs in appendix B and table 3 shows the summary for electricity consumption p. $m^2$ and the difference between the consumption of the shopping malls for each year.

**Table 3: Shows a summary for electricity consumption for Bryggen and Bruuns Galleri.**

| Electricity consumption p. $m^2$ | 2008 (kWh/$m^2$)* | 2009 (kWh/$m^2$) | 2010 (kWh/$m^2$)** |
|---|---|---|---|
| Bruuns Galleri | 45,91 | 39,07 | 9,11 |
| Bryggen | 27,73 | 23,31 | 4,19 |
| Difference between electricity consumption | 40% | 40% | 54% |

* = Only the time period from May to December of 2008.
** = Only the time period from January to April of 2010.

As can be seen in table 3 that Bryggen used 40% less electricity p. $m^2$ for 2008 and 2009 and for the months that have passed of 2010 the difference is 54%. This significant difference between the shopping malls cannot solely be due to the fact that commissioning was used in the building process of Bryggen. However the difference is to some extent the success measure of the commissioning process to have identified and recommended specific care for:

- Cooling systems
- Automatic controls
- Hydraulic balancing
- Careful planning of lighting zones and lighting control in public areas
- Meetings with design engineer about total economy issues for ventilation and cooling
- O&M personnel were included in the commissioning process during the construction phase and because of that did know the system well before the opening.

There are also reasons that may have increased the electricity consumption in Bruuns Galleri and therefore increase the difference between the shopping malls. Some of the reasons are:

- Problems with O&M providers.
- High turnover of O&M personnel.
- Limited focus on data analysing to identify upcoming problems and possible improvements.
- No specific O&M related focus on technical installations, HVAC, Cooling, BMS etc. during the building process have resulted in installations below average measured with an O&M scale

## 6.2 Energy used for heating and hot water production

The energy used for heating and hot water production for each month for Bryggen and Bruuns Galleri for the time period May 2008 to April 2010 can be seen in graphs in appendix C and table 4 shows the summary for energy used for heating and hot water production p. $m^2$ and the difference between the consumption of the shopping malls for each year.

**Table 4: Shows key values for energy used for heating and hot water production for Bruuns Galleri and Bryggen from May 2008 to April 2010.**

| Energy used for heating and hot water production p. $m^2$ | 2008 (kWh/$m^2$)* | 2009 (kWh/$m^2$) | 2010 (kWh/$m^2$)** |
|---|---|---|---|
| Bruuns Galleri | 10,393 | 30,195 | 20,201 |
| Bryggen | 11,879 | 19,775 | 11,743 |
| Difference between energy consumption: | -14% | 35% | 42% |

* = Only the time period from May to December of 2008.
** = Only the time period from January to April of 2010.

The water consumption for each month per square meter for Bruuns Galleri and Bryggen can be seen in appendix D and table 5 shows the yearly water consumption for both shopping malls per square meter for the time period May 2008 to April 2010.

**Table 5: Shows key values for water consumption for Bruuns Galleri and Bryggen from May 2008 to April 2010**

| Water consumption p. $m^2$ | 2008 ($m^3$/$m^2$)* | 2009 ($m^3$/$m^2$) | 2010 ($m^3$/$m^2$)** |
|---|---|---|---|
| Bruuns Galleri | 0,165 | 0,257 | 0,085 |
| Bryggen | 0,091 | 0,129 | 0,035 |
| Difference between water consumption: | 44% | 50% | 59% |

* = Only the time period from May to December of 2008.
** = Only the time period from January to April of 2010.

The data available does not give a clear picture how the difference is because during the period from July to September in 2009 the meters in Bryggen are probably not working as intended. Table 6 shows the difference between these months from 2008 and 2009 and as can be seen it is not normal that the consumption drops by more than 450% between years.

**Table 6: Shows the difference between years in Bryggen over three months.**

| Month | Bryggen – 2008* (m3/m2) | Bryggen – 2009* (m3/m2) | Difference 2008-2009 |
|---|---|---|---|
| July | 0,57722 | 0,0057 | -9950% |
| August | 0,69496 | 0,0546 | -1174% |
| September | 1,05106 | 0,1809 | -481% |

* = Only the time period from May to December.

The commissioning process in Bryggen did not have any focus on decreasing water consumption for the shopping mall so they are presented here to show that water consumption is quite consistent between years in both shopping malls.

Consumption for Bryggen from May to December for 2008 and 2009 did only increase by 0,4% and the first 4 months of 2010 compared to 2009 has decreased by 8% and the story is similar for Bruuns Galleri where consumption only increased by 6% from 2008 to 2009 and just 3% for 2010 compared to same months of 2009. Therefore it can be assumed that the difference between the two shopping malls in energy used for heating and hot water productions is due to difference in energy used for heating.

Bruuns Galleri and Bryggen have either similar or Bruuns Galleri uses quite less energy for heating and hot water production until June 2009 then suddenly Bryggen shows consumption that is 9% less then Bruuns Galleri and from there Bryggen has on average used 39% less then Bruuns Galleri and consumption of Bruuns Galleri has increased by average 17% from 2008 to 2009 as can be seen in graphs in appendix C.

As stated above based on how consistent the water consumption has been for both shopping malls the difference in energy used is due to heating. What the problem is is hard to identify but due to how high turnover of O&M staff Bruuns Galleri has experienced it should not be ruled out that part of the reason for such an inverse development of energy consumption for heating maybe because of how the system is maintained and tuned.

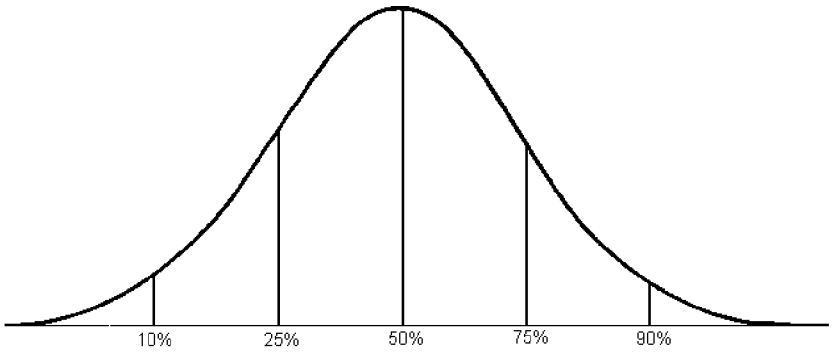

**Figure 28: Shows the normal curve.**

It should be clear now that Bryggen uses less energy p. $m^2$ compared to Bruuns Galleri but is Bruuns Galleri a bad example that would make most shopping malls look good in comparison? To answer this question will the yearly consumption p. $m^2$ values for 2009 be compared to a normal curve for energy consumption for shopping malls in Denmark in 2005 (ELO-sekretariatet, Teknologisk Institut, 2010). The electricity consumption and energy used for heating for Bruuns Galleri fall between the 25% and 50% and the water consumption falls below 10%. This shows that the energy consumption for electricity and heating is below mean values compared the normal distribution curve for shopping malls in Denmark 2005 and the water consumption is below the 10%. This should show to some degree even though the normal distribution curve is from 2005 that Bruuns Galleri is far from being the worst example.

## 6.3 Operational and maintenance costs

Even though there might be factors that could have an effect on the total energy consumption of these shopping malls, good or bad, it should though be clear that Bryggen uses less energy p. $m^2$. But is Bryggen also less expensive in operation and maintenance of the building systems than Bruuns Galleri? To get a rough idea how these two shopping malls compare, the data on operational cost for building systems for both buildings will be analyzed since commissioning mainly affected the building systems in Bryggen.

The data that was available limited the possibilities to identify non-energy benefits in Bryggen due to commissioning but with the data available will the O&M costs, excluding energy costs, for both shopping malls be analyzed to find out if there is a difference between them.

The data that was available in both cases was from the first year in operation and up to April 2010. But the O&M cost data for Bryggen 2008 is missing several values therefore does it only give meaning to compare 2009 and January to April of 2010.

The work that is included in the O&M building system cost data is all service and repair on building systems such as ventilation, cooling and BMS programs. Table 7 shows the values p. $m^2$ for both buildings for the period described earlier.

**Table 7: Shows the O&M costs for Bruuns Galleri and Bryggen for 2009 and 2010 p. $m^2$.**

| O&M costs p. m2 | 2009 (DKK/$m^2$) | 2010 (DKK/$m^2$)* |
|---|---|---|
| Bruuns Galleri | 5,62 | 1,81 |
| Bryggen | 5,01 | 2,03 |
| Difference between O&M costs: | 11% | -12% |

* = Only the time period from January to April of 2010.

As table 7 shows that the difference between the operational costs of the buildings is not great. Bryggen has 11% lower O&M costs p. m2 for 2009 but for the period of 2010 it has used 12% more than Bruuns Galleri. Due to how short period of a time is available for comparison the data is not extensive enough to show trends in O&M costs and therefore is it hard to justify that one building has lower O&M costs than the other. However from the data available it seems that O&M costs p. $m^2$ for these two buildings might be quite similar. Since it can be expected that there are some spikes in O&M costs due to several reasons such as:

- Regular service of building system that is not annual.
- Work related to equipment changes e.g. changing filters.
- Service and repair due to unforeseeable situations.

For Bryggen it is a positive result that O&M costs are similar because that shows that it is not more expensive to run and maintain a building systems that have a high performance level and efficiency as showed earlier how more efficient it is in energy consumption compared to Bruuns Galleri.

From this limited data it can be interpretive that O&M costs are a constant up to a point since both Bruuns Galleri and Bryggen have similar O&M costs p. $m^2$ while the outcome is the opposite. Therefore is it an important role of the management division in head of the O&M staff to utilize the budget in the most optimized way to ensure performance level does not drop.

## *6.4 Would commissioning have had positive effect on Bruuns Galleri?*

In 2008 were five years since Bruuns Galleri was taken in operation and therefore was time for the 5 year inspection. Grontmij|Carl Bro was hired to do the five year inspection of the building. The results from the five year inspections showed number of problems and when these problems are analyzed the results were that a lot of the problems are either design flaws or poor methods of work by the contractors. This also shows that the quality assurance process used during the building process was far from being successful and the owner of the building did not his needs and requirements fulfilled.

The five year inspection categorized the problems into three different categories:

- Construction issues
- HVAC issues
- Electricity issues

The number of problems reported in each category was as follows:

- Construction issues – 118 issues
- HVAC issues – 62 issues
- Electricity issues – 32 issues

Of course it is not expected that the results from a five year inspection are zero issues but when the issues that were reported are reviewed it shows that some of these issues could have been prevented with proper quality assurance process.

Some of the issues that were reported in the five year inspection but could have been prevented if commissioning would have been used along with the normal quality assurance process are:

***Construction issues:***

- Screws between brackets and washer/rail in windows were galvanised instead of being stainless. This causes heavy corrosion between the screw, bracket and washer/rail.
- Several issues are regarding that the roof leaks and the consequences of the leakage such as damaged ceiling tiles.
- Construction joints in the south basement wall are not waterproof and there is a leakage.
- Joints of pipes from toilets were not according to standard which caused bad odour inside the building.

***HVAC issues:***

- 23 out of 62 issues concerned lack of documentation which is one of the key benefits of commissioning.
- Drawings of HVAC systems were not completed neither drawings from design phase nor drawings that have been updated to show the system as-built.
- Cooling water temperature is not affected by the outside temperature.
- Cooling pipes were leaking at joints and correct labelling of type of pipe and direction of flow were lacking.

***Electricity issues***

- Ground wires were found unconnected in the fuse box and the main fuse box was not delivered according to specification
- Few damper motors were located in the ceiling in places where it was hard to maintain them. Which increases the O&M cost.
- In general were electrical and other outlets not labelled
- Electrical and other outlets were located in places that did not fulfil laws and rules set by the Danish Safety Technology Authority.

The issue with the joints of pipes coming from toilets was known before the five years inspection and Steen and Strom had reached out to several different professionals to scrutinise the system and try to identify the issue that is causing the bad odour. These professionals were not successful in being able to identify the problem causing the odour and the reason why is probably their lack of experience on the actual operation of the piping and/or knowledge about standards for piping. For some time the solution for the issue was to clean the pipes regularly to minimize the odour. This solution is an excellent example of a "band-aid" approach and what results the "band-aid" approach has. When Grontmij|Carl Bro were brought in to see if they could identify the problem causing the odour they were successful and part of the solution was in the joints of the pipes. The pipes were with a joint with 90° angle instead of using two 45° angle joints in each turn. This is an issue that could have been avoided if the design of the piping system would have been scrutinised by a expert in piping during the design phase.

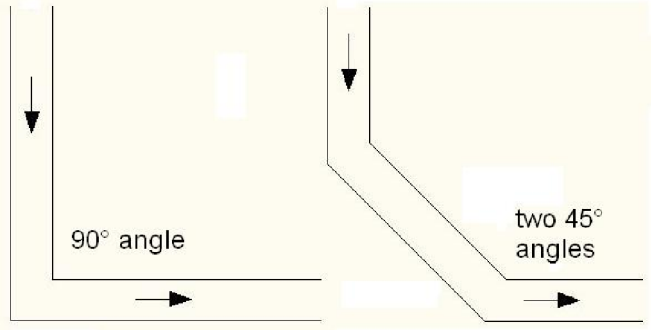


**Figure 29: Shows the difference between a 90° pipe joint and a two 45° pipe joints.**

Other issues mentioned earlier such as labelling of electrical and other outlets and lack of documentation in HVAC systems are issues that can increase operational cost significantly due to O&M staff are forced to guess or use trial and error to figure out where a specific

equipment is located in the building for example where the Ethernet outlet is that is causing the loop in the local net.

It is although not guaranteed that a commissioning process would have identified all these issues but if the process is well developed and the members of the commissioning team are experienced it is more likely that at least the biggest issues would have been identified. To find solution to some of these problems such as lack of documentation, joint of pipes from bathrooms and electrical and other outlets locations during the building process are example of issues that would have resulted in first cost savings if commissioning would have been used and therefore lower the payback time of the commissioning process plus the cost of applying the necessary solution to fix each issue is always cheaper during construction than to apply the changes in operation phase.

So based on the issues identified in the five year inspection report it is clear that Bruuns Galleri would have gained a lot to have included a commissioning process throughout the building process. Plus the amount that has been spent on "band-aid" solutions and the cost that lies in issues that have still not been fixed is probably far more than the total cost of a commissioning process.

It is easy afterwards to look at for example the five year inspection report and judge from that if commissioning would have been cost effective but it should not be overlooked the value for the owner of being handed a building at day one that works as intended. Also does the cost of commissioning decrease if the project is well designed and constructed but the possibilities are still at hand to make the commissioning process cost effective.

## *6.5 Whole life cycle costs calculation as a decision tool*

Whole Life Cycle Costs (WLCC) is a technique to calculate the total cost of a system or equipment for a defined period of time. It is a structured approach that addresses all the elements that have to be thought of when calculating initial and future costs and can be used to produce a cost profile of a system or equipment over its anticipated life-span. The results of a WLCC analysis can be used to assist management in the decision-making process where there is a choice of options. The accuracy of WLCC analysis diminishes as it projects further into the future, so it is most valuable as a comparative tool when the same long term assumptions apply to all the options.

In the shopping mall Bryggen in Denmark the technique whole life cycle costs calculation was used as a decision tool to decide what the cooling water temperature should be. The calculations were performed by the design engineers firm Niras A/S.

First step was to identify what air temperature were preferred inside the shopping mall and the temperatures that were preferred were:

- 24 °C during the summer.
- 22 °C during the winter

Next step was to identify needed parameters to be able to calculate electricity usage per year for different cooling water temperatures. The key parameters were:

- Coefficient of Performance (COP) value for cooling system: 4
- Ventilation cooling: 1.200 kW
- Store cooling: 900 kW

Next were three different temperatures for the cooling water defined that would be used in the calculations, number of hours of free cooling for each temperature and total operating hours (including free cooling) were found out from opening hours for the shopping mall then net total operating hours which were calculated by subtracting number of free cooling hours from total operating hours. Table 8 shows the values for all these parameters and the total kWh for each year.

**Table 8: Shows key parameters and their value for the whole life cycle cost calculation for the cooling water temperature for Bryggen (Grontmij|Carl Bro, 2006).**

| Cooling water temperature | Hours of free cooling per year (h/year) | Operating hours per year (h/year) | Net operating hours per year (h/year) | Total kWh per year (kWh/year) |
|---|---|---|---|---|
| 6 °C / 12 °C | 645 | 3.923 | 3.278 | 1.528.648 |
| 9 °C / 15 °C | 1.303 | 3.923 | 2.620 | 1.385.691 |
| 12 °C / 18 °C | 1.884 | 3.923 | 2.039 | 1.559.515 |

As can be seen in table 8 the lowest total kWh per year was for the cooling water temperature 9 °C / 15 °C. The cooling water temperatures used in the calculation have always 3 °C between each test. To see if the temperature 9 °C / 15 °C had the lowest energy usage the same calculations were made with temperatures +/- 1 °C of 9 °C / 15 °C. The results showed that the optimum temperature lies between 9 °C / 15 °C and 10 °C / 16 °C therefore it was decided that the cooling water temperature should be 9 °C / 15 °C.

This usage of whole life cycle cost calculation is an excellent example of how WLCC can be used to minimize operating costs and give decision makers a valuable tool to be able to rationalise their decisions with facts.

The calculation does not take the different costs of installing the cooling system depending on the temperature spans, into account. This hidden part of the calculation is done by the contractor, and it is related to the price of the equipment that must be installed to suit the different solutions. The WLCC actually includes the building costs plus the O&M costs in a specified period. Probably will the actual calculation result in an extra bill from the contractor while it requires more expensive cooling sections in ventilation plants, fan coils etc. when the temperature rises.

The complete report from the whole life cycle cost calculations done by Niras A/S and used by Grontmij|Carl Bro can be found in appendix A.

# 7 How the commissioning process is in Grontmij|Carl Bro

After having spent three months following a few commissioning processes at Grontmij|Carl Bro the author found out that their process is not as detailed as described in chapter 3. That does not have to mean that it is not as good but it is missing a few steps throughout the process. The reason for this is not solely because of how Grontmij|Carl Bro have developed their commissioning process but also how the market has responded to commissioning and what it expects of commissioning regardless of what it has to offer.

Building commissioning was first used by Grontmij|Carl Bro in the year 2000 and since then they have been developing their process. Grontmij|Carl Bro has not been involved in many whole building commissioning projects but over the last 10 years they have gained a lot of experience in commissioning projects with main focus on HVAC systems.

Apart from the size of the project the steps that Grontmij|Carl Bro follows throughout the commissioning process are always the same just with different emphases from project to project. The steps that describe the commissioning process at Grontmij|Carl Bro are:

- Interview the customer of what his expectations are for the building system that is going to be commissioned.
- Verify that the OPR (building program) clearly states what the acceptance criteria for performance level and efficiency for the building system are.
- Scrutinising the construction documents regarding the specific building system that will be commissioned and document all identified issues in a “commissioning report”.
- The design team receives a copy of the commissioning report and is asked to review the issues and comment on what actions will be taken.
- Developing testing paradigms together with the contractors
- On site inspection when building systems are close to finished being installed.
- When the building system has been installed it is tested and the data gathered to verify if it fulfils the OPR.
- Analyze the test data to determine if the system fulfils the OPR.
- Update the commissioning report to show present status of issues that were identified.
- Send the customer a copy of the commissioning report and the test results for the building system.

The first step in the commissioning process for Grontmij|Carl Bro is to interview the customer and identify clearly what his expectations, needs and requirements for the building system that is going to be commissioned are. From there the next step is to go over the OPR, called building program in Denmark, to see if that particular system has been documented with clear and precise acceptance criteria for performance level and efficiency. If Grontmij|Carl Bro is included in the beginning of the building process these two steps are done in the pre-design phase. If they are included when the design phase has started the possibility to change the OPR without added cost is not possible.

Next step in the process is to start scrutinising the design to look for issues that can be improved or do not meet the acceptance criteria in the OPR. All the issues that are identified are documented in a document they call "Commissioning report" it should be noted that what Grontmij|Carl Bro call commissioning report is more in style with the Issue log described in section 3.1.3. When the building system has been scrutinised and all issues documented the commissioning report is sent to the company in head of the design and they are asked to go through the document and comment, in the report, on what actions will be taken on the issues. If they think that no action is needed for some of the issues they are asked to show arguments to support their decision.

It is common for the commissioning report to be bounced back and forth between Grontmij|Carl Bro and the company in charge of design until all issues have been addressed. In the commissioning reports the author has seen through my co-operation with Grontmij|Carl Bro in this thesis it is often the case that some of the issues are flaws or mistake that the design team overlooked and will be solved with the suggestions from the commissioning team in mind but there are also some issues that the design team does not think needs to be changed or fine tuned and there is nothing Grontmij|Carl Bro can do since there role as commissioning authority is only to identify possible problems but the design team has the power to decide whether or not they will change their design as long as it fulfils the OPR. These steps are preferably performed during the design phase but can be done in the construction phase but that will very likely add cost and time delays.

When the scrutinising is done and design team has addressed all the issues and the owner has gone over the commissioning report with comments from both parties. Grontmij|Carl Bro comes back in the building process when systems are close to finished being installed and they do on site inspections to prepare for test procedures and verify that the system is being installed according to contracts. When the systems are installed Grontmij|Carl Bro does the test, are present when the test is done or they trust the contractor to do the test. But regardless of if they do the test, are present when it is done or not on site they always go over the test data and the report the contractor makes where he shows the results from the test and that the system does fulfil all the acceptance criteria of performance level and efficiency of the OPR. These steps occur at the end of construction phase or beginning of operation phase in new constructions but in existing buildings they occur in operation phase.

When Grontmij|Carl Bro has gone over the report from the contractor and test data and approved that the building system does fulfil the OPR the customer, in most cases the owner of the building, receives a copy of the commissioning report that has been updated to show the status of all issues, and the results from the tests.

The commissioning report follows the building in the future, and is updated at regular intervals, for example when one-year and five-year inspections are done.

The commissioning process in Grontmij|Carl Bro shows great potentials and has established a good base to build upon. Possible improvements that can further develop their commissioning process will be discussed in next sub-chapter.

## *7.1 Possible improvements*

No process is perfect therefore is always room for improvements but as the process gets better the value of the improvement may become less visible.

As mentioned earlier the commissioning process that Grontmij|Carl Bro has developed is missing few steps compared to a typical commissioning process described in chapter 6. Therefore are the possible improvements to try to include more of the steps in chapter 6 in their commissioning process.

Based on the authors experience over the three months at Grontmij|Carl Bro there are a few areas the author would focus initially try to improve. These areas are:

- Clearer order and setup
- More documentation
- Increase the scope of the commissioning process
- Data gathering after commissioning projects

### *Clearer order and setup*

- Use the internal network storing system more.
- Add the possibility for participants in the project to view and/or upload newer version of documents or drawings through a web site that would also update the internal network storing folder.

The internal network storing system is already available but has to be used more and the author thinks that if it were possible for participants in projects outside of Grontmij|Carl Bro to upload and/or view the newest version of all relevant documents for a specific project would decrease time wasted to sort documents and the situation when two participants are analyzing a document without being aware they are not viewing the same version of the document.

This improvement would not only improve the commissioning process but all projects where there are multiple participants since the newest version of all documents whether

it is a drawing or a time schedule it is always available at this specific website that is accessible by all relevant participants.

An example of a web based program that could solve this is ProjectWeb and Grontmij|Carl Bro is already offering ProjectWeb service for companies (Grontmij|Carl Bro, 2010). So the knowledge of the program and the program itself is available at Grontmij|Carl Bro but it just has to be put to use for their own benefits.

***More documentation***

- Make a commissioning plan in the beginning that is updated throughout the building process.
- Publish commissioning reports after each phase and a final report after construction that summarises key commissioning activities and issues from the issue log.
- More strict and standardised use of documents, commissioning plan, OPR, Basis of Design, Issue log, milestone reporting, plan for continuous commissioning etc. all with the focus that bureaucracy is minimised!
- Seek certification of the commissioning processes

In the early stages of a project to make a document called commissioning plan as described in sections 3.1.5 and then update it as described in sections 3.2.4 and 3.3.5 will serve as a good overview tool for the commissioning authority and the commissioning team to see who is responsible for each activity. After discussion with Ole Teisen from Grontmij|Carl Bro regarding such a plan he said that it is used in some projects but agreed that it should be used in all projects.

As mentioned earlier that Grontmij|Carl Bro calls their issue log a commissioning report but if they would change the name to issue log and start publishing commissioning reports after each phase and a final version at the end of the commissioning process that contains the information listed in section 3.5.2. By publishing such reports after each phase gives a nice overview how last phase progressed and if it was not in line with what was expected if can be fixed in next phase instead of realising at the end of the commissioning process that some activity or other issue was not getting the expected results.

***Increase the scope of the commissioning process***

- More emphasises on ensuring O&M staff are capable of maintaining the performance level.
- Persuade the customers to include more focus points, for example the building envelope.

As section 4.4 and chapter 5 have shown that high performance level and efficiency are not guaranteed even though they are attained at the beginning of operation it needs to be maintained. To maintain the performance level a proper O&M staff is needed that is capable of maintaining the building system so the energy savings are maintained

throughout the lifetime of the building. From the data from Bryggen it can be seen that the systems are not very consistent from year to year and by putting more emphasises on ensuring O&M staffs capability to maintain the performance level the benefits of the commissioning process are more likely to be long lasting.

To further develop their commissioning process without increasing its scope could be to examine what has worked in countries that are more experienced with commissioning in similar projects, in size and complexity and try to learn from their experience and improve their commissioning process.

***Data gathering after commissioning***

- Start gathering data on energy consumption and O&M costs of building systems that have been commissioned.

By starting to gather data on energy consumption and O&M costs of building that have been commissioned serves mainly two purposes.

- To increase the knowledge that can be learned from previous projects.
- To be used as a benchmark of the success Grontmij|Carl Bro commissioning process has achieved in its previous projects.

The data gathered on energy consumption and O&M costs can increase what can be learned of previous projects by seeing how solutions to problems develop over time and from that can the solutions that did not last be eliminated instead of being repeated with the good intention and solutions that resulted in long lasting benefits be used with the knowledge that they last.

The results from such data gathering can then also be used for Grontmij|Carl Bro to see how their commissioning process is developing based on results and these results can then be used to show possible new customers what has been the results from previous commissioning projects.

But regardless of how or what route Grontmij|Carl Bro chooses to take to further develop their commissioning process it would be wise to establish data gathering on their commissioning projects to be able to review how their recommended changes behave over time and in what direction the process is developing based on results from previous projects.

# 8 Future of commissioning and how it can be implemented

As the building process is today in Denmark the commissioning process is still not viewed as "business as usual" and until that has been changed the commissioning process needs help to be involved in more building projects. One of the biggest barrier commissioning has in Denmark and other countries where commissioning is taking its first steps towards being "business as usual" is cultural barrier. The cultural barriers are quite different from one participant of the building process to another. Some of the cultural barriers commissioning is trying to overcome are:

- Lack of understanding what building commissioning is and its purpose within the building process.
- Negative attitude among design professionals and contractors towards the commissioning team because they feel like the commissioning team is watching over their shoulder.
- Owners think that what commissioning has to offer should already be provided by the design team and contractors.
- Owners view the cost of commissioning as added cost without taking in to consideration the possible payback time.

How can commissioning then be more implemented if these are the barriers it is facing?

In general when new technology or concept is trying to be implemented there are two ways that can be chosen:

- Forced implementation through laws, regulations and standards.
- Unforced implementation where what the technology or concept has to offer and how it can be used are introduced and then the market is given the power to decide if they want to use the technology or concept.

Both these ways have their advantages and disadvantages and the main advantages for the unforced implantation can be described with the phrase "Survival of the fittest", from Herbert Spencer, in that sense that if the technology or concept is good the market will notice that and start using it to their advantage without being forced and on the same time will similar technologies or concepts be under in the battle for recognition and usage. The disadvantages of the unforced implementation are that often can the market be blind on what is best for itself and therefore make the wrong decisions regarding what new technology or concept should be implemented.

The forced implementation is the opposite of the unforced one as the names imply and therefore are the advantages of the forced one the disadvantages of the unforced one and vice versa. What is quite important if the forced implementation route is chosen is that the people responsible for taking the decisions to what will be forced to be implemented are objective and can be trusted to make decisions with the interests of the market solely in mind instead of their own. The forced implementation process is not far from how the political setting is in the western world were the public votes who will be the leaders of the country and trust them to guide and make decisions that are in favour of the public and country.

To get back to the question how can commissioning be more implemented when these are the barriers it is facing? The route that should be taken to achieve that is a mix of the forced and unforced implementation. As was discussed in chapter 2.3 how commissioning evolved in the USA the approach that was taken there is not far from what I think is the optimal way to implement commissioning into the normal building process.

The steps that the author finds are ideal ways for commissioning to be more implemented without going solely the forced way are:

- Use extensive commissioning process in the next large construction of a public sector building construction and use it as a showcase for commissioning.
- Regular updates on the results from the commissioning process of the showcase.
- Laws, regulation and standards updated to state that public sector buildings above a specific size have to use commissioning in their building process and regularly after that.
- Keep publishing and gathering the results from commissioning projects in a databank.

The next building for the public sector that is going to be constructed should use an extensive commissioning process throughout the building process and afterwards go into ongoing commissioning process. The point of that would be to show what the benefits of commissioning are and how they can be achieved and with ongoing commissioning illustrate that it is important to monitor these benefits so they are long lasting and possible increase the value of the benefits and make new benefits through improvements. The results from such a project should be used as a showcase for commissioning and what it can do to increase energy savings, smoother turn over from contractor and more optimized O&M phase.

Such a case could also show that it is possible without much added cost to document benefits of commissioning throughout the life time of a building and an extensive databank could be established were the method used in the showcase is applied in commissioning projects to come. From there when the databank is large enough a research can be made to see what the trend of the benefits of commissioning are. The optimum solution to such a databank would be to get a university involved who would help in identifying necessary parameters and possible ways they can be measured.

When the results from such a showcase are available they have to be presented and published so the public and interested companies can know what the outcome was. It would also be recommended to have a workshop were the methodology and how it was used is introduced and taught to future commissioning authorities. Such a process is quite important because it will encourage knowledge sharing for common problems and what has worked best for each one.

Around the time when the results from the showcase of the commissioning process are known it would be a suitable time for the government to update laws, regulations and standards to state that specific public building types have to use commissioning throughout the life time of the building. The reason why this is a good time to force usage of commissioning is because the methodology has been tested on the showcase building and the results are known therefore is there less doubt to what the outcome will be. So it can be viewed like the government is expending the showcase to include more buildings gradually until the experience and knowledge of commissioning is great enough to handle all public buildings and hopefully by that time the private sector has realised the economical possibilities that commissioning has to offer.

If commissioning were to come to a point where it has become “business as usual” it is important that documentation of benefits and updating the databank is not stopped because it is an important benchmarking tool for the commissioning process in each country to know how the development is. The following questions could be answered if such a databank existed. Have there been changes that have lead to improvements in more benefits or added value of each benefit or have the changes caused relapse in development of commissioning?

Like stated above that a similar method was used in the USA to implement commissioning with the difference that the first step was to force usage but the results are that commissioning is gaining more and more momentum and in some states such as California it is among the closest to implement commissioning as “business as usual”. With that in mind and the results commissioning has had on buildings there the author finds the optimum solution to be a mix of forced and unforced implementation.

The future of commissioning will be greatly affected of how the implementation of commissioning to become “business as usual” progresses but the positive possibilities commissioning can have such as great reduction in $CO_2$ pollution because of energy savings and improved in-door air quality that increases the productivity of workers are among the benefits that should ensure that commissioning becomes “business as usual”. Regardless of how that will progress it is vital that an approved certification process is established that companies that want to be able to offer commissioning service have to have employees that have passed this certification process. It would probably be best if there were to be made an ISO standard for the commissioning process that all companies would follow and the certification process would then be a test to determine if companies are in fact following the ISO standard on day to day basis. Similarly to the ISO 9001 certification process for quality management systems. The sooner such a standard is made

the better since it will eliminate some of the weaknesses and threats commissioning faces in today's world such as companies offering commissioning service that is merely a test, adjust and balance service and commissioning authorities with limited experienced and knowledge are not capable of serving as a commissioning authority. The weaknesses and threats that could be eliminated with certification process do only make the implementation of commissioning harder because of the bad reputation these issues are causing.

# 9 Discussion

The commissioning process in Denmark has over the years been allowed to develop without supervision which is fine however it is important to start looking into what results the commissioning process is achieving. This is especially important due to the fact that there is no certification process for companies or employees offering commissioning service and therefore there is no guarantee that the results are overall positive. It is important that the company or organization that leads the research is capable of being objective and has no financial connections to any of the stakeholders in such a research since that would decrease the credibility of the results from the research. With these requirements for the leading company or organization it would be most suitable that a university would lead such a research and work in co-operation with companies that are or have provided commissioning service in building projects.

Such a research would be quite expensive since it would take at a minimum a few years before any results could be published, since first the methodology has to be developed and data gathered and screened to see if it is suitable. Such research could be done partly through a Ph.D. project where the methodology is made and applied to a small sample of buildings to get a glimpse if the methodology needs further improvement. The comprehensive study could then be carried out through funds and grants from the government and by applying for grants to the EU.

As has been showed in this report that there have been several studies that have looked into and tried to measure the value of benefits of commissioning, both energy and non-energy, economically and numerically. These researches have shown without a doubt that by using building commissioning energy savings are achieved. In December 2009 there was a large conference in Copenhagen on climate change with the purpose to try to make a world agreement on reducing $CO_2$ emissions in each country by a certain percentage. For most countries that rely heavily on un-sustainable energy resources they could go a long way in fulfilling the percentage of reduced emissions by commissioning high energy consuming buildings to achieve energy savings which leads to reduced $CO_2$ emissions.

A small chapter in the research done by Mills (2009) took the median whole building energy saving for existing buildings and did a rough estimate what the total energy savings would be in dollars for the next 20 years and what the total energy saving would corresponds in emission of $CO_2$. The results were $30 billion and the total decrease of energy usage corresponded to 340 megatons of $CO_2$ that would not be emission into the atmosphere. This estimate is over a long period of time but it is only set forward to show

how large numbers both in savings and reduced $CO_2$ emission could be achieved if commissioning would be used in all non-residential buildings. The median value that is used in these calculations is far from being an example of best use of practice which makes this estimate more likely to be accurate.

## *9.1 SWOT analysis of commissioning*

The aim with the SWOT analysis is to summarise the key advantages and disadvantages of building commissioning that have been stated in this thesis as well as bring forth other advantages and disadvantages that may not have been stated in the thesis due to the author did not find any reference to back up these issues.

To summarise the advantages and disadvantages of building commissioning a SWOT (Strength, Weakness, Opportunities and Threats) analysis will be used to further divide advantages into either strengths or an opportunities and the disadvantages into either weaknesses or threats.

By doing so it gives a clear idea of what issues should be emphasized to make the building commissioning process even better, what opportunities give the possibility of introducing building commissioning to improve the building and the building process, what weaknesses should be resolved to improve the building commissioning process and it also shows what threats should be avoided.

### *9.1.1 Strengths*

- Helps the owner to identify, document and define a measurable acceptance criteria for his true requirements and needs for the building in the OPR.
- Encourages increased communication between all involved parties.
- Helps all parties to meet its cost objective by reducing costly change orders by identifying errors as early as possible.
- Increases the likelihood that the construction is finished on time due to fewer conflicts and change orders.
- Verifies that the building meets all requirements in the OPR such as minimum energy efficiency requirements.
- Has been proved to be successful in being cost effective quality assurance process.
- Through increased/ensured indoor air quality the comfort, safety and healthy environment is achieved.
- The extensive documentation of key information of the building and its systems helps the O&M staff to maintain the performance level of the building throughout its life span.
- Reduces energy and operating cost by ensuring high performance level and efficiency of all commissioned building systems.
- Through combination of numerous commissioning activities have had the result to reduce occupants complaints and warranty issues.
- Uses whole life cycle cost calculations as a decision tool throughout the building commissioning process.

### *9.1.2 Weaknesses*

By reading about building commissioning and what benefits it can bring for the building process it might seem that building commissioning is a "win win" method in that sense that building commissioning can only generate positive results. But there are disadvantages that have been holding building commissioning back. These disadvantages are:

*Cost*

- Owners rarely want to see any additional cost added on to an already expensive project.
- Owner's have bad experience with commissioning due it having unsatisfying return on investment.
- Many owners have the opinion that they should not pay extra for a service that is set out to ensure that the owner's requirements and needs are meet since they feel it is already included in the cost of the design team and contractors.

*Lack of certified commissioning providers*

- The lack of certified building commissioning providers is a weakness because there can be companies that state they offer building commissioning service but in fact are just selling a cheap TAB (Test and Balancing) service and with that the reputation of building commissioning decreases and bad experience of so called commissioning spreads among owners.
- Due to few companies being certified there is a lack of a standard building commissioning process which prevents that application of consistent practices.

Some might not see cost of commissioning as being additional cost for a building project but as the building process is today building commissioning is not viewed as a necessary part of the building process and can therefore be skipped. But like has been mentioned before in this report that most of the problems identified through the commissioning process often are discovered later in the buildings life cycle but often then the cost of fixing that problem are greater than the benefits it gives therefore not fixed and just coped with. But if they were fixed during the construction phase the benefits would far outweigh the cost of solving the problem.

The bottom line is that with such different building commissioning processes in use the experience owners have or have heard of commissioning are so variable and can therefore not justify the cost for a commissioning process due to uncertainty of the outcome. The lack of standardisation and inconsistent outcomes is diminishing the reputation that successful commissioning projects have built.

### *9.1.3 Opportunities*

By opportunities the goal is to list up instances were building commissioning would be beneficial for the building process and the building.

- The owner has an unclear idea regarding requirements and needs for the building.
- Unclear requirements regarding minimum acceptance criteria for performance level of building systems and equipments.
- Where complex and/or large building systems will be/are installed.
- Complex buildings like hospitals or laboratories.
- Lack of functional performance testing.
- Inadequate O&M manuals, training of O&M personnel and system documentation.

### *9.1.4 Threats*

Threats are external disadvantages that often cannot be handled in any other way then try to avoid them. The threats that commissioning faces nowadays are:

- Economy in a depression where any additional cost on top of the buildings project cost is often skipped.
- Buildings with low level of complexity and small building systems and therefore favour TAB procedure.
- Lack of experienced and educated commissioning authorities.
- Increase of companies offering building commissioning which would not pass a certification process and therefore damages building commissioning reputation as a quality assurance process.

*Construction delays*

- Increased construction time
- Requires the cooperation of many people at one time, which can add cost if it is not clearly defined in relevant contracts.
- Time delays due to increased documentation that might take longer time than expected because of inexperience of parties involved.

Construction delay is listed as one of the possible threats of building commissioning since there have been cases that have reported construction delays due to commissioning. However when projects that experience construction delays because of building commissioning are examined the cause is usually because the commissioning team were included late in the building process and therefore are not able to identity flaws/errors as soon as if they would have been from the beginning of the project and the complication it adds to solve these flaws/errors so late in the construction process is in fact the reason for the construction delays. So construction delays can easily be avoided by including the commissioning team in the building process from the beginning and clearly stating what is expected of each party throughout the building project.

Buildings with low level of complexity and small building systems might favour TAB procedure but as figure 13 and table 1 showed in sub chapter 4.4 that buildings with low level of complexity can gain just as much from the commissioning process if applied properly. But the reason it is listed as a threat is that such buildings are not yet viewed as suitable projects for commissioning to be included in the building process.

With time and constant development of building commissioning the threats of inexperienced and uneducated commissioning authorities and inadequate building commissioning programs will be eliminated by standardisation and certification processes both for companies and personnel which will decrease the spread of bad experience of commissioning among building owners.

# 10 Conclusion

This chapter will summarise the context of this report which has been focused around the objectives stated in chapter 1. The main aim with this thesis was to look into what is commissioning, how it can be applied within the building process, what results it has showed on buildings, how commissioning is used in Denmark, do a case study were two similar buildings are compared with the main difference that commissioning was used in one project and not the other one and what are the advantages and disadvantages of commissioning.

The commissioning process may look like a process that would complicate the existing building process with its extensive documentation, communication and co-operation of multiple parties at the same time. But if done properly the real experience is that it simplifies the building process because through the extensive documentation and communication all issues are clearly defined, get solved in a structured way and there is less uncertainties. The research on the construction of school projects in Texas, USA is a good example were the building project got simplified because of the use of commissioning and the results of that were reduced change orders, warranty claims and project handover from contractor to owner was on time.

In this thesis there has been much focus on what the results have been in the USA and how it has been done there. The reason why is they are the closest to getting commissioning as “business as usual”, most guidelines that are used worldwide are made by organizations in the US and one of the most important reason is they have invested heavily in data gathering on commissioning projects and analysing of this data to publish what results can be expected of commissioning. It is clear that the results that have been achieved with use of commissioning in the building industry in the USA are very positive and have proven that if commissioning is properly applied it can be cost effiective and if the development keeps moving in that direction it will be a huge success for the commissioning process and next to guaranteed that commissioning will be “business as usual” and become part of the “normal” building process in USA.

These researches that have been conducted in the USA with the purpose to measure the impact of the benefits of commissioning especially on energy consumption, non-energy benefits, one-time cost savings and the cost effectiveness of commissioning can be used as a reference for other countries to see what can be achieved with today’s knowledge and experience. There have not been any similar studies performed in Denmark or other European countries but with time that will hopefully change. Because such studies are

quite important both as an "advertising" tool to have facts behind the possible results that are advertised and to see without doubt what affect commissioning has had on buildings and how the development of the process and its results is. Such studies can serve a similar purpose as regular benchmarking of buildings to identify in time if the development has gone of path.

Building commissioning has many advantages over other quality assurance processes such as clearly defined OPR were the owner's needs and requirements have been translated into acceptance criteria based on measurable values that can then be verified by defined test procedures. But as with everything the commissioning process has also disadvantages but the disadvantages that the process itself has are overpowered by the barriers commissioning is trying to overcome.

Building commissioning has many benefits that can improve the performance level of the building and its value. One of the main benefits is decreased energy consumption but this benefit does not only benefit the building but also the climate because how low percentage of the energy consumed in the world is attained from renewable energy resources and most of the largest countries rely heavily on energy attained from fossil fuels. There can be a huge decrease in emission of $CO_2$ if buildings with high energy consumption would be commissioned to achieve lower energy consumption.

The commissioning process in Denmark has been used for several years but it is still in early development due to how slowly the building industry has seen the possibilities the commissioning process can bring to the building process and how few large commissioning projects there have been in Denmark. The comparison of Bruuns Galleri and Bryggen showed clearly that there is difference between the two shopping malls in energy consumption p. $m^2$ and part of that difference is due to commissioning. How much cannot be found out with the data available.

The results from analysis of the 5 year inspection report of Bruuns Galleri support what has been put forward in the report that most of the issues that are identified during the commissioning process will be identified at some point over the lifetime of the building. Which adds value to the thought that cost of commissioning should not be viewed as additional cost to the building process but rather as an investment that with time will be paid back and at the same time ensures a building that is operational from day one and is according to the needs and requirements the owner defined in the pre design phase.

# References

ASHRAE. (2005). *ASHRAE Guideline 0-2005.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Berkeley Lab. (2010). *Building Commissioning - A Golen Opportunity for Reducing Energy Costs and Greenhouse-Gas Emissions*. Retrieved April 16, 2010, from What Is Commissioning?: http://cx.lbl.gov/definition.html

Building Commissioning Association. (2010). Building Commissioning 101- slide show. Edmon, WA, United States of America: Building Commissioning Association.

California Commissioning Collaborative. (2006). California Commissioning Guide: New Building. California, United States of America.

Claridge, D. E., Turner, W. D., Liu, M., Deng, S., Wei, G., Culp, C., et al. (2003). *High Performance Commercial Building Systems - Is Commissioning Once Enough?* Atlanta: 25th World Energy Engineering Congress.

Claridge, D. E., Turner, W. D., Liu, M., Deng, S., Wei, G., Culp, C., et al. (2003). *High Performance Commercial Building Systems - Is Commissioning Once Enough?* Atlanta: 25th World Energy Engineering Congress.

Della Barba, M. P. (2005). *The Dollar value of Commissioning.* National Conference on Building Commissioning.

ELO-sekretariatet, Teknologisk Institut. (2010). *Energiledelsesordningen (ELO)*. Retrieved May 29, 2010, from ELO Nøgletal: http://elo.femsek.dk/NGLrap/08_2005/rapport(320-5210-3).htm

Evans, M. P. (2010). *Building Commissioning*. Retrieved April 15, 2010, from A Golden Opportunity for Reducing Energy Costs and Greenhouse-Gas Emissions: http://cx.lbl.gov/cx.html

Friedman, H., Potter, A., Haasl, T., & Claridge, D. (2003). *Strategies for improving persistence of commissioning benefits.* Public interest energy research.

Grondzik, W. T. (2009). *Principles of Building Commissioning.* New Jersay: John Wiley & Sons, Inc.

Grontmij|Carl Bro. (2006). *Bryggen - Køleanlæg - Driftsparametre - Optimiring af kølevandstemperatur.* Copenhagen: Grontmij|Carl Bro.

Grontmij|Carl Bro. (2010). Commissioning - Kvalitetsstyring af byggeri. Copenhagen, Denmark: Grontmij|Carl Bro.

Grontmij|Carl Bro. (2010). *Grontmij | Carl Bro ProjectWeb*. Retrieved May 24, 2010, from Welcome: http://www.projectweb.com/Default.asp

Heinz, J. A., & Casault, R. B. (203). *APPA*. Retrieved May 23, 2010, from Commissioning Provides Value to Campus Facilities : http://www.appa.org/FacilitiesManager/article.cfm?itemnumber=1511&parentid=1506

Heinz, J. A., & Casault, R. B. (2004). *The building commissioning handbook, second edition.* Washington: Building Commissioning Association and APPA.

Heinz, J. A., & Casault, R. B. (2004). *The building commissioning handbook, second edition.* Washington: Building Commissioning Association and APPA.

Mills, E. P. (2010). *A Golden Opportunity for Reducing Energy Costs and Greenhouse-Gas Emissions.* California: Lawrence Berkeley National Laboratory.

Mills, E. P., & Mathew, P. P. (2009). *Monitoring-Based Commissioning: Benchmarking Analysis of 24 UC/CSUIOU projects.* California: Lawrence Berkeley National Laborator.

National Energy Management Institute. (2001, November). *National Energy Management Institute.* Retrieved March 8, 2010, from Building Commissioning Market - Industry Analysis: http://www.nemionline.org/downloads/hvac/1_Building%20Commissioning.pdf

Portland Energy Conservation, Inc. (2008). *16th National Conference on Building Commissioning*. Retrieved April 28, 2010, from Benner Award 2008: http://www.peci.org/ncbc/2008/ncbc_benner_08.html

Portland Energy Conservation, Inc. (2010). *National Conference on Building Commissioning*. Retrieved 4 28, 2010, from History of Commissioning: http://www.peci.org/ncbc/about/cx-history.html

Portland Energy Conservation, Inc. (n.d.). *Portland Energy Conservation, Inc*. Retrieved April 19, 2010, from History of Commissioning: http://www.peci.org/ncbc/about/cx-history.html

The Texas State Energy Conservation Office. (2007). *The Viability of Commissioning in New School Construction.* Texas: BESL.

*U.S. department of energy*. (n.d.). Retrieved May 10, 2010, from Commissioning: http://www1.eere.energy.gov/buildings/commercial/commissioning.html

U.S. General Services Administration. (2005). *The Building Commissioning Guide.* U.S. General Services Administration.

University of California. (2010). *University of California*. Retrieved May 2, 2010, from Chapter 6 - Pre-Design phase: http://www.ucop.edu/facil/fmc/facilman/volume2/ch6.html

Wikimedia Foundation. (2010). *Wikipedia*. Retrieved April 15, 2010, from Ship commissioning: http://en.wikipedia.org/wiki/Ship_commissioning

# Appendix A
# Whole life cycle cost calculations for Bryggen

**Rådgivende ingeniører og planlæggere A/S**

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Fax 8732 3200
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CVR-nr. 37295728
Tilsluttet F.R.I

**BRYGGEN**

**KØLEANLÆG -DRITFSPARAMETRE**

**Optimering af kølevandstemperatur**

15. december 2006

## 1. Formål

Formålet med nærværende notat er:

At fastlægge det optimale kølevandstemperatursæt for ventilations- og butikskøling i forbindelse med opførelse af Bryggen.

Dette notat omhandler alene de driftsmæssige parametre. De anlægsøkonomiske forhold ved de forskellige løsninger angives af NCC.

## 2. Opsummering

Ved en rumtemperatur på 24 °C om sommeren og 22 °C om vinteren vurderes den optimale kølevandstemperatur være:

$$T_F / T_R = +9\ °C / +15\ °C.$$

## 3. Forudsætninger

De efterfølgende beregninger er baseret på følgende forudsætninger:

Rumtemperatur i de kølede lokaler: +24 °C

COP-værdi på køleanlæg er anslået til 4

Udetemperatur i henhold til: Referenceåret

Kølebehovet er opgjort til:

- Ventilationskøling 1.200kW
- Butikskøling 900kW

Der er regnet med følgende driftstider:

| | |
|---|---|
| Mandag – fredag: | 06.00 – 21.00 |
| Lørdag: | 06.00 – 18.00 |
| Søndag: | Lukket |

Der regnes med en temperaturstigning på 1 °C på ventilationsluften. Ventilationskøling kan derfor dækkes med kold udeluft, når udetemperaturen er lavere end 17 °C.

Butikskøling antages at være konstant hele året.

Frikøling vurderes at kunne dække kølebehovet til butikskøling, når udetemperaturen er 6 °C lavere end kølevandets fremløbstemperatur.

Energiberegningerne er foretaget ved følgende kølevandstemperatursæt:

- $T_F$ / $T_R$: 6 °C / 12 °C
- $T_F$ / $T_R$: 9 °C / 15 °C
- $T_F$ / $T_R$: 12 °C / 18°C

4. **Opgørelse af driftstimer**

Der er regnet med følgende årlige driftstider:

| | |
|---|---|
| Driftstimer, hvor $t_u$ > 17°C: | 613 h/år |
| Dvs. ventilations- og butikskøling i | 613 h/år |
| Driftstimer, hvor $t_u$ < 17°C: | 3.923 h/år |
| Dvs. butikskøling i | 3.923 h/år |

Heraf kan frikøling dække kølebehovet i følgende antal driftstimer for de forskellige kølevandstemperatursæt:

- $T_F$ / $T_R$: 6°C / 12°C: 645 h/år
- $T_F$ / $T_R$: 9°C / 15°C: 1.303 h/år
- $T_F$ / $T_R$: 12°C / 18°C: 1.884 h/år

Antallet af driftstimer med dækning af butikskølebehovet ved mekanisk køling kan herefter opgøres ved de forskellige kølevandstemperatursæt:

- $T_F$ / $T_R$: 6°C / 12°C: 3.923 – 645 = 3.278 h/år
- $T_F$ / $T_R$: 9°C / 15°C: 3.923 – 1.303 = 2.620 h/år
- $T_F$ / $T_R$: 12°C / 18°C: 3.923 – 1.884 = 2.039 h/år

5. **Opgørelse af energiforbrug**

Opgørelse af energiforbrug ved $T_F$ / $T_R$ = +6°C/+12°C:

| | |
|---|---|
| Ventilationskøling | 198.612 kWh |
| Butikskøling | 945.513 kWh |
| Tørkøler | 85.147 kWh |
| Rumkøling | 299.376 kWh |
| *I alt* | *1.528.648 kWh* |

Opgørelse af energiforbrug ved $T_F$ / $T_R$ = +9 °C/+15 °C:

| | |
|---|---|
| Ventilationskøling | 169.188 kWh |
| Butikskøling | 669.231 kWh |
| Tørkøler | 79.497 kWh |
| Rumkøling | 467.775 kWh |
| *I alt* | *1.385.691 kWh* |

Opgørelse af energiforbrug ved $T_F$ / $T_R$ = +12 °C/+18 °C:

| | |
|---|---|
| Ventilationskøling | 153.250 kWh |
| Butikskøling | 497.250 kWh |
| Tørkøler | 77.415 kWh |
| Rumkøling | 831.600 kWh |
| *I alt* | *1.559.515 kWh* |

6. **Optimering af energiforbrug:**

Som det fremgår af afsnit 5 Opgørelse af energiforbrug, er det årlige energiforbrug lavest ved et kølevandstemperatursæt på +9°C/+15°C. Energiforbruget er undersøgt ved kølevandstemperaturer, som springer med 3°C. For at kontrollere om +9°C/+15°C giver det laveste energiforbrug, er energiforbruget tillige undersøgt ved +8°C/+14°C og +10°C/+16°C.

Opgørelse af energiforbrug ved $T_F$ / $T_R$ = +8°C/+14°C:

| | |
|---|---|
| Ventilationskøling | 178.996 kWh |
| Butikskøling | 756.207 kWh |

| | |
|---|---|
| Tørkøler | 81.419 kWh |
| Rumkøling | 408.240 kWh |
| I alt | 1.424.862 kWh |

Opgørelse af energiforbrug ved $T_F$ / $T_R$ = +10°C/+16°C:

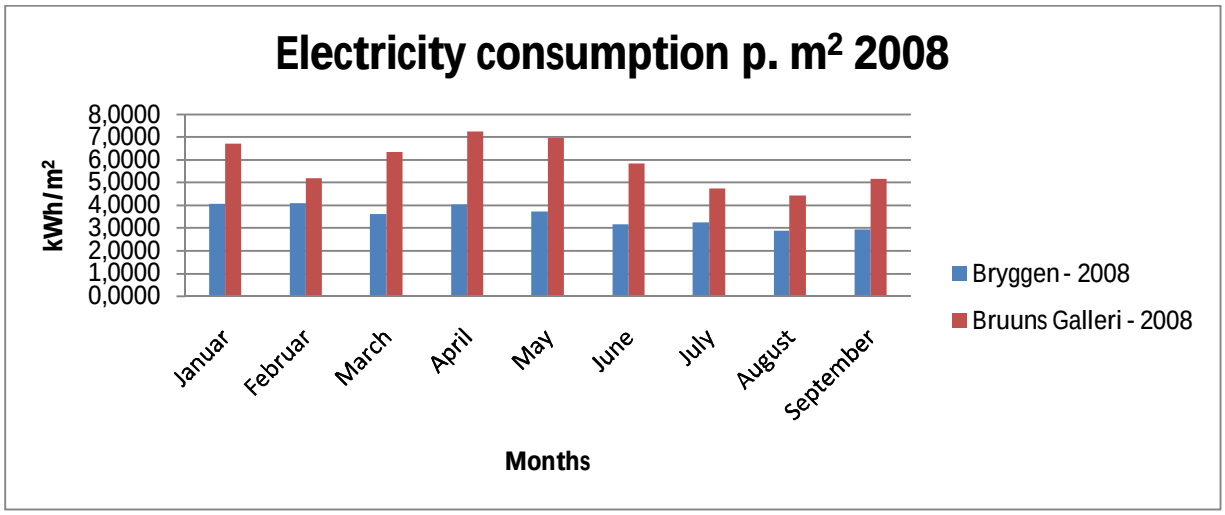
| | |
|---|---|
| Ventilationskøling | 164.284 kWh |
| Butikskøling | 610.839 kWh |
| Tørkøler | 78.918 kWh |
| Rumkøling | 530.712 kWh |
| I alt | 1.384.753 kWh |

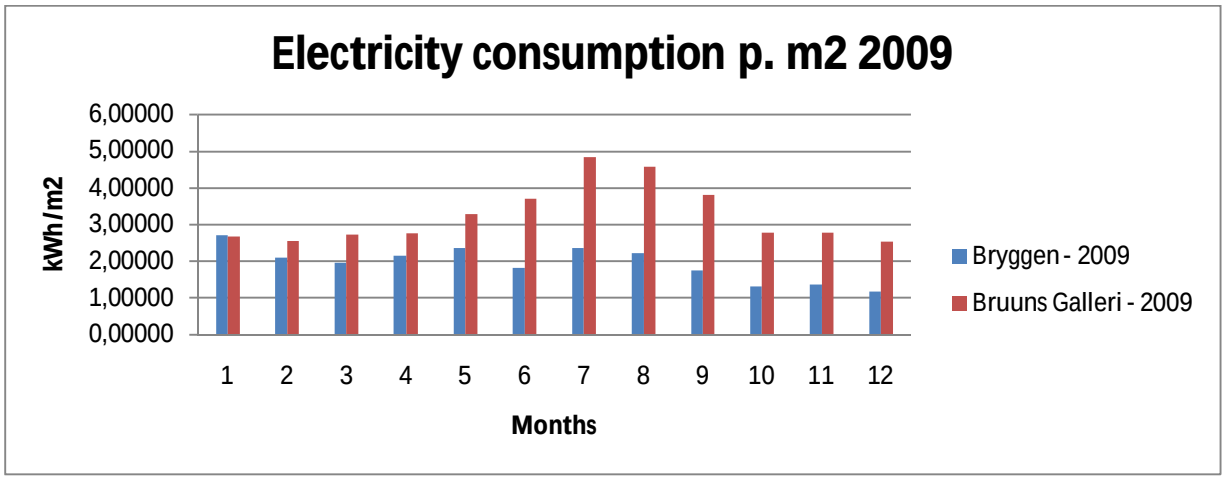
Som det ses er energiforbruget stort set lige lavt ved temperatursættene +9°C/+15°C og +10°C/+16°C. Det optimale kølevandstemperatursæt vil derfor ligge midt mellem de to nævnte temperatursæt.

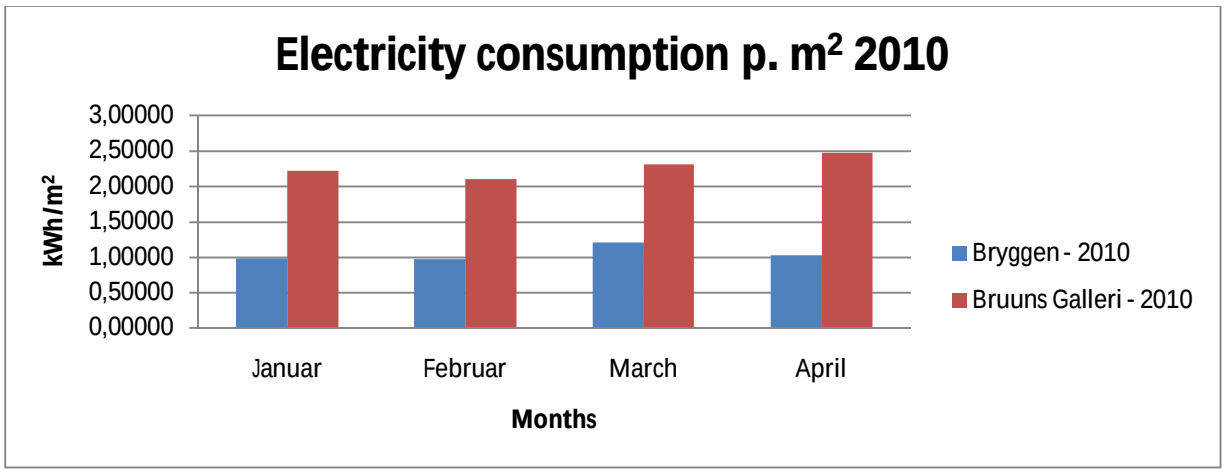
Det optimale kølevandstemperatursæt vil derfor være: $T_F$ / $T_R$ = +9,5°C/+15,5°C. Dette temperatursæt er baseret på en rumtemperatur på 24°C ved sommerforhold. Om vinteren vil man nok ønske en rumtemperatur et par grader lavere. Det kan derfor anbefales at vælge det "optimale" kølevandstemperatur sæt til $T_F$ / $T_R$ = +9°C/+15°C.

Søren Lykke Jensen

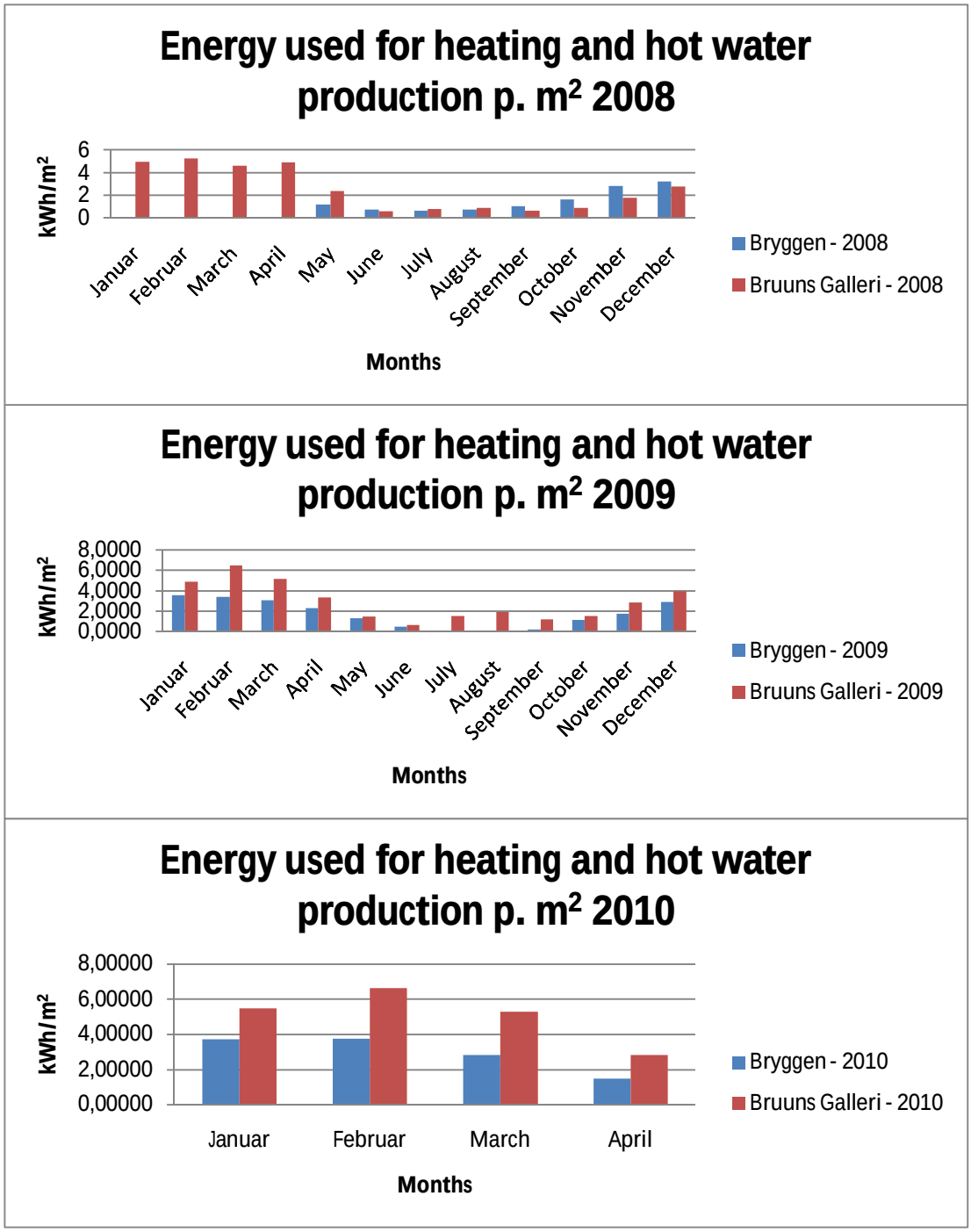
# Appendix B
# Comparison of electricity consumption p. month between Bruuns Galleri and Bryggen.



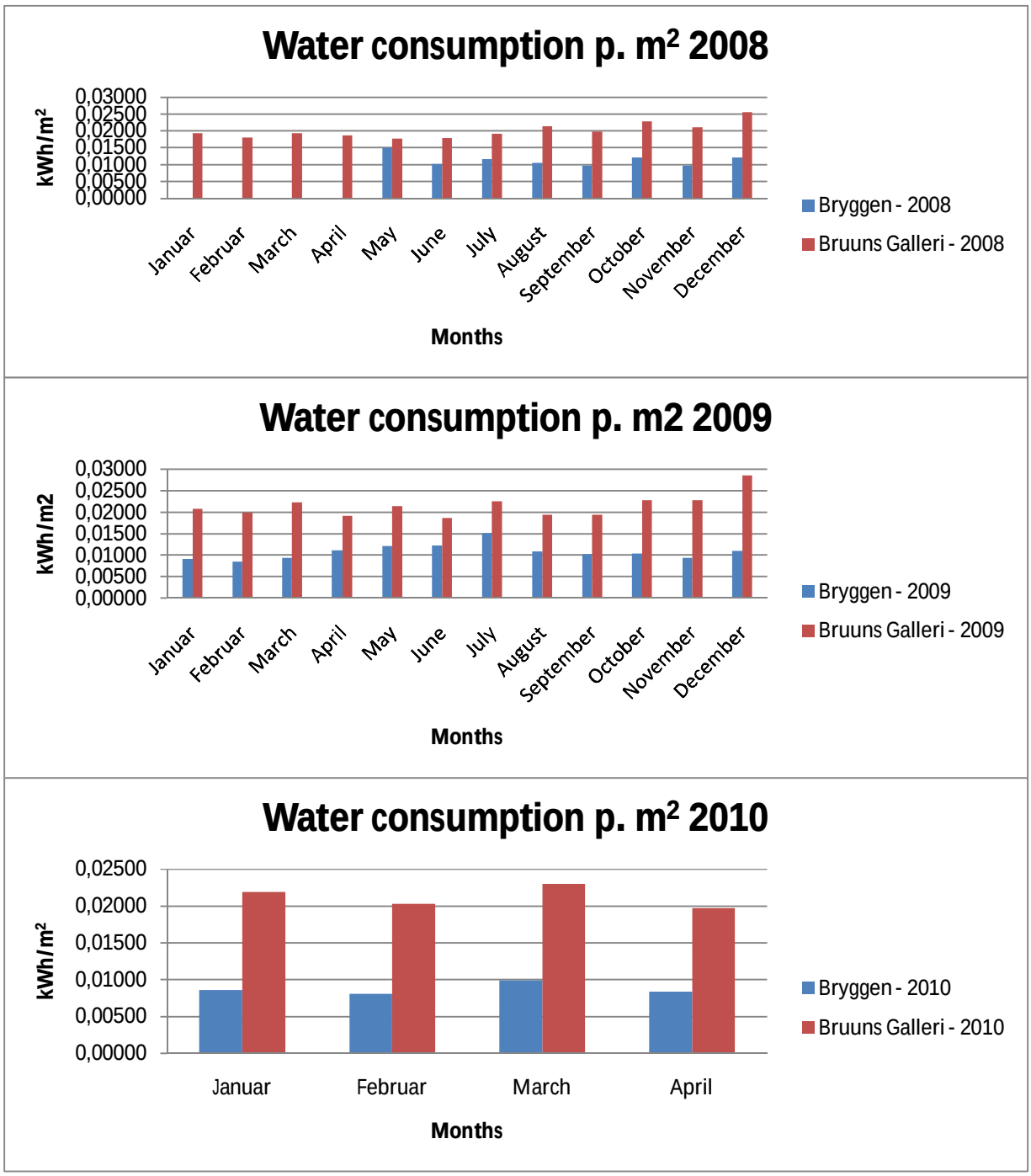



# Appendix C
# Comparison of energy used for heating and hot water production p. month between Bruuns Galleri and Bryggen.



# Appendix D
# Comparison of water consumption p. m² p. month for Bruuns Galleri and Bryggen

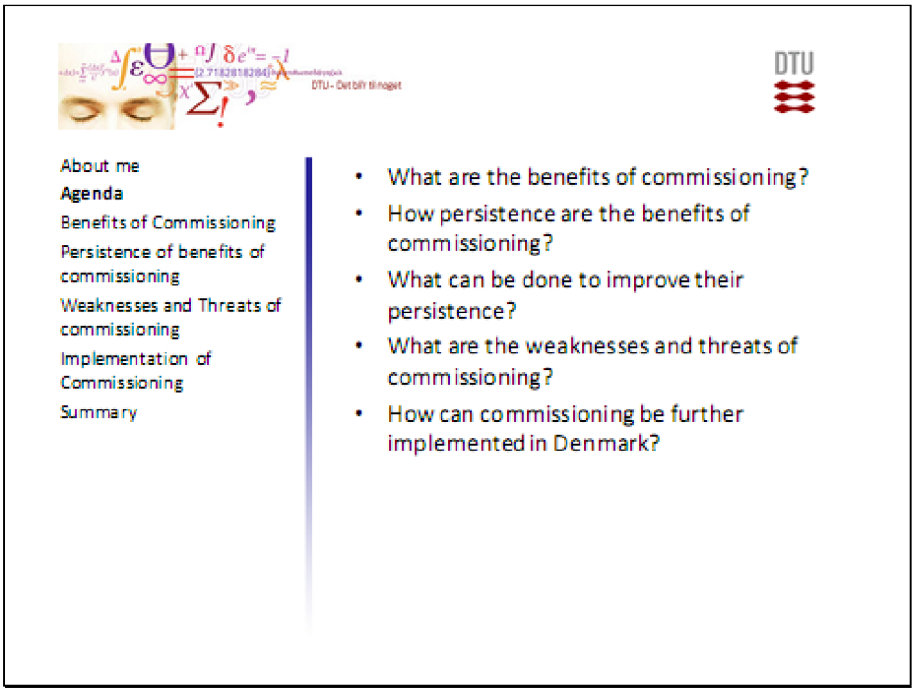


# Appendix E
# Slides from Danvak meeting presentation

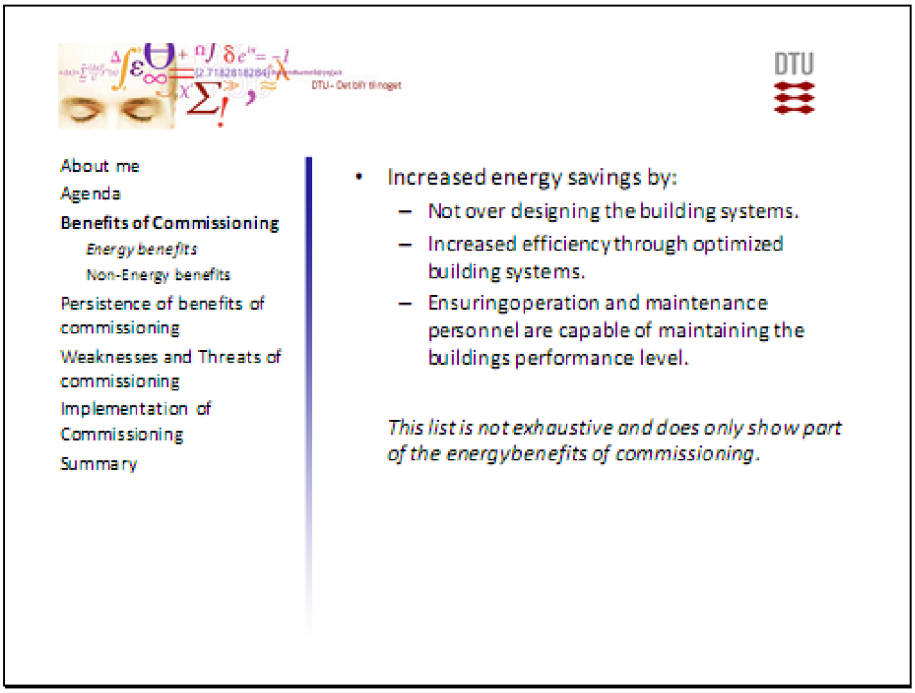
Slide 1


Slide 2

Slide 3




Slide 4



Slide 5

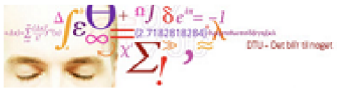
DTU



- Proper training process for operation and maintenance personnel.
- All systems and equipments are tested to verify that the acceptance criteria that is defined in the OPR (building program) is fulfilled.
- Extensive documentation process throughout the building process.
- Whole life cycle cost calculations (Total economy) is used as a decission tool were possible.

*This list is not exhaustive and does only show part of the non-energy benefits of commissioning.*

Slide 6



DTU

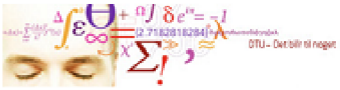


Shows the non-energy benefits that were experienced in most building projects.

- Existing buildings
  - Improved/ensured thermal comfort
  - First cost savings
  - Improved equipment life
  - Improved/ensured indoor air quality
- New constructions
  - Reduced change orders and warrenty claims
  - Improved/ensured thermal comfort
  - First cost savings
  - Improved equipment life
  - Improved/ensured indoor air quality

Source: Evans, M. Ph.D, *Building Commissioning - A Golden Opportunity for Reducing Energy Costs and Greenhouse-Gas Emissions*

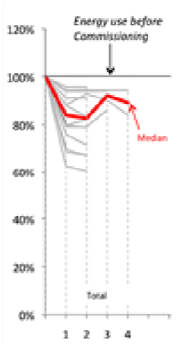
Slide 7



DTU

About me
Agenda
Benefits of Commissioning
**Persistence of benefits of commissioning**
*How persistence are they?*
What are the main causes for short life span?
How can it be changed?
Weaknesses and Threats of commissioning
Implementation of Commissioning
Summary

- The researches that have looked into the persistency have showed that if properly maintained the tendency is towards increased energy savings with time.




Source: Evans, M. Ph.D. *Building Commissioning• A Golden Opportunity for Reducing Energy Costs and Greenhouse•GasEmissions*

Slide 8

DTU

About me
Agenda
Benefits of Commissioning
**Persistence of benefits of commissioning**
How persistence are they?
*What are the main causes for short life span?*
How can it be changed?
Weaknesses and Threats of commissioning
Implementation of Commissioning
Summary

- System repairs with a "band-aid" approach
- Hardware failure, lack of maintenance or regular wear and tear.
- Little or inadequate operational training on building systems.
- High turnover of operation and maintenance personnel.
- Lack of documentation and documents from the commissioning process.
- No performance tracking or benchmarking.

Slide 9

DTU



- Proper operation training on building systems on site for O&M personnel.
- Time for the O&M personnel to be able to study and optimize the building systems.
- Management division that has focus on optimizing building performance and reducing energy costs.

Slide 10

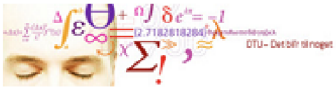
DTU



- *Cost*
  - Owners rarely want to see any additional cost added on to an already expensive project.
  - Owners have bad experience with commissioning due it having unsatisfying return on investment.
  - Owners thought on what commissioning offers and that it is already included in contracts with design team and contractors.
- *Lack of certified commissioning providers*
  - Can cause a spread of bad experience of commissioning.
  - Lack of a standardized building commissioning process.

*These are just examples of some of the main weakness that commissioning faces.*

Slide 11



DTU

About me
Agenda
Benefits of Commissioning
Persistence of benefits of commissioning
**Weaknesses and Threats of commissioning**
- Weaknesses
- *Threats*

Implementation of Commissioning
Summary

- Economy in a depression.
- Buildings with low level of complexity and/or small building systems.
- Lack of experienced and educated commissioning authorities.
- Increase of companies offering building commissioning which would not pass a certification process.
- *Construction delays*
  - Increased construction time
  - Requires the cooperation of many people at one time, which can add cost if it is not clearly defined in relevant contracts.
  - Time delays due to increased documentation that might take longer time than expected because of inexperience of parties involved.

*These are just examples of some of the main weakness that commissioning faces.*

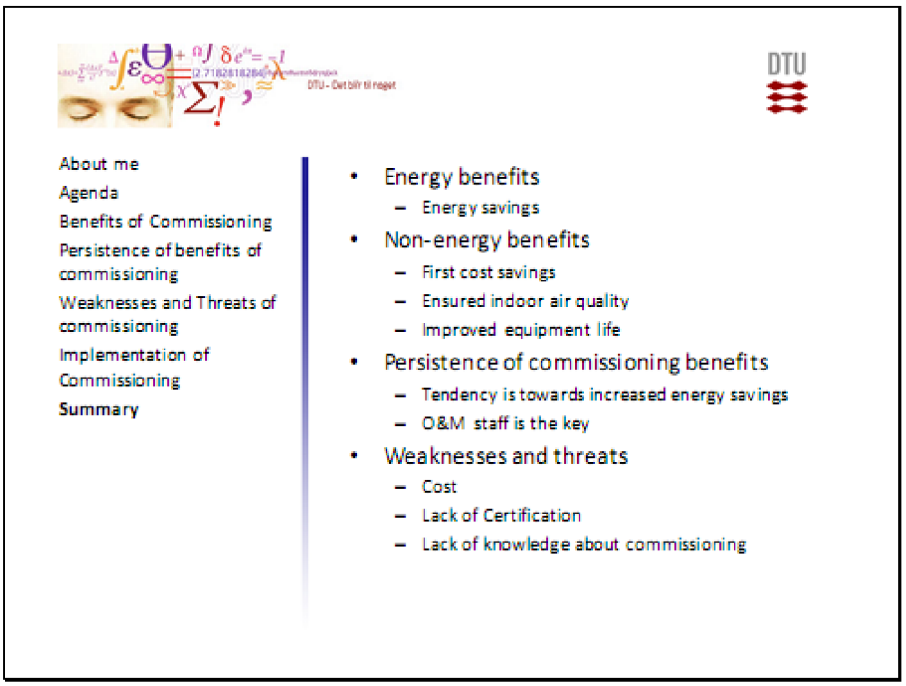
Slide 12

DTU

About me
Agenda
Benefits of Commissioning
Persistence of benefits of commissioning
Weaknesses and Threats of commissioning
**Implementation of Commissioning**
Summary

- Forced vs. unforced implementation process.
- Make a showcase of what commissioning can do and how it can be done.
- Publish the results.
- Update laws, regulation and standards to make commissioning a requirement for specific public sector buildings.
- Keep publishing results from the showcase.
- A neutral partner should handle data gathering and analyzing to get true results.

Slide 13




Slide 14