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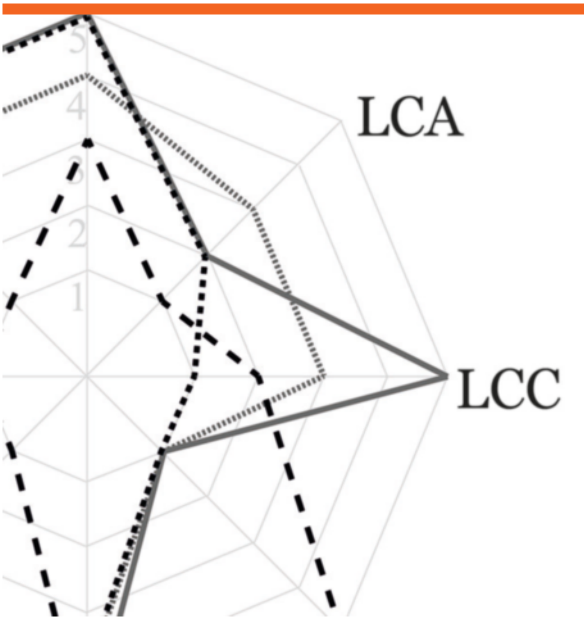

Mathilde Landgren

PhD Thesis

Department of Civil Engineering
2019

DTU Civil Engineering Report-Byg R-398

DTU Civil Engineering
Department of Civil Engineering

DEVELOPING A METHOD FOR INTEGRATED SUSTAINABLE DESIGN (ISD)

Mathilde Landgren

PhD Thesis

Department of Civil Engineering, DTU
2018

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Developing a Method for Integrated Sustainable Design (ISD)

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PREFACE

This thesis presents the research conducted between October 2015 and September 2018 as an industrial PhD.

The research contributes to the ongoing development of sustainable building design. By the development of the Integrated Sustainable Design (ISD) method it aims to grasp the complexity of sustainability and transform it to an operational design method for practitioners in architectural offices in Denmark. The method is based upon studies of state-of-art design processes and levels of knowledge of sustainability topics in architectural offices. The ISD-method is adjustable to specific architectural work cultures in practice as well as the different character of projects.

The thesis works in the context of integrated design aiming at accommodating sustainable building design, through knowledge-based design based on technical inputs and visual communication.

DTU, Kgs. Lyngby, September 2018

Mathilde Landgren

ACKNOWLEDGEMENTS

I would like to thank my supervisors, Lotte (DTU), Ole and David (JJW), Jørn (Lendager Group), and Peter Andreas (DanskeArk), for their guidance throughout the PhD study. Thanks to the DTU Civil Engineering department for giving me the opportunity to do the PhD research and the Innovation Fund Denmark for financial support.

My gratitude is also extended to all at JJW Architects for including me in their office, involving me in their projects and in general showing interest in my project. Having such welcoming colleagues have been valuable for me in the work as PhD student.
This research project has reached out to the building industry through questionnaires and interviews, the project would not have been the same without the number of respondents and interviewees – a great thanks to all participating.

Finally, I would like to express my deepest gratitude to my family for their invaluable love and support through the three years of PhD studies and hard work.

ABSTRACT

In recent decades, there has been increased focus on reducing the energy consumption of buildings in operation to limit the use of fossil fuels and related emissions. As a result of continuously tightening and tuning building energy regulations it is now realised among experts, researchers, and politicians, that a limit has been reached. As a result, the focus has recently changed to address emissions from the entire life cycle of the buildings. Sustainable buildings then became a much more complex matter. The complexity of the built environment places great responsibility on the design team to deal which must now include more specialised knowledge in a wider range of sustainability topics. Integrated design that uses more technical input in the design process is the best way for different specialists, within energy performance, indoor climate comfort, LCC and LCA, to collaborate with the design team and to thereby implement the information that is needed to ensure more sustainable buildings. The Integrated Energy Design (IED) method had been developed prior to this PhD research and was intended to ensure that technical input in the initial design phase would influence later decisions that determined energy consumption. Sustainable design implies quantification of design decisions to ensure knowledge-based design. Architects must also be able to quantify architectural quality to support their design decisions. DGNB can be used as a tool to create a reference framework for comparison and quantification.

The PhD research was conducted in this context. It investigated whether the inclusion of LCC and LCA in the IED-method is possible, to create a more sustainable design method. By combining the familiar Integrated Energy Design (IED) method with the DGNB certification system criteria, a method for Integrated Sustainable Design (ISD) was developed, with the goal of combining the design process with the sustainability process in a project, to ensure quantifiable documentation of the sustainability ranking of a design project, without compromising its architectural quality. The aim was to use digital engineering tools that use technical knowledge to inform the design process, and to show that knowledge-based design will ensure sustainable architecture.

Mixed methods were used through this PhD research. Questionnaires completed by staff working at architectural offices and interviews with sustainability experts were used to determine the state-of-the-art in sustainable architecture and implementation of technical knowledge in the architectural design process. The literature and a set of existing case projects at JJW were mapped to identify the state-of-the art in sustainability elsewhere and the degree of sustainability in JJW projects. This was followed by case studies, where the PhD researcher actively participated in design teams to provide technical input, whose effects were observed and analysed upon. The case studies were supported by questionnaires and interviews at JJW. From these studies, the ISD-method was developed.

It was found that IED is currently an integrated part of the design culture, due to the historically increased focus on energy performance in Danish building regulations. However, a mapping of IED against DGNB shows that only a few DGNB criteria are directly fulfilled, so a new method is needed to ensure more sustainable buildings. The IED method was expanded to include LCC and LCA, to increase the level of sustainability. The Danish Description of Service was used as the basis for the ISD design method, to ensure easy implementation in practice and to allow the method to be applied across more design phases, instead of just the initial design phase that is the sole focus of the IED-method. This thesis examined the implementation of ISD at JJW, but the ISD-method is a generic design method that can be adapted for use in any architectural office.

Keywords: Integrated Sustainable Design, Sustainable Architecture, Case study research, Work culture profile, Life Cycle Cost, Life Cycle Assessment.

RESUMÉ

I de seneste årtier har der været øget fokus på at reducere energiforbruget for bygninger i drift for at begrænse brugen af fossile brændstoffer og de relaterede emissioner. Som et resultat af konstant at stramme energikravene til bygninger er det vi nu nået til et niveau, hvor eksperter, forskere og politikere ved at der ikke kan opnås meget mere ad den vej. Derfor er fokus de seneste år ændret i retning mod emissionerne fra hele bygningernes livscyklus, samtidig med et bredere perspektiv på bæredygtighed inklusiv totaløkonomi og social bæredygtighed. At designe bæredygtige bygninger er dermed blevet mere komplekst.

Den øgede kompleksitet i byggeriet skaber øgede krav til designteamet til håndtering af designprocesserne. Designteamet har brug for mere specialiseret viden inden for et bredere udvalg af bæredygtighedsemner. Tekniske input til designet kan håndteres gennem integreret design. Det er en måde at samarbejde og implementere de nødvendige oplysninger for at sikre bæredygtige bygninger. Metoden 'Integrated Energy Design' (IED) blev udviklet for at sikre tidlig designpåvirkning på energiforbrugsrelaterede designbeslutninger, fordi det blev klart at de tidlige design beslutninger (geometri, vindues facade ration, geometri etc.) havde meget større effekt på energiforbruget end tekniske komponenter såsom solceller og varmepumper.

Et generelt aspekt relateret til bæredygtighed er et øget behov for at kvantificere designbeslutninger til at fremme videns baseret design. Arkitekterne har derfor øget fokus på at kvantificere både den arkitektoniske kvalitet samt bæredygtigheden i deres projekter, og dermed understøtte deres designbeslutninger. DGNB, er et værktøj til at skabe et fælles grundlag for sammenligning og kvantificering af bæredygtighed i byggeriet. Det er i denne kompleksitet at dette Ph.d. projekt navigerer. Et af formålene med projektet er, at undersøge om det er muligt at imødekomme en mere bæredygtig designmetode ved, at inkludere LCC og LCA i IED-metoden.

Ved at kombinere den velkendte IED-metode med DGNB certificeringssystemets kriterier, udvikles en metode kaldet 'Integrated Sustainable Design' (ISD). ISD-metoden sigter mod at kombinere designprocessen med bæredygtighedscertificeringsprocessen i én samlet proces, frem for to parallelle processer, som det ofte gør sig gældende i praksis. Ønsket er at sikre kvantificerbar dokumentation for niveauet af bæredygtighed i et designprojekt, uden at gå på kompromis med den arkitektoniske kvalitet, samtidigt med at gevinsterne fra IED inddrages. Målet er, at informere designprocessen med teknisk viden via digitale værktøjer, som kan holde trit med hastigheden i en design proces. Dette ph.d. projekt understreger, at videns baseret design sikrer bæredygtig arkitektur og at det starter i de tidlige design beslutninger.

Gennem dette Ph.d. projekt er der anvendt forskellige metoder, for at undersøge ovennævnte resultater. For at identificere state-of-the-art for bæredygtig arkitektur og implementering af teknisk viden i designprocesser, er der foretaget en spørgeskemaundersøgelse hos arkitekttegnestuer, interviews med eksperter i branchen. For at identificere state-of-the-art for bæredygtighed i projekterne hos JJW, er der lavet et litteraturstudie og en kortlægning af eksisterende projekter. Efterfølgende har den Ph.d. studerende foretaget flere casestudier design processer hos JJW, med aktiv deltagelse i form af tekniske inputs til designteamet i virkelige designprocesser. Yderligere spørgeskemaer og interviews understøttede disse casestudier hos JJW. Det er på baggrund af disse studier, at ISD-metoden er blevet udviklet.

Ud fra dette Ph.d. projekt kan det konkluderes, at IED er en integreret del af designkulturen i Danmark. Det er vurderingen at denne kultur for IED primært skyldes øgede politisk fastsatte reguleringer for energiforbrug til bygninger i drift. Kortlægningen af IED og DGNB viser imidlertid, at kun få DGNB-kriterier direkte opfyldes

ved brug af IED, og en ny metode er nødvendig for at fremme bæredygtighed i bygninger. IED-metoden udvides med LCC og LCA for at øge bæredygtighedsniveauet og det undersøges i projektet, hvad effekten er og hvordan det kan gøres operationelt i en kommerciel praksis. Den danske ydelsesbeskrivelse anvendes som basis for ISD-metoden for at sikre en let implementering i praksis. Desuden tillader dette, at ISD-metoden spænder over flere designfaser end blot den indledende designfase, som IED-metoden ellers fokuserer på. ISD-metoden er en generisk designmetode, der kan tilpasses til den enkelte tegnestuers design proces kultur.

SCIENTIFIC PAPER SUMMARY

2015

Quantifying Sustainability in Architecture		
Landgren, Mathilde; Jensen, Lotte B.; Heller, Alfred; Kiesslinger, Jørn; Hornbek, Ole; Sattrup, Peter Andreas		
Part of: Book of Abstracts. DTU's Sustain Conference 2015, 2015, Technical University of Denmark (DTU), Lyngby		
Presented at: DTU Sustain Conference 2015, 2015, Lyngby		
Type: Conference abstract in proceedings (Peer reviewed)		
Status: Published	Year: 2015	

2016

Paper (1) – see APPENDIX A

Mapping one year's design processes at an architecture firm specialized in sustainable architecture – How do sustainability certification systems affect the design processes?		
In: Proceedings of the Integrated Design Conference ID@50, 2016, University of Bath (ISBN-13: 978-0-86197-192-3. ISBN-10: 0-86197-192-2)		
Landgren, Mathilde; Jensen, Lotte B.; Kiesslinger, Jørn; Sattrup, Peter Andreas; Hornbek, Ole; Heller. Alfred		
Presented at: International Conference on Integrated Design, 2016, Bath		
Type: Conference abstract in proceedings (Peer reviewed)		
Status: Published	Year: 2016	

2017

Paper (2) – see APPENDIX B

How does sustainability certification affect the design process? – Mapping final design projects at an architectural office.		
Landgren, Mathilde; Jensen, Lotte B.		
In: Architectural Engineering and Design Management (ISSN: 1745-2007), vol.: 14, issue: 4, pages: 292-305,2017		
Type: Journal paper (peer reviewed)		
Status: Published	Year: 2017	DOI: http://dx.doi.org/10.1080/17452007.2017.1397496

Paper (3) – see APPENDIX C

Integrated Energy Design and Life Cycle Assessment in Refurbishment Design Processes		
Landgren, Mathilde; Jensen, Lotte B.		
In: A S H R A E Transactions (ISSN: 0001-2505), 2017		
Presented at: 2017 ASHRAE Annual Conference, 2017, Long Beach, CA		
Type: Conference paper (peer reviewed)		
Status: Published	Year: 2017	

2018

Paper (4) – see APPENDIX D

Mapping the communication of engineering knowledge using visuals to improve interdisciplinary design team performance for sustainable building design.		
Landgren, Mathilde; Jensen, Lotte B.		
Presented at: 2018 Inno-BSR Symposium, HCU, Hamburg, 2018		
Type: Working paper for journal paper (8) (peer reviewed)		
Status: In review	Year: 2018	

Paper (5) – see APPENDIX E

Decision support for large scale remediation strategies by fused Urban Metabolism and Life Cycle Assessment		
Ohms, Pernille; Andersen, Camilla; Landgren, Mathilde; Birkved, Morten		
In: International Journal of Life Cycle Assessment (ISSN: 0948-3349), 2018		
Type: Journal paper (peer reviewed)		
Status: Published	Year: 2018	DOI: http://dx.doi.org/10.1007/s11367-018-1445-9

Paper (6) – see APPENDIX F

Integrated Design Processes – A Mapping of guidelines with Danish conventional 'silo' design practice as the reference point.		
Landgren, Mathilde; Skovmand Jakobsen, Signe; Wohlenberg, Birthe ; Jensen, Lotte B.		
In: Architectural Engineering and Design Management (ISSN: 1752-7589)		
Type: Journal paper (peer reviewed)		
Status: Published	Year: 2018	DOI: 10.1080/17452007.2018.1552113

Paper (7) – see APPENDIX G

Design process cultures as drivers and obstacles to sustainable architecture - Identifying knowledge involved in design decisions at architectural offices in the Nordic countries.		
Landgren, Mathilde ; Jensen, Lotte B.		
Presented at: 2018 PLEA, Hong Kong		
Type: Conference paper (peer reviewed)		
Status: Accepted	Year: 2018	

Paper (8) – see APPENDIX H

Informing sustainable building design – the importance of visualizing technical information and quantifying architectural decisions.		
Landgren, Mathilde ; Jakobsen, Signe S. ; Wohlenberg, Birthe ; Jensen, Lotte B.		
In: Archnet-IJAR: International Journal of Architectural Research, Emerald Publishing Limited 2631-6862		
Type: Journal paper (peer reviewed)		
Status: Accepted on December 8th 2018	Year: 2019	DOI 10.1108/ARCH-12-2018-0025

GLOSSARY

The Glossary includes an overview of terms and abbreviations used throughout the thesis, to aid readability. All terms and abbreviations are provided here with a short description. Some terms might have different descriptions depending on who defined them, either from an architect's point of view or engineer's point of view. In this thesis, the point of view is that of a PhD researcher with a background in Architectural Engineering, a technical view of architectural work and processes.

TERM	DESCRIPTION
Architectural competition	The classical architectural competition, where a proposal for the project is made and visualized by renderings and drawings supplemented by technical details, has changed a lot. Now in the more commonly used type of architectural competition, the proposal is described in words. Another important part of this type of submission is a detailed description of the team set-up, including architects and engineers. Their portfolio of relevant projects is also provided to emphasise the capabilities of the team.
BR15 and BR18	Current building regulations in Denmark during the period of this PhD research.
Brundtland Report	In 1987 the (WCED) published the report of "Our Common Future", also known as the Brundtland Report.
ECO	Economic quality, as defined by the DGNB system.
ENV	Environmental quality, as defined by the DGNB system.
Danish Description of Service ***(Ydelsesbeskrivelsen)***	The Danish Description of Service, in which the building design phases and tasks are defined by for the Danish building industry. *Initial design* *(Indledende fase)* - *Pre-design* *(Ideudvikling)* - *Concept design* *(Programfase)* - *Schematic design* *(Skitsefase)* *Design proposal* *(Design forslag)* - *Outline proposal* *(Dispositionsforslag)* - *Project proposal* *(Projektforslag)* *Detailed design* *(Projekteringsfase)* - *Preliminary project* *(Forprojekt)* - *Main project* *(Hoved projekt)* *Construction* *(Udførelse)* *Commiccioning and use* *(Ibrugtagning og drift)*
Descriptive	Describing in an objective and non-judgemental way.
Design decision	A design decision made by the architects at the office unless otherwise stated.
Design method	A method used to guide the design process.
Design process	The process of developing a design project from the initial idea to the completed project.
Design Team	A group of architects from the office cooperating in a team with engineers with different specialities.
DGNB	The Danish version of the German certification system for sustainable buildings. (Deutsche Gesellschaft für Nachhaltiges Bauen)
Digital engineering tools	Digital tools to calculate and simulate various engineering topics.
DK-GBC	Danish Green Building Council, an association whose goal is to promote sustainable buildings in Denmark, considering the entire building value chain.
EPD	Environmental Product Declaration
GHG	Green House Gas
Green-page-strategy	An internal tool at JJW Architects for aligning the sustainability concepts and criteria in a specific project through all its phases. This term is only used in a short period of time, while developing the strategy. Later it is included in the One-page-strategy.

Holistic approach	Includes technical knowledge on environmental, economic and social sustainability in the design process by which architecture and engineering approaches are combined to create a common best practice solution.
HVAC	Heating, Ventilation, and Air Conditioning
IED	Integrated Energy Design, a design method to ensure energy efficient buildings.
Informed design process	An informed design process is defined as a process with investigations, which can be simulations and calculations etc., that are different from case to case.
JJW sustainability vision	For each project, JJW selects a specific focus that will be highlighted throughout the design process. The narrative about the building and the sustainability focus is based upon this focus.
LCA	Life Cycle Assessment
LCAByg	LCAByg is Danish software for performing LCA in the building industry. It is available free online.
LCC	Life Cycle Costing
LCCByg	LCCByg is Danish software for performing LCC calculations in the building industry. It is available free online.
Mapping	A method used to document inputs, answers, and observations in one common matrix, to provide an overview.
One-page-strategy	An internal tool at JJW Architects that is used to briefly describe the economic setup, who is responsible for each task, and the sustainability approach, from the initial design phase, through all phases, to the final built project.
PE_{tot}	Primary Energy total use
Prescriptive	When imposing a method or rule.
Refurbishment	Refurbishment of an existing building, either of a part of it or the full building, depending upon the specific project.
Remediation	For highly PCB-contaminated buildings, for example, remediation to remove the PCB affected building materials and components may be required before a refurbishment is possible.
Screening of tasks	Using the DGNB criteria to filter the client's wishes for the building in order to define the main focus areas.
Sustainable approach	Having a specific focus within the DGNB framework as a part of the design project from the very beginning.
Sustainability expert	A person with additional knowledge within sustainability, either through DGNB training or other additional training and experience.
SOC	Social quality, as defined by the DGNB system.
The design process is informed by	The person with a given profession who interrogates the design team at various stages in the design process.
WCED	The World Commission on Environment and Development (WCED) was established in 1983.

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Aim and objectives

The research for this PhD took place in the interface between the professions of architecture and engineering. The goal was to study the awareness of sustainability knowledge and how it is implemented in a case study architectural office. The research documented how digital engineering tools influence the design process and design methods in the architectural profession. It was based on the well-known Integrated Energy Design (IED) method, which is the first step towards sustainable buildings and operates in the framework of the DGNB certification system, which has become the leading definition of sustainability parameters in the Danish building industry. The research assumed that a closer collaboration across disciplines enhances the implementation of sustainable solutions in architecture.

By combining the method of IED with an integration of the social, environmental and economic approaches to sustainability, in the framework of the DGNB certification system, a method of Integrated Sustainable Design (ISD) was developed as a part of this PhD. The hypothesis is that this will lead to holistic design methods, and thus increase sustainability over the entire lifecycle of the building:

- Where the quantification of sustainability was defined by the standardized certification schemes of the DGNB, taking a systematic approach at all stages of the building design,
- Where the integrated design process ensured that current legal building requirements were fulfilled,
- Where the method was implemented and analysed in case studies at an architectural office at various design stages,
- Without compromising the architectural quality, and possibly even enhancing it.

The following research questions were formulated:

- How to integrate the DGNB certification criteria into the early design stages?
- How to integrate the DGNB certification criteria into the design methods at the company?
- How to integrate the DGNB certification criteria in the Integrated Energy Design method?

The research in this PhD aimed to investigate whether knowledge-based design ensures sustainable architecture. By applying the IED-method in the early design phases and extending the ideas to include Life Cycle Costing (LCC) and Life Cycle Assessment (LCA), a holistic approach to sustainability was defined. The research was based on data from the process towards sustainable architecture at an architectural office in Denmark and overall data from other architectural offices in the Nordic countries.

1.1.1 Hypothesis

This study aimed to test the main hypothesis:

By combining the method of Integrated Energy Design (IED) with the integration of social, environmental and economic approaches, an Integrated Sustainable Design (ISD) method is created, one that will improve holistic design and lead to:

- Higher sustainability ranking in the framework of DGNB or other quantifiable documentations of sustainability
- Fulfilment of the current legal requirements in Denmark.
- An operational integrated design process that works efficiently in a current architectural practice
- Excellence in architectural quality.

The sub-hypotheses used to elaborate and fully test the main hypothesis are as follows:

Sub-hypothesis 1 - The parameters of IED are an integral part of DGNB.

Sub-hypothesis 2 - When IED is expanded to include LCA and LCC, a higher level of sustainability is attainable.

Sub-hypothesis 3 – Sustainable design requires an integrated design process and an interdisciplinary work process.
Sub-hypothesis 4 - LCA and LCC can be used as design parameters from the early design phases.
Sub-hypothesis 5 - Digital engineering tools containing technical knowledge are necessary to support a design process focusing upon sustainability.

1.1.2 Executive summary

This PhD thesis consists of four sub-stories, each taking a specific approach derived from a specific sub-hypothesis. The sub-stories are woven together to describe the final pattern of the PhD research.

1st story: IED is the first wave and LCA+LCC is the second wave of an integrated design process leading to documentable sustainable buildings

Early sustainability approaches had their main focus upon limiting energy consumption in the operation phase and thereby the use of fossil fuels. Due to this development, Integrated Energy Design (IED) has for several decades played a bigger role in the architectural and engineering industries, since energy consumption and indoor climate have been the main topics in the industry at political level. IED can therefore be seen as the first wave of progress towards sustainable buildings and now there is a new wave, which focuses upon the entire life cycle of a building. The life cycle includes the materials and economy, here assessed with: Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). The integration of IED in practice and this new wave were both documented in a literature survey, in interviews with professionals in practice and in questionnaires. The research was conducted within the framework of the DGNB certification system, to quantify sustainability in an established rating system that is widely used in Denmark. The fact that LCA and LCC are both highly weighted in the DGNB certification system means that they are a natural focus for better certification and increased sustainability in the building industry.

2nd story: Development of a method for Integrated Sustainable Design from knowledge of design processes in practice.

The overall research topic for the PhD was to understand (descriptively) and develop (prescriptively) a design method for Integrated Sustainable Design (ISD). The research method involved the investigation of a number of architectural office working profiles. These profiles were developed by means of questionnaires and interviews.

ISD is based upon the well-known Integrated Energy Design (IED) method combined with the framework of the DGNB certification system to insert sustainability into a known rating system that is widely used in Denmark.

ISD includes a wide range of topics: design processes, integration of technical knowledge, design decisions, collaboration between different professions, use of design methods and simulation tools, interdisciplinary design teams, etc. The goal of the ISD-method is to integrate the sustainability process into the design process, combining what are now two parallel processes in order to improve sustainable design in practice.

3rd story: Development of operational methods in the development of sustainability at JJW Architects

The overall goal of the PhD was to investigate and develop a method for Integrated Sustainable Design (ISD). The purpose was to develop an operative method based on the specific work flows used at JJW Architects. Participation in design teams in case study processes made it possible to map the design processes, work flows and collaboration in use. The case studies were supplemented by interviews and questionnaires at the office.

ISD is based upon the well-known Integrated Energy Design (IED) method and in the framework of the DGNB certification system, it becomes a way of introducing sustainability into an already known rating system that is used in Denmark. To ensure easy implementation in practice, the process of the ISD method was based on the Danish Description of Service, which is already used to describe design processes. The ISD method was adapted to JJW by addressing and augmenting their own internal tool (the one-page-strategy) to include sustainability.

4th story: Integrated Sustainable Design (ISD) is a DGNB 'light' version

The overall goal of the PhD was to develop a method for Integrated Sustainable Design (ISD). The purpose is to define the method in the framework of DGNB. Certification is an expensive and time-consuming process, which requires special knowledge within different topics, so the purpose is to develop a ”DGNB-light” version which is so smooth and operational, that it could be widely implemented in almost all design projects. ISD is then essentially a simplified and focused version of DGNB, which is easier to use in practice.

The method was developed in case studies at JJW Architects, which provided an overview of the use of DGNB in practice as well as the complications that can occur. The case studies were supplemented by interviews and mapping of the interactions that occurred.

1.1.3 Structure of the thesis

The thesis is structured as seen in Figure 1, with an introduction, a method section, a results section including the papers relevant to each topic, followed by a discussion, and a conclusion. In the diagram the relations between the hypotheses and the papers are illustrated.

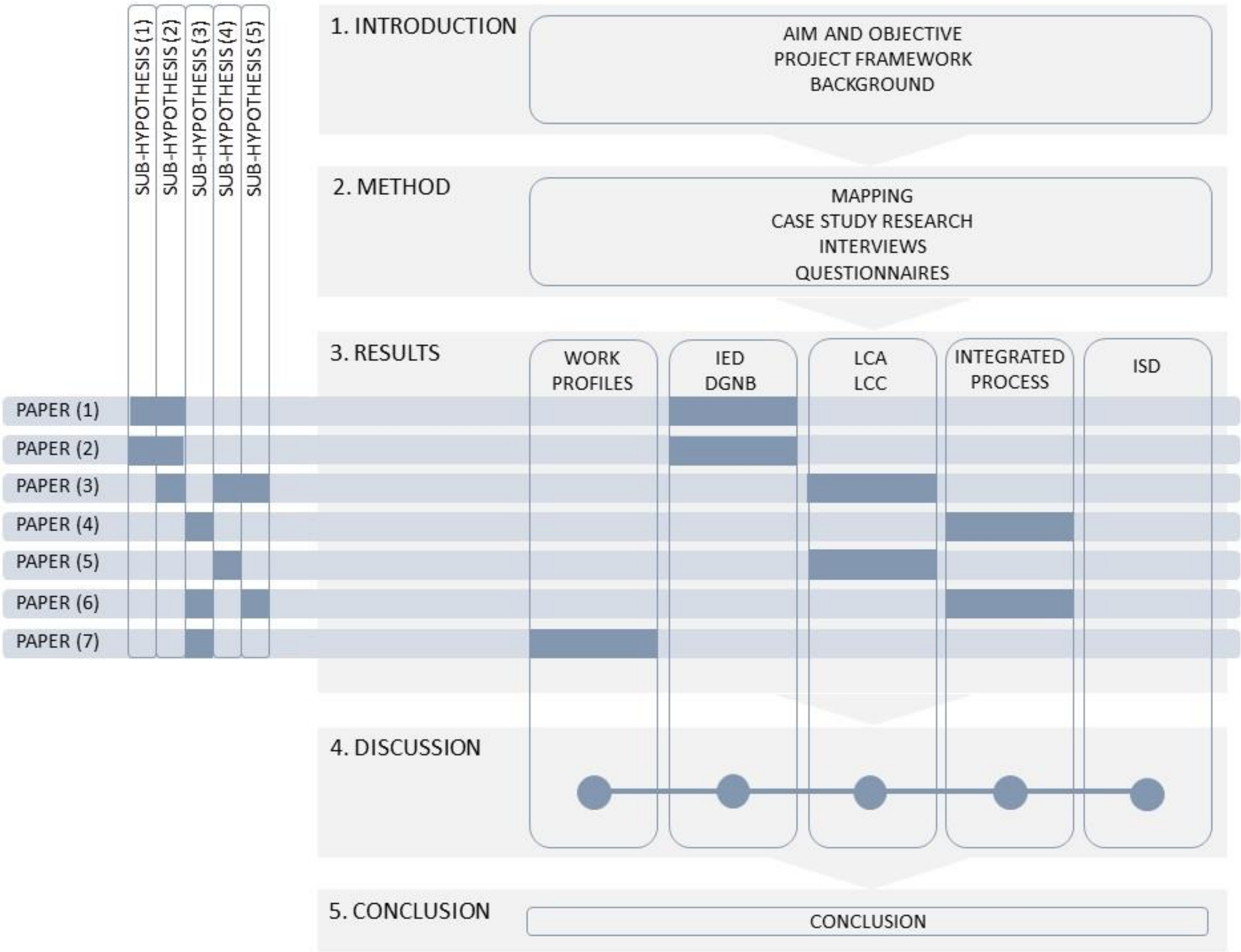


Figure 1 - Structure of thesis, linking hypothesis, papers and themes together.

1.2 Project framework

In recent years it has become more usual to include other professions and competences in the different professions in the Danish building industry. Contractors often include engineering and architectural competence in their companies, engineering consultancies buy up architectural offices and architectural offices employ engineers internally - some even establish an engineering department. One reason for these developments is the economic benefit and possibility for growth, but they are also due to the increased demands from clients that they be given the full package (Espersen & Sejr, 2018).
Figure 2 illustrates the traditional engagement of different professions throughout the life of a building, from client to architectural consultants and engineering consultants, to the contractor who realises the building and finally to the facility management that operates the building. The tendency described will create bigger differences from the big interdisciplinary companies to the small disciplinary companies. This PhD research operates in the interface between engineers and architects, as illustrated by the red dot in Figure 2.

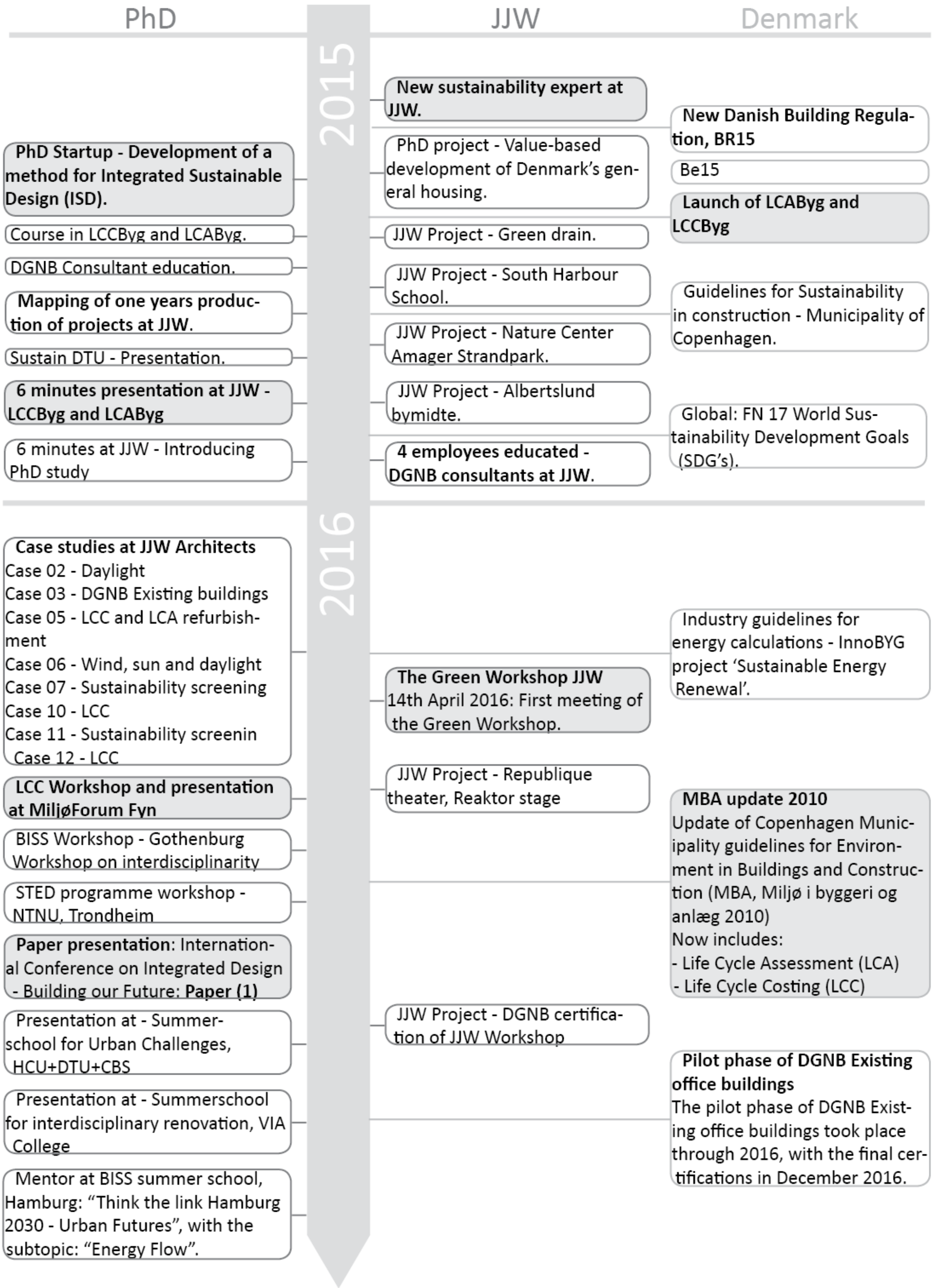
Figure 2 - The traditional flow of professions through a building life time – the value chain. Based on (Sattrup, 2017). The red dot is the area of which this PhD research is emerging.

Accompanying the tendency for bigger companies to contain a mix of disciplines there has been a change in the way architectural competitions are organised, as they are now more often closed rather than open competitions, with a focus on the composition of the team, the portfolio of the company and the economic tender, rather than on the visualisations and advanced architectural drawings of the traditional competitions (Lykke Sørensen, Frandsen, & Borgestrand Øien, 2014). This change challenges the traditional workflow of an architectural office and has resulted in more focus being placed upon the competence of the design team and on reference projects. In architectural competitions and legislation there has been an increased demand for sustainability in order to both reduce the environmental footprint of buildings and to emphasise the environmental profile of the client (DANSKE ARK and FRI, 2017). Currently, sustainability is included to varying degrees in architectural projects, in which the differentiating parameters of sustainability are one of the factors used to distinguish between competing companies. Architects now try to quantify design decisions by basing them on calculations and simulations of daylight, acoustics, energy performance, indoor thermal comfort, LCA, and LCC (Brunsgaard & Larsen, 2015; Landgren & Jensen, 2017; Nielsen, 2012; Strømann-Andersen, 2012).

Timeline

To provide an overview of the main initiatives towards sustainable buildings, Figure 3 illustrates the main topics and milestones in periodic order as a timeline. The timeline has three main levels; sustainability in Denmark, sustainability at JJW Architects, and the development of this PhD research. The selection of points at the level of sustainability in Denmark consists of national building regulations, to provide an overview of their development in Denmark, the requirements of the Municipality of Copenhagen as an indicator of the general level of sustainability at the Municipality level, the development of DGNB in Denmark as the basis of national sustainability certification, and some tools that are used at the national level. The selection of points at the JJW level consists of sustainability strategies, projects with different sustainable approaches, and other initiatives towards a more focused sustainability approach. Finally, at the level of the development of this PhD research, they consist of several presentations at JJW and other places, participation in case studies at JJW, questionnaire distributions, participation in an interdisciplinary project (BISS), conference paper presentations, and journal paper publications.

Along with the selection for points on the PhD timeline a deselection occurred, as the entire building industry in Denmark underwent a rapid development in terms of sustainability. Architectural, engineering and contracting companies began to emphasise their strategy for sustainability and develop tools and methods internally to support them. Sustainability therefore became an even more complex matter to align and grasp in one PhD study, making it necessary to alter the selection. The timeline in Figure 3 was developed from a thorough literature study and from experience obtained in the PhD research itself, which became an important part of the foundation of the PhD research.


PhD
JJW
Denmark
2015
New sustainability expert at JJW.
New Danish Building Regulation, BR15
PhD Startup - Development of a method for Integrated Sustainable Design (ISD).
PhD project - Value-based development of Denmark's general housing.
Be15
Launch of LCAByg and LCCByg
Course in LCCByg and LCAByg.
JJW Project - Green drain.
DGNB Consultant education.
JJW Project - South Harbour School.
Guidelines for Sustainability in construction - Municipality of Copenhagen.
Mapping of one years production of projects at JJW.
JJW Project - Nature Center Amager Strandpark.
Sustain DTU - Presentation.
6 minutes presentation at JJW - LCCByg and LCAByg
JJW Project - Albertslund bymidte.
Global: FN 17 World Sustainability Development Goals (SDG's).
6 minutes at JJW - Introducing PhD study
4 employees educated - DGNB consultants at JJW.
2016
Case studies at JJW Architects
Case 02 - Daylight
Case 03 - DGNB Existing buildings
Case 05 - LCC and LCA refurbishment
Case 06 - Wind, sun and daylight
Case 07 - Sustainability screening
Case 10 - LCC
Case 11 - Sustainability screenin
Case 12 - LCC
Industry guidelines for energy calculations - InnoBYG project 'Sustainable Energy Renewal'.
The Green Workshop JJW
14th April 2016: First meeting of the Green Workshop.
LCC Workshop and presentation at MiljøForum Fyn
JJW Project - Republique theater, Reaktor stage
MBA update 2010
Update of Copenhagen Municipality guidelines for Environment in Buildings and Construction (MBA, Miljø i byggeri og anlæg 2010)
Now includes:
- Life Cycle Assessment (LCA)
- Life Cycle Costing (LCC)
BISS Workshop - Gothenburg Workshop on interdisciplinarity
STED programme workshop - NTNU, Trondheim
Paper presentation: International Conference on Integrated Design - Building our Future: Paper (1)
Presentation at - Summerschool for Urban Challenges, HCU+DTU+CBS
JJW Project - DGNB certification of JJW Workshop
Pilot phase of DGNB Existing office buildings
The pilot phase of DGNB Existing office buildings took place through 2016, with the final certifications in December 2016.
Presentation at - Summerschool for interdisciplinary renovation, VIA College
Mentor at BISS summer school, Hamburg: "Think the link Hamburg 2030 - Urban Futures", with the subtopic: "Energy Flow".

-

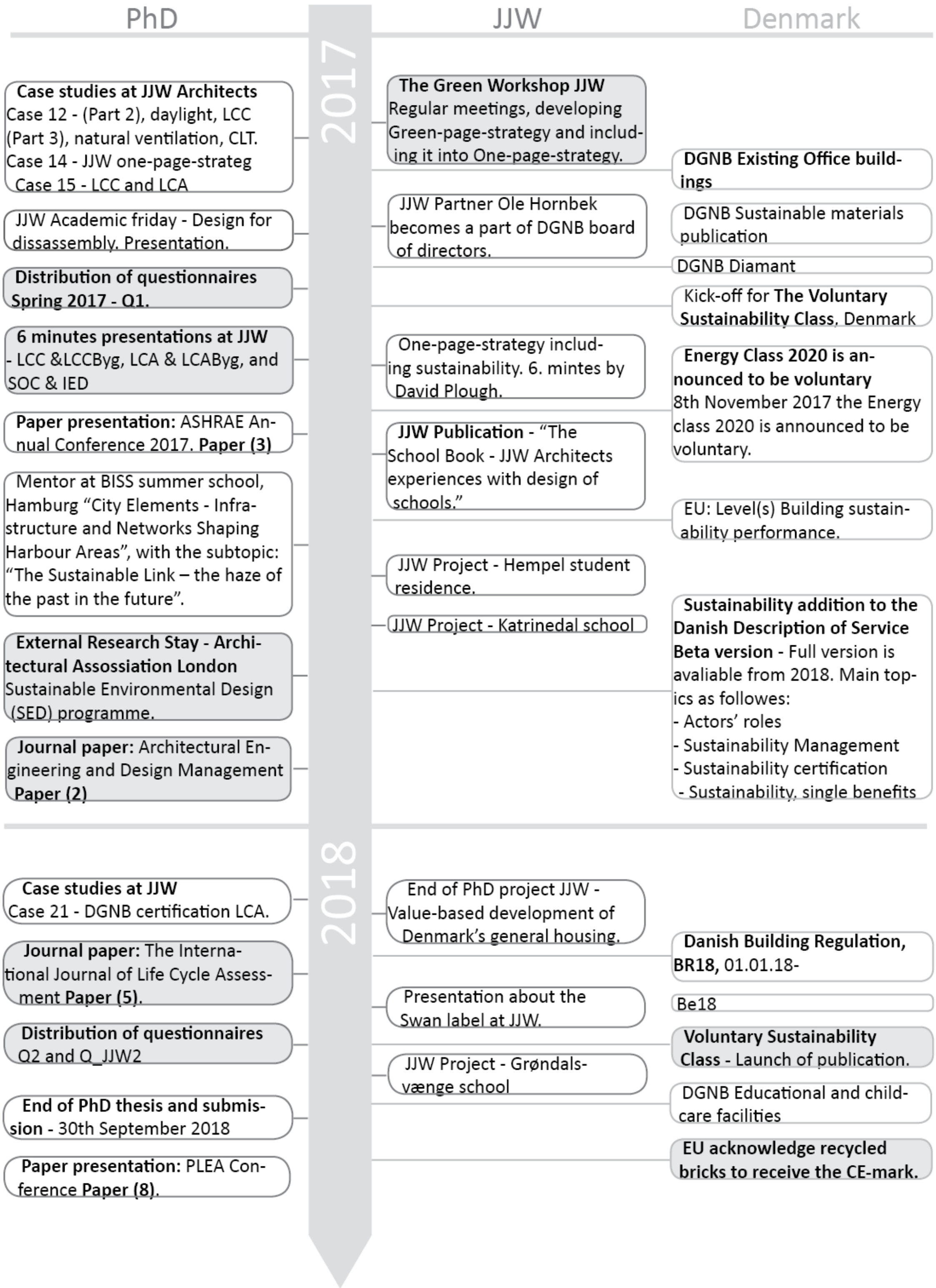


Figure 3 - Global, Danish and JJWs development of sustainability in the building industry.

1.2.1 JJW Architects and DTU

Architecture is important for the sustainability of a building, in relation to its service life and its value, and the ‘good story’ of a building and its sustainability often originates in the architectural sketches and initial ideas, so collaboration with an architectural office was an essential. The present PhD research project was based on a close collaboration between the Architectural Engineering department at the Technical University of Denmark (DTU) and JJW Architects.

The Department of Civil Engineering at DTU has a high worldwide ranking and the department of Architectural Engineering is a part of it (THE, 2018). Two other PhDs at the department have involved close links between the engineering and architectural fields of research (Nielsen, 2012; Strømann-Andersen, 2012).

JJW is one of the larger architectural offices in Denmark, with approximately 80 people working in their office in Copenhagen, known as the ‘JJW Workshop’, which they designed and moved into in 2008. The mix of employees mainly consists of architects, landscape architects and constructing architects, which is very typical for architectural offices in Denmark, although some offices have now started to include architectural engineers and civil engineers in their teams (JJW Arkitekter, 2018). JJW identify their work as follows:
“*UNIQUIFICATION OF THE COMMON INDOOR SPACE: We make the living spaces we all need into something special. Our vision is to take social responsibility and create tailor-made spaces that match the user's reality.*” (JJW Arkitekter, 2018)
And their identity as company to be based upon the following:
“*THREE BOTTOM LINES: Our vision is to create innovative and socially committed solutions. Therefore, we work with three bottom lines; job satisfaction, professional quality and consolidation, because all three are crucial for creating value and meaning for all involved in a building project. The three bottom line concepts work in interaction and support each other - none of them can stand alone*.” (JJW Arkitekter, 2018)

The four photos in Figure 4 show the work environment at the ‘JJW Workshop’.

Figure 4 - Photos from the office ‘JJW Workshop’, photos by Torben Eskerod (JJW Arkitekter, 2018).

JJW has already carried out several projects with a specific focus on sustainability. Figure 3 level 2 illustrates the development of their concern about sustainability in a timespan from 2008 till 2018. Figure 5 shows their projects focussing on different aspects of sustainability within the DGNB framework, illustrated by the DGNB wheel.

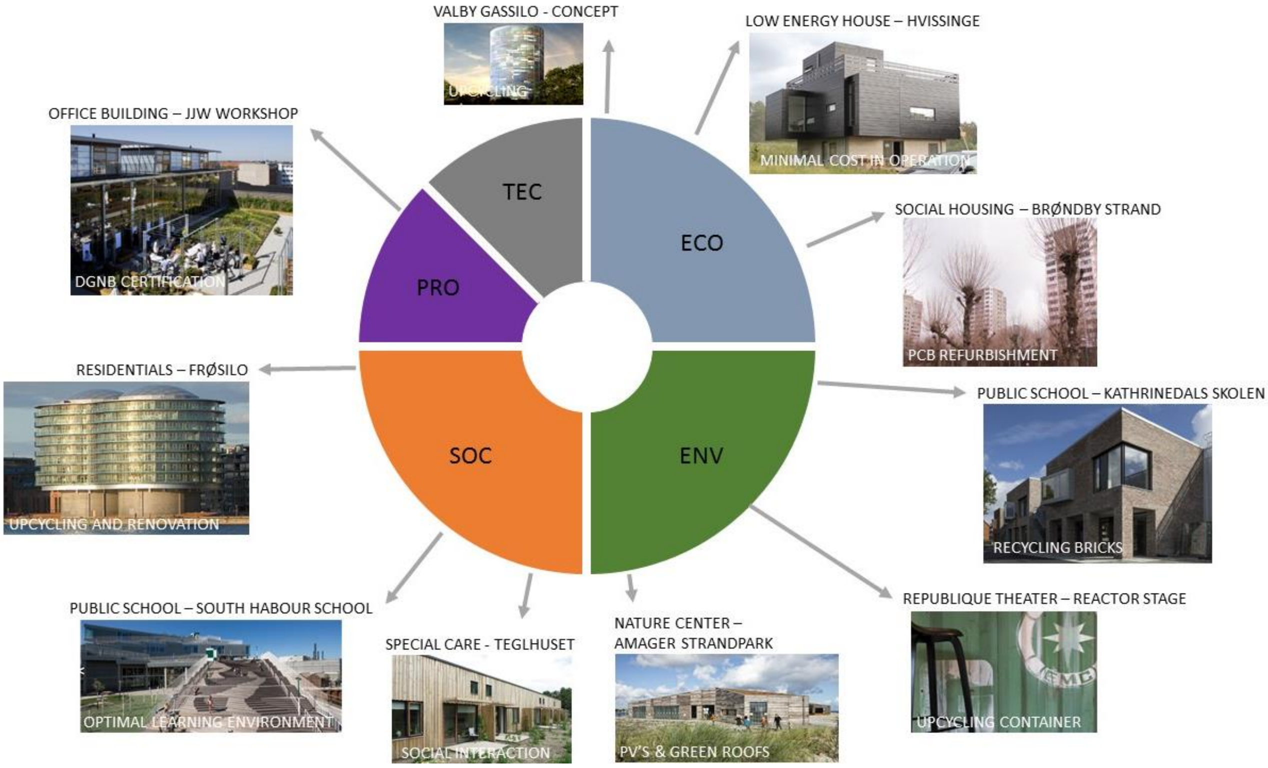


Figure 5 - The history of green projects at JJW in relation to the DGNB wheel, which project photos from (JJW Arkitekter, 2018).

JJW started early with their ambitions for sustainable architecture, by adopting the Passive House strategy and developing several buildings with this concept. However, market interest changed because of a political focus on more strict energy requirements, so their focus changed towards DGNB. The DGNB certification system was selected because it takes a more holistic approach compared to other systems, here explicitly mentioned in 'SOC 3.1 – Measures to ensure architectural quality'. They continued their development in sustainable architecture emphasizing their green strategy, educating employees in DGNB and publishing pocketbooks about green strategies and sub-topics within sustainability (JJW Arkitekter, 2018). Their buildings were becoming more and more complex due to the development of technology, strict building requirements, and their goal of producing sustainable buildings, so the level of knowledge required increased considerably. Architects, who are expected by the building industry to be generalists, now needed knowledge they did not have to ensure that they could meet the expectations of the building projects they undertook.

JJW, with its explicit goal of sustainability, has functioned as a testbed for implementation of ISD elements and prototype versions. Intended for architectural practice, ISD is a method based on simple graphics and descriptions referring to simple tools in the context of DGNB. As the following statement from a JJW webpage states, they support the Danish Green Building Council by emphasizing the use of the DGNB in their projects.

"As a framework for our work with sustainability we have chosen to be a part of the DGNB society in Denmark. We believe that we improve sustainability in the industry the most by being a part of a common platform, which covers the entire building industry. In relation to this we decided to be among the first in the country to DGNB certify an existing office building – our own office. This has sharpened our awareness of the need to understand the building in operation and focus upon robustness, lifetimes, life cycles and the building as a source of resources. A knowledge we transfer to our other projects."

[(JJW Arkitekter, 2018) Translated from Danish to English, and their publication "Uniquification of the common" (Særliggørelsen af det almindelige)]

JJW thus wants to develop a new operational method for sustainability that can be used in practice by their employees in all their projects. Their aim is to raise the general level of basic knowledge about sustainability among their employees. The purpose of this is to ensure the office can fulfil their ambitions for sustainable buildings in reality, so that this will characterize the company and brand it to clients and the industry. They thus want to develop a method that is based upon the company's work flow and design methods to guide their projects towards a sustainable vision and if desired by the client also to complete certification. The method must be simple and must create a more dynamic process for each project, where sustainability is continuously implemented throughout the integrated design process.

Tools and methods at JJW

JJW has always had a focus upon sustainability to some degree, as the timeline in Figure 3 shows, which illustrates what happened from 2008 when they moved to their newly built office. This focus has resulted in several projects and some publications, as previously mentioned. As an internal process tool, JJW has developed their 'One-page-strategy vol. 1', which is completed at every project start and at each phase change or project hand over, to maintain the vision of process, economy, collaboration, and time, seen in Table 1.

Table 1 - One-page-strategy vol. 1, internal tool at JJW Architects.

One-page-strategy vol. 1

- ECONOMY AND AGREEMENT
    - Contractual relationships
    - Counselling Form
    - Scope (which phases/services)
    - Economic basis for the assignment's solution
    - Economic framework according to agreement
- CRITERIA OF SUCCESS
    - Customer success criteria:
      Time, economy, quality, other. What has the client been saying and how have we interpreted it?
    - JJW's success criteria:
      Business: Business Economics, including the ambition factor
      Architecture and design: Pragmatically or architecturally ambitious.
      Other success criteria - e.g. Development of sustainability specialization, project management.
- FOCUS AREA
    - Description of the main idea for the project
    - Areas in the project with high/low priority?
    - Define design drivers and prioritized parameters.
- RISKS
    - What are the risk areas of the project?
- JJW DEVELOPMENT AREAS
    - Areas that will contribute to the development of JJW's professional knowledge, working methods or the like.
    - How does knowledge sharing happen?
- PLANNING AND MANAGEMENT
    - How can we manage the case so that the criteria for success can be met within each focus area, and identified risks and development areas?
    - When are architectural and design decisions to be made?
    - How should the case be manned in terms of the special skills required by the task?

In 2016 and 2017 an internal group 'The Green Workshop' was established to place sustainability at the top of the agenda for JJW. The main concern was to develop a tool to assist the design teams to manage their design process so as to realise the sustainability vision all through the design process. For this purpose a tool called the 'Green-page-strategy' was developed. The tool includes a DGNB wheel to be filled out from the initial design phase, which highlights the sustainability focus by having a broad focus upon sustainability. This tool was subsequently included in the 'One-page-strategy' vol. 2, to ensure coherence and limit the tools to one common strategy, as seen in Table 2.

Table 2 - One-page-strategy vol. 2 including sustainability topics, internal tool at JJW Architects, where the sustainability topics from green-page-strategy is highlighted with bold text.

One-page-strategy vol. 2

- ECONOMY AND AGREEMENT
    - Contractual relationships
    - Advice for counselling
    - Scope (which phases/services)
    - **Prerequisites for Sustainability Integration**
    - Economic basis for the assignment's solution
    - Economic framework according to agreement
- SUCCESS CRITERIA
    - Customer success criteria:
      Client values, **Process, environment, economy, social, technical.** What has the client said and what have we interpreted?
    - JJW's success criteria:
      Architecture and Design: Pragmatically or architecturally ambitious.
      Other success criteria e.g.: Process, development, special counselling, and competence development.
- FOCUS AREA
    - **10 sustainability concepts:**
      1. Energy concept, 2. Water concept, 3. Concept for indoor climate, 4. Concept for the flexibility and adaptability of the building, 5. Concept for building maintenance and cleaning, 6. LCC concept, 7. Concept for sustainable choice of materials and resource awareness, 8. Concept for the social sustainability, 9. Concept for exterior and landscape, 10. Concept for sustainable waste handling and use optimisation in use phase.
    - **Wheel for weighting process, environment, economy, social, technical** (Appendix)
    - Weighting, designation of key areas.
    - Set up "design drivers" and determine the priority parameters.
- RISK AND HANDLING
    - What are the risk areas of the project
- JJW DEVELOPMENT AREAS
    - Design one development area where the project will help to develop JJW
    - What is its output - competencies, references, challenging technical / architectural / process
- PLANNING AND MANAGEMENT
    - How the case should be planned.
    - How should the case be manned in terms of the special skills required by the assignment
    - When should architectural and design decisions be made
    - Pixie meeting: The above must be completed and read before Pixie meeting defines: Role, Responsibility, Rules, and Relationships.

As seen in Table 2, the topics related to sustainability are marked with **bold** text. Here sustainability is defined by the DGNB system by addressing process, environment, economy, social, and technical criteria. There are now a list of 10 focus areas for sustainability in the strategy to ensure a holistic approach to sustainability in each project. The 10 concepts were not taken directly from the DGNB system, but were categorised cross the groups of criteria to ease understanding and use for employees who are not familiar with the system. There is an appendix with the DGNB wheel that must be filled in, see Figure 17, which also emphasizes the influence of the DGNB system.

The One-page-strategy is filled out by the project leader in the start of the project before the Pixie-meeting, as seen in Table 2. The Pixie meeting includes the entire design team to set roles, responsibility, rules and relationships for the specific case.
JJW has thus retained freedom of choice of methods in the design process development, but the tool is an important way to maintain a focus upon the same topics in the same way. How to ensure that the vision of sustainability is reached in the One-page-strategy is not specified and this is left to the individual project leader to implement.

1.2.2 The international setting

To investigate the use of knowledge-based design with a focus upon parametric design tools, the PhD researcher had an 'external research stay' at the Sustainable Environmental Design (SED) Programme at the Architectural Association (AA) in London (Architectural Assossiation London, 2018). She had the honour to join the M.Arch. Programme with Prof. Simos Yannas in charge in order to observe and learn how the students were taught the simulation tools and how they used them in their design projects.

To obtain a detailed insight into interdisciplinary design projects also took part in the Baltic International Summer School (BISS) research project over a period of two and a half years. As a mentor at the summer school in 2016 and 2017 at HafenCity University in Hamburg, was able to see how interdisciplinary design projects evolve and how sustainability could be actively used in a setup where the students had little or no knowledge about this topic. Elements of different design processes were 'tested' on the team of students that the researcher supervised as a mentor at the summer schools. By participating in the related Symposium in 2017 and 2018 she was able to present her own work in an interdisciplinary context and obtain feedback from PhD students and a committee of experts from various professions in the building industry.

1.2.3 PhD setup

This PhD research is a moment in time, a brief snapshot of the state of the art that existed while this PhD research took place. It is thus a piece of the puzzle that must lead to a more sustainable future in the built environment. The previously described rapid development of building complexity, sustainability and changes in traditionally fixed professions in the building industry was the basis and context for the study.

The PhD project investigated how the DGNB certification system can be used as a design tool from the earliest design phases and throughout the design process. DGNB was used as the framework for sustainability because it was already a well-known and widely used system in Denmark and because the collaborating architectural office (JJW) was also using its terminology as the basis of their own approach. The criteria used in the research carried out for this PhD concern the energy- and indoor-climate related Social criteria as well as the environmental and economic criteria with a focus on LCA and LCC. Content from the IED method was thus used as a basis and the environmental and economic aspects were then added.
The research topic was to develop an Integrated Energy Design (IED) method to include a wider range of sustainability parameters in a new design method called Integrated Sustainable Design (ISD).

As illustrated in Figure 6, this research was part of a second wave of sustainability development in Denmark. The two waves can be described as follows:
<u>First wave:</u> DTU have had 3 PhD students at Henning Larsen Architects in Denmark. They worked with the Integrated Energy Design method and on how to use it in practice, using case studies. This was a step towards sustainable buildings, with Energy and indoor climate as the focus.

Second wave: The present PhD research examined sustainability in a broader perspective, using the DGNB certification system as its framework. By means of a technical approach, the design methods that were in use at the JJW architectural office were analysed as the basis for the definition of a new method known as “Integrated Sustainable Design” (ISD). A method, which is intended be easily adaptable by architectural offices and will ensure an increased focus on sustainability throughout all the design phases of a building.

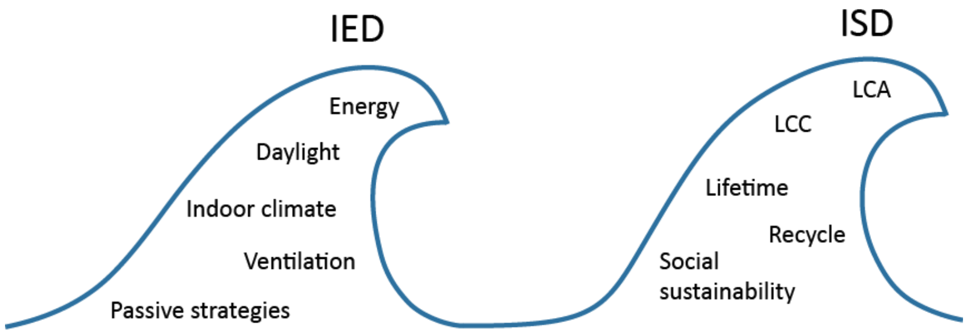


Figure 6 - The two waves of sustainability in the building industry, first was the IED method now the next wave will be the ISD method.

The goal was to define a new method that both architects and engineers can use to ensure sustainability from the earliest design phase, one that requires alternative working methods in relation to sustainability.

The method was implemented and developed in case studies at JJW. The wide range of sustainability issues included economic, environmental and social aspects, so the following aspects were added to the energy and indoor climate perspective of IED: Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social parameters.

The raw material of the case studies were the design teams and projects at JJW, and the PhD researcher contributed additional technical tools and technical knowledge about energy design and sustainability by her active participation. The PhD researcher communicated with the architects using visuals, using them to inform about the design process. When this process had been conducted several times, it resembled an iterative design process which guided the design process to ensure that the technical aspects and sustainability would be implemented and integrated into the design.

As previously illustrated in Figure 3 the PhD duration was from October 2015 till September 2018. Starting with a general focus upon DGNB and IED, followed by a focus upon LCA and LCC. The case studies at JJW formed a large part of the research, in which the design teams were provided with technical knowledge and the result was recorded. The PhD also included paper presentations at some conferences, other presentations, publication of journal papers and other related projects.

Sustainability is a complex topic and some specifications had to be made to limit the focus in this PhD research. The definition of sustainability was defined by the criteria in the DGNB certification system, as it is the most widely used certification system in Denmark. To specify the focus in this PhD research even more, the social criteria (SOC) were defined as the topics of indoor thermal comfort, acoustics and daylight, while for environmental criteria (ENV) the main focus was LCA, and for economic criteria (ECO) the main focus was LCC. Simulation tools and calculation tools that could address the topics related to the three main criteria, were used to inform the design process in each case studies. Knowledge of and use of these tools was part of the background of the PhD researcher, as an MSc Architectural Engineer at DTU, with some additional courses in LCA that were taken during the PhD, and training as a DGNB consultant. Her knowledge level about 3D modelling tools was due to her professional background, but was mostly at the level of a general overview of each tool rather than its use, and this is argued to be sufficient for communication with the experts involved.

1.3 Background

In this section, sustainability issues are elaborated both from a global perspective and from a national perspective in Denmark. Recent developments in the political and societal arenas had a great impact upon the architectural business and thus on the research topic of this PhD.

1.3.1 State of the art in the research area

The global context

The political agenda for building energy requirements and quantifying the environmental footprint of buildings have threads back into global history. The term sustainability was not used internationally before 1969, when it was introduced at the International Union for Conservation of Nature (IUCN), as a part of "perpetuation and enhancement of the living world" (Adams, 2006). Since industrialisation and until the oil crisis in 1973, industrial production grew rapidly and was accompanied by an increase in mining (Brundtland, 1987). Realising that the world's resources of fossil fuels was not infinite and documentation of their environmental impacts were a kick starter for sustainability on the global political agenda (Brundtland, 1987). This, among other things, resulted in an increased focus on limiting the use of fossil fuels and reducing the energy consumption of buildings in operation (Hildebrandt, 2016).

In 1983 the World Commission on Environment and Development (WCED) was established, based on the increased focus upon sustainability at several UN conferences. Later, in 1987 the (WCED) published the report Our Common Future, also known as the Brundtland Report, with the purpose of establishing "*A global agenda for change*" (Brundtland, 1987). Sustainable development was defined in the following citation from the report:

"*Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.*" (Brundtland, 1987)

This report was the basis for further development of the concept of sustainability in subsequent years, leading to formulation of the threefold goal of environmental, economic and social sustainability in 1992 at the United Nations (UN) conference in Rio de Janeiro (Brundtland, 1987; UNCED, 1992). Focus now moved from the energy consumption of buildings and how it affected environmental sustainability to include economic and social sustainability. This became the general meaning of sustainability that is used today, as seen in Figure 7.

Figure 7 - The threefold goal of sustainability; environmental, economic and social.

Climate Change is also a global driver for sustainable development, as human activities are the source of a large proportion of worldwide greenhouse gas (GHG) emissions (Pohl, 2016). Both the United Nations

Framework Convention on Climate Change (UNFCCC) in 1992 at the Earth Summit and the Kyoto Protocol in 1998 emphasized this global issue of man-made global warming and the need for change (United Nations, 1992, 1998).

UN 17 Sustainability Development Goals (SDG's) were recently redefined to place global sustainability permanently on the agenda (United Nations, 2017). All 17 goals can be seen in Table 3, showing the diversity of the 17 topics for the common goal of a sustainable future.

Table 3 - The UN 17 Sustainability Development Goals (SDG's) (United Nations, 2017).

The UN 17 Sustainability Development Goals (SDG's) (United Nations, 2017)		
1 No poverty	7 Affordable and clean energy	13 Climate action
2 Zero hunger	8 Decent work and economic growth	14 Life below water
3 Good health and well-being	9 Industry, innovation and infrastructure	15 Life on land
4 Quality education	10 Reduced inequalities	16 Peace, justice and strong institutions
5 Gender equality	11 Sustainable communities and cities	17 Partnerships for the goals
6 Clean water and sanitation	12 Responsible consumption and production	

Here climate change is acknowledged in 'Goal 13 -Take urgent action to combat climate change and its impacts'. It is stated that "*Emissions anywhere affect people everywhere*" (United Nations, 2017), to underline that these are global responsibilities. The European Union (EU) set key targets as Table 4 indicates:

Table 4 - Key EU targets for 2020 and 2030 (European Commission, 2016).

Key EU targets for 2020	**Key EU targets for 2030**
20% cut in greenhouse gas emissions compared with 1990	At least 40% cut in greenhouse gas emissions compared with 1990
20% of total energy consumption from renewable energy	At least 27% of total energy consumption from renewable energy
20% increase in energy efficiency	At least 27% increase in energy efficiency

In the long-term perspective the EU climate action states: "*By 2050, the EU aims to cut its emissions substantially – by 80-95% compared to 1990 levels as part of the efforts required by developed countries as a group.*" (European Commission, 2016).

To accommodate the goals for a reduction of emissions related to the build environment, sustainability certification systems have been an ongoing guideline for consultants, developers and contractors in practice. The first well developed and comprehensive sustainability certification system was BREEAM (Building Research Establishment Environmental Assessment Method) introduced in 1990 by the British Building Research Establishment (BRE). The aim was to develop cost effective and energy efficient assessments of buildings (BREEAM, 2018). In 2000 LEED (Leadership in Energy and Environmental Design), was introduced in the USA by the US Green Building Council (USGBC, 2018). Both certification systems were part of the 1st generation of sustainability certification systems, defined by the common aim of reducing the energy use of buildings in operation (Ebert, Eßig, & Hauser, 2011).

DGNB is a German certification system developed in 2007 by the German Green Building Council (DE-GBC, 2018). It focuses on all three sustainable pillars of sustainability, SOC, ENV and ECO, and includes DGNB in the 2nd generation of sustainability certification systems (Ebert et al., 2011). BREEAM, LEED and DGNB were developed along with other sustainability certification systems worldwide, such as Green Star from Australia in 2003 and Miljöbyggnad from Sweden in 2009 (GBC-Australia, 2018; SE-GBC, 2018). Overall the Building Sustainability Certification Tools (BSATs) defines certification systems as tools in practice (Ebert et al., 2011).

The context of energy requirements in Denmark

To compare the EU key targets of decreasing Green House Gas (GHG) emissions by 20% in 2020, as seen in Table 4 above, the Danish building regulations aim to decrease emissions by 50% from 1990 to 2020 for the building mass in total (Danish Energy Agency, 2015). The Danish energy regulations for buildings in operation are thereby in the forefront for reducing the use of fossil fuels (Hildebrandt, 2016).

In recent decades the Danish building industry has increased its focus on sustainability in order to be able to reach the EU goals for 2020, since about 40% of all greenhouse gas emissions are from the building industry (Koch & Buhl, 2013), which also accounts for approximately 35% of Denmark's total energy consumption (Dansk Byggeri, 2017).

The first time requirements were set for the energy consumption of buildings in operation was in the building regulation of 1977, which came into force in 1979 (Boligministeriet, 1977). It was not until the building regulation of 2006 (BR06) that requirements concerning the energy consumption of buildings in operation was aligned with the requirement of fulfilling a so-called energy frame (Energi Styrrelsen, 2007):

"*From 1st of April 2006 according to the building regulation, all new buildings must fulfil an energy frame for the total need for energy to use for heating, ventilation, cooling and domestic hot water and for 'non-residential buildings' also lighting.*" (Energi Styrrelsen, 2007)

These requirements were based on the EU directive EPBD (Energy Performance Building Directive) concerning the energy consumption of buildings in operation ("EUR-Lex - 52008DC0772 - EN - EUR-Lex," n.d.; Togeby et al., 2008).

Danish building requirements have since 2006 been tightened and tuned concerning the energy consumption of buildings in operation and the effects are seen in Figure 8. The long-term perspective for decreasing energy consumption has also affected the market for new products for low energy consuming buildings (Pohl, 2016).

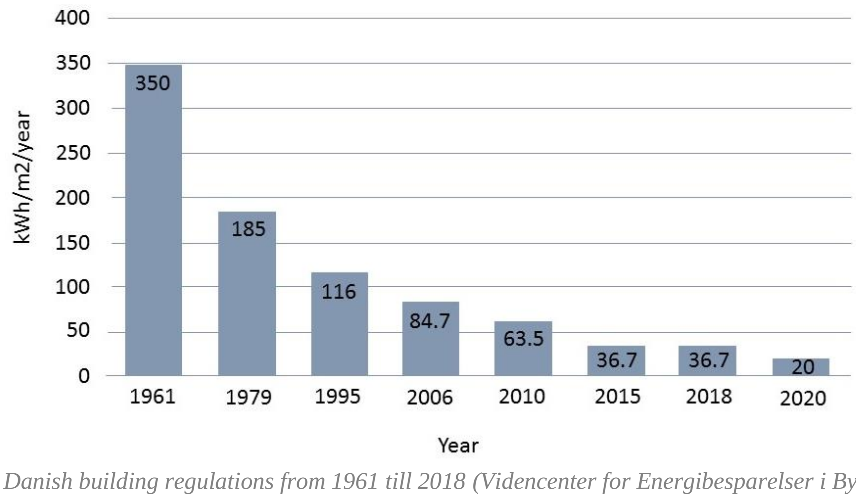


Figure 8 - The Danish building regulations from 1961 till 2018 (Videncenter for Energibesparelser i Bygninger, 2018).

As a result of the ongoing tightening of the building regulations the BR2020 it was decided on 8th November 2017 that it should be elective and not the next building requirement, as was previously intended by BR15 (Trafik- Bygge- og Boligstyrelsen, 2018). Instead BR18 was introduced on 1st January 2018 to replace the existing BR15. As seen from Figure 8 the limit for decreasing the energy consumption in buildings compared to the energy consumption related to the other life cycles of the buildings has been reached and as seen in the figure the same energy frame has been adopted for 2018 as in the 2015 regulations (Trafik- Bygge- og Boligstyrelsen, 2018).

1.3.2 The complexity of sustainability

Sustainability has in recent decades been an important topic, which has led to a great deal of discussion at all levels of society, from the highest political levels to the individual consumer and user of buildings. This has led to great confusion, since the topic is such a broad one without a consistent definition. The definition of "to sustain" means 'to maintain' according to Oxford Dictionaries (Oxford Dictionaries, 2018). This definition seems rather simple, but within the building industry, a large number of terms concerning sustainability can be combined in a web, having several links spanning from term to term in a complex mesh. Figure 9 illustrates how a wide number of sustainability terms are interconnected and linked in such a web. The web illustrates how environmental, economic and social sustainability are interconnected, while the next layer of related topics are interconnected and so on. For economic sustainability, for instance, there are links to DGNB, the circular economy, primary energy, LCC, reuse, recycle and upcycle, as well as thermal indoor climate, sustainability management, refurbishment, and daylight. Here the circular economy has strong links to environmental sustainability, materials, and reuse, recycling and upcycling. To underline the complexity, there are even more terms and definitions, not shown here in Figure 9.

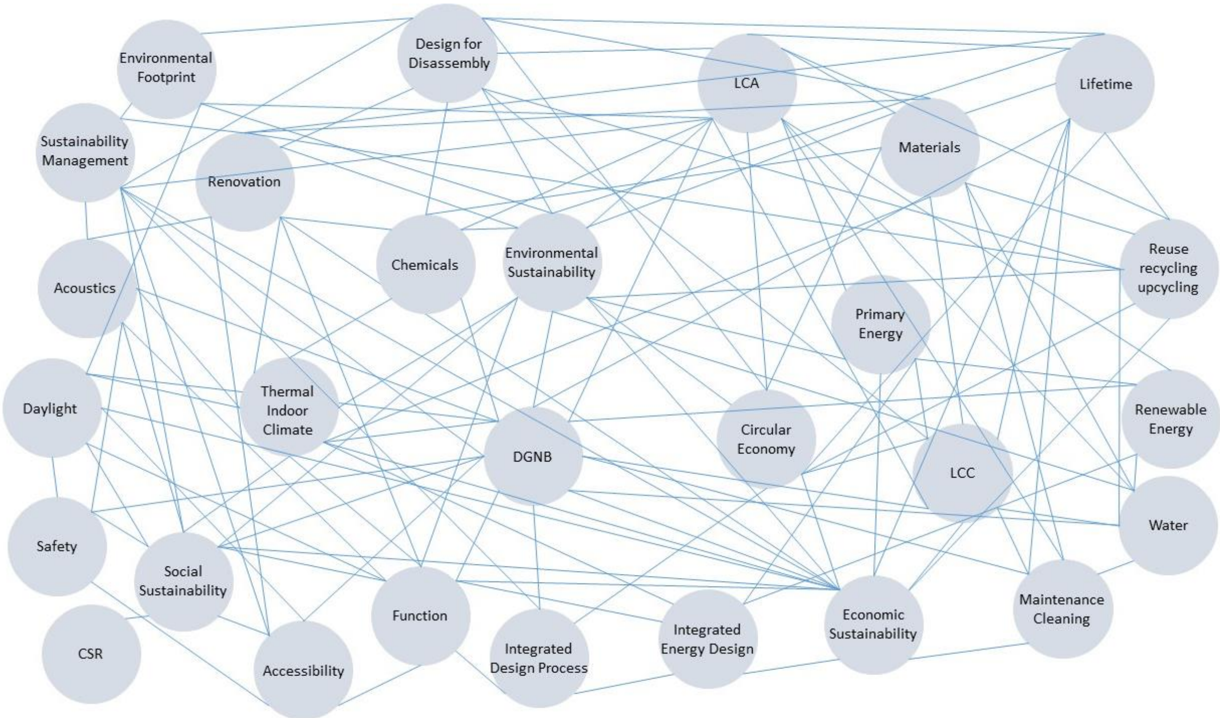


Figure 9 - A wide number of sustainability terms are interconnected and linked in a web.

With this illustration in mind, the present PhD research attempted to grasp it all but decisions and limitations had to be made to sharpen the project and the research process.

1.3.3 Environmental footprint

As seen in the previous sections, the development of energy regulations globally and in a Danish framework has been the driving factor that has limited GHG emissions of buildings in operation (Danish Energy Agency, 2015). When the entire life cycle of a building is included, emissions from the additional life cycle phases are included in the total emission of a building, as seen in Figure 10, so the total emissions are increased. There is a tendency now for the building industry to try to include the entire life cycle when defining the actual environmental footprint (DK-GBC, 2014; Københavns Kommune, 2016; SE-GBC, 2018). New research shows how the embedded energy of office buildings and single-family house is higher than the energy consumption of the buildings, in terms of the resulting GHG emissions and the Primary Energy consumption (PE_{tot}) of the building in operation (Birgisdottir & Madsen, 2017). This is an important argument for including the entire life cycle when calculating the environmental footprint of buildings.

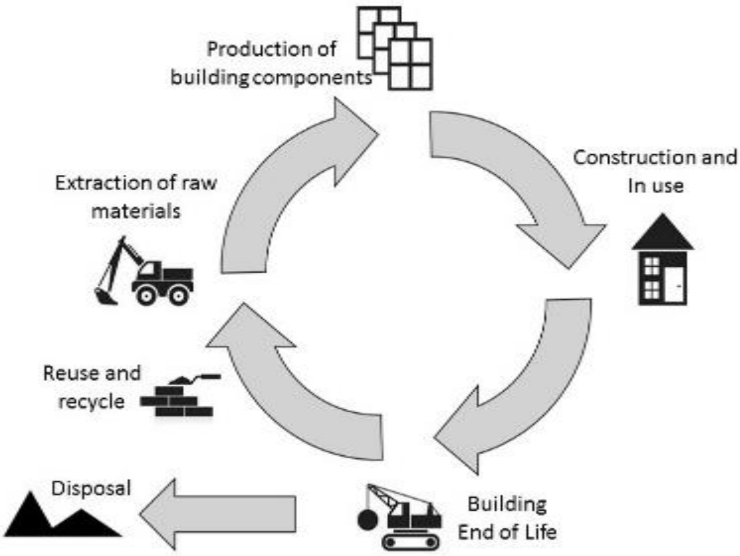


Figure 10 - Illustration of all life cycle phases for a building.

One tool for deriving the environmental footprint is Life Cycle Assessment (LCA), which can be used as a tool at various levels: material, component or the entire building level including operation, and it can be used from the earliest design phases (Marsh, Nygaard Rasmussen, & Birgisdottir, 2018). LCA was introduced around 1970 and until 1990 it was a wide and rather divergent approach, but from 1990 till 2000 the LCA approach became more aligned between research and practice, resulting in its political use and the standards that apply today (Guinée, 2016).

Despite the long history of using LCA in practice, it is relatively new in the building industry and at the moment in the Danish building industry there are no building requirements concerning LCA, although some municipalities have started to request LCA to some degree in their projects (Københavns Kommune, 2016). The Municipality of Copenhagen, for instance, stipulated LCA as a part of their Environmental requirements for all their buildings in 2016, see Table 5, and since 2010 overall LCA considerations have been included (Københavns Kommune, 2010, 2016).

Table 5 - Life Cycle Assessment requirements from Copenhagen Municipality, Denmark, translated from Danish into English (Københavns Kommune, 2016).

<table>
<tr><td colspan="3">Life Cycle Assessment
For all new buildings a life cycle assessment, LCA, of building components has to be conducted to qualify selections of constructions with the lowest negative environmental impact. The client selects at least one of the mentioned building components and evaluate at least two variations of the selected building component(s). Selection of building component and variations have to be explained.</td></tr>
<tr><td>Building component</td><td colspan="2">Following indicators have to be evaluated</td></tr>
<tr><td rowspan="2">1. Building basis
2. External walls
3. Internal walls
4. Deck, stairs, ramps, balconies, attics
5. Roofs
6. HVAC</td><td>1. Environmental footprint</td><td>2. Primary energy consumption</td></tr>
<tr><td>1.1 Global Warming Potential (GWP)
Unit: kg CO_2-equivalents
Environmental problem: Climate change
1.2 Ozone Depletion Potential (ODP)
Unit: kg R11-equivalents
Environmental problem: Degradation of the stratospheric ozone layer
1.3 Photochemical Ozone Creation Potential (POCP)
Unit: kg C_2H_4-equivalents
Environmental problem: Summer smog
1.4 Acid Potential (AP)
Unit: kg SO_2-equivalents
Environmental problem: Forest and fish killings
1.5 Eutrophication Potential (EP)
Unit: kg PO_4-equivalents
Environmental problem: Eutrophication</td><td>2.1 Use of none-renewable energy (the amount of the primary energy consumption based on none-renewable energy)
2.2 Collected use of primary energy
2.3 Share of renewable energy</td></tr>
</table>

There are five overall life cycle phases, which are again sub-divided into modules according to the DGNB certification system (DK-GBC, 2014). The letter defines the phase and the number indicate the module; A1-3: Manufacturing phase, A4-5: Construction phase, B1-7: Use phase, C1-4: End of life phase and D: Advantages and loads outside the system boundary, as illustrated in Figure 11 (DK-GBC, 2014). As seen in Figure 11, the DGNB certification system includes only eight modules: A1, A2, A3, B4, B6, C3, C4 and D (DK-GBC, 2014).

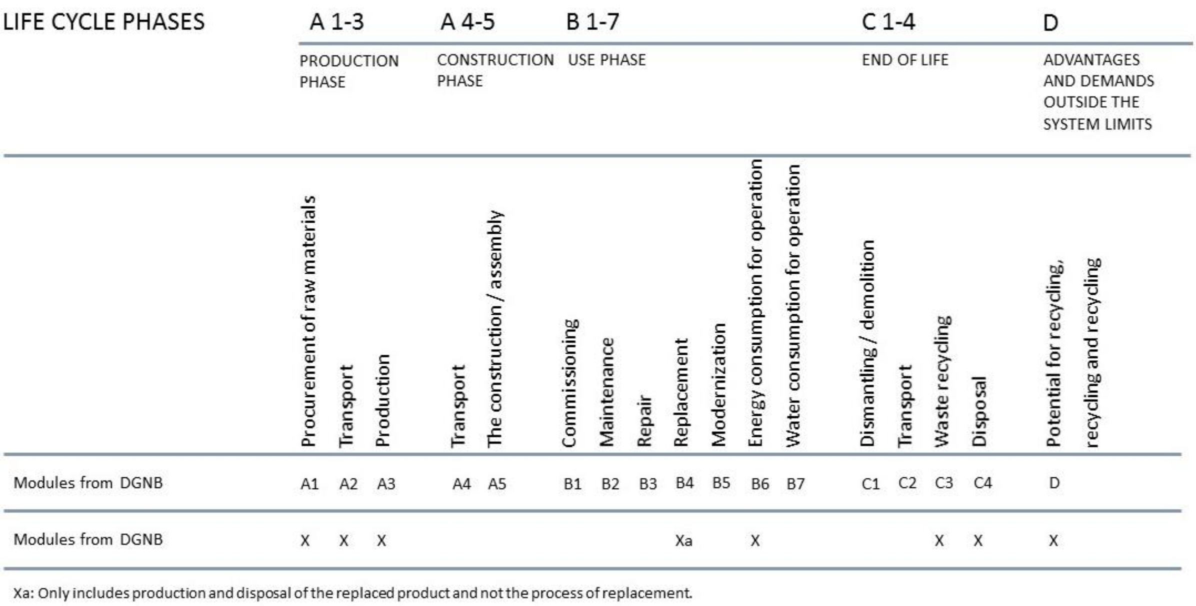


Figure 11 - The five overall life cycle phases, subdivided into modules according to DGNB. Modified from DGBN (DK-GBC, 2014).

A LCA is based on specific product data for each material, based on an Environmental Product Declaration (EPD), which has been developed according to ISO 21930: 2007, updated in 2017 to ISO 21930: 2017 to ensure all relevant data are included with the right unit (International Organization for Standardization, 2017). An EPD describes the material specifications of the given product through all life cycle phases, including chemicals, treatments and disposal. These EPD's are the basis for many databases. There are several available databases online worldwide, although the most commonly used in a Danish context is the German Okobau.dat, hence the LCA tool LCAByg has this as its basis (Byggeforskningsinstitut, 2015; ÖKOBAUDAT, 2018). Another database: Ecoinvent was developed in Switzerland and is used both for complex software such as Gabi and simpler software such as Quantis Suite and OpenLCA (Ecoinvent, 2018; Ohms, Andersen, Landgren, & Birkved, 2018).

The focus on environmental sustainability and scarce resources has led to new popular terms in the building industry: Circular economy, Design for Disassembly, Recycling and Upcycling, Urban mining and many other terms (Marsh et al., 2018). These topics also underline the importance of handling refurbishment carefully as well as the issues that are relevant to such a process. Hazardous materials have to be taken into account both for the work process but also for the purpose of reuse (Ohms et al., 2018).

In Denmark building materials from before 1950 are often reused, due to their high quality and since they most likely do not contain hazardous substances (Mortensen, Birgisdottir, & Aggerholm, 2015). PCB was prohibited in 1977, as we now know there is a health impact (Miljø- og Fødevareministeriet, 2018). For all the newly invented materials it is still not known whether they might contain hazardous substances. Research studies have tried to map the materials for reuse in existing buildings to increase the possibility of reusing materials and components from existing buildings in the future (VHGB, KADK, Teknologisk Institut, & Innobyg, 2016). When considering reuse and design for disassembly it is important to consider the different materials incorporated in the layers of the building, hence the different layers or components may have different life times. The joints between the different materials are also of importance, as they may determine whether it is possible to disassemble at all.

Despite the importance of the environmental footprint, this is not always the top priority in practice, where economy has a great impact, as a part of this PhD research has shown (Landgren, 2017). One of the reasons that LCC might be easier to use in practice is the focus upon limiting only one common unit - the price, whereas LCA includes a long list of units for each environmental footprint, as seen in Table 5.

A useful tool from the economic perspective is Life Cycle Costing (LCC) and in Denmark a tool LCCByg was introduced in 2015 to promote the use of LCC in practice (Haugbølle, 2015). As for LCA, the costs for the entire life cycle of the building are all included, so the range of considerations is wider than the product costs. However, minimizing costs can result in less material usage and thereby reduced energy consumption for the production of the building materials, so the sustainability approach has over a period of years developed from LCA and LCC to Life Cycle Sustainability Analysis (LCSA), which according to a thorough literature study by Guinée (2016) still faces many challenges (Guinée, 2016). Some of these are the lack of alignment and consistency in the methods, the lack of a guide for implementation in practice and for analysing the results.

1.3.4 Technological development in the built environment

Existing design methods and simulation tools form a foundation for state-of-the-art sustainability in practice. Along with the increased focus upon sustainable buildings in recent decades, simulation tools and software have been developed as required. At the intersection of social and environmental sustainability, energy consumption and indoor climate are important topics (Ding, 2008; Ebert et al., 2011; Kongebro, 2012; Löhnert,

Dalkowski, & Sutter, 2003). A broad field of simulation tools are available to assist the building designer in analysing daylight conditions, thermal comfort, and energy consumption of the building. There are tools that stands alone to analyse single aspects and others that are linked through plugins to 3D modelling tools to enable the same model to be used for various analyses (Kongebro, 2012; Strømann-Andersen, 2012). Building Information Modelling (BIM) is the common term for 3D modelling that combines information across disciplines into one model and the design process then becomes easier to communicate and handle in such interdisciplinary design tasks as sustainability (Kongebro, 2012; Strømann-Andersen, 2012). In the last decade the criterion of environmental sustainability has been further developed by including LCA tools. They are available at various levels of detail, mostly as a separate tool but more plugins have recently been developed to link them to existing 3D modelling tools to ease the design process. LCA is a complex matter, which depends on very precise measures and knowledge about the materials used. To obtain more inputs for the refurbishment of existing buildings, a 3D scanning can be used as the basis of a BIM model, by integrating the scanning into the 3D model (Landgren, 2017).
Despite the development of simulation tools to support building design projects with technical knowledge in many ways, their use in practice has been challenged in several research studies, so they are as yet not as interdisciplinary or integrated as was intended (Brunsgaard, 2009; Urup, 2016).

1.3.5 Building Design Process

The Traditional Design Process (TDP) has its roots back in history, where the architect first designed the building and then the engineer was only later included in the process to deal with the technical aspects (Brunsgaard, 2009; Urup, 2016). Following the development of digital engineering tools for a more complex building industry, the Integrated Design Process (IDP) was developed. The IDP supported an interdisciplinary work flow and the iterative workflow needed among disciplines to ensure implementation of technical knowledge in the design processes and not only as an add-on after the design had been finalised (Brunsgaard, 2009). Here the importance of early influence in the design process was emphasised to reduce the cost of design changes, as illustrated in the graph in Figure 12 (Kanters & Horvat, 2012).

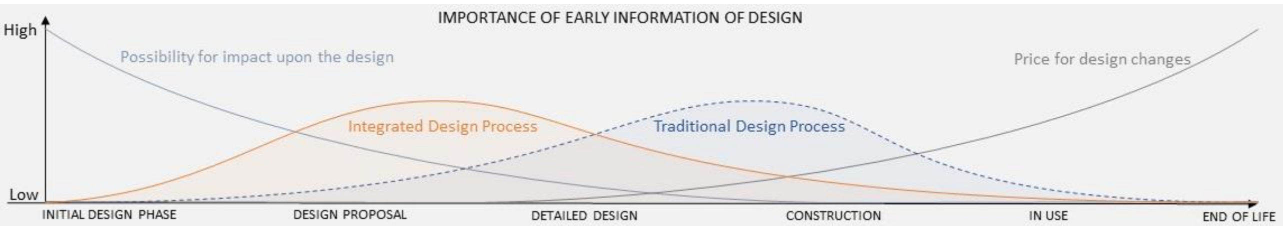


Figure 12 – Modified version of the MACLeamy curve, the importance of early design decisions.

Studies have shown that many national descriptions of services still use the TDP and do not include IDP, which makes it difficult to change design processes in practice towards more interdisciplinary work flows (Brunsgaard, 2009). As a part of the first wave of implementation and development of sustainability, where energy consumption and indoor climate were the main focus, the Integrated Energy Design (IED) method was developed (Löhnert et al., 2003). Integrated design however, does not mean that one should be specialist in all topics and include it in practice, rather it means to seek to understand different perspectives of the project through collaboration (DeKay, 2011).
Within the design phases "Integrated Energy Design" (IED) has been the most common approach for decreasing the environmental footprint by limiting the energy consumption of buildings and the use of fossil fuels (Brunsgaard et al., 2014). The IED method is a specialised version of the Integrated Design Processes (IDPs), but it also emphasises the importance of early design influence (Brunsgaard et al., 2014; Löhnert et

al., 2003). IED was developed in a Norwegian innovation project INTEND in 2007-2009 (Holanek, 2009). Later other researchers tested the method in practice at a big Nordic architectural office in 2012, through their PhD research and further developed the IED method to make it more usable in practice, as seen in Figure 13 (Kongebro, 2012; Nielsen, 2012; Strømann-Andersen, 2012). This was the starting point for the present PhD research.

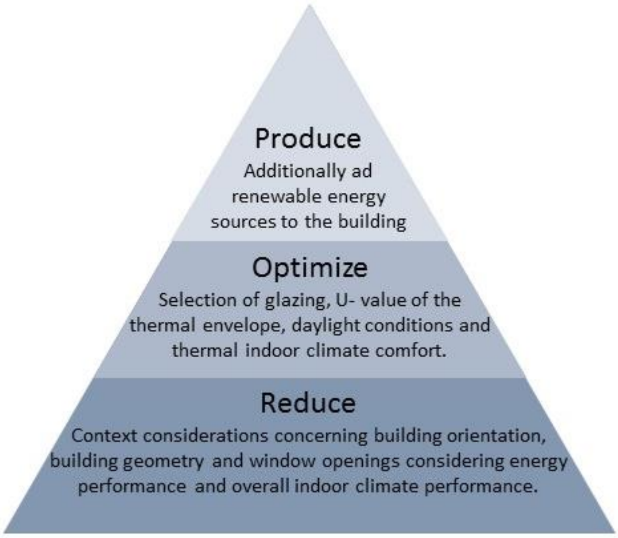


Figure 13 - The Kyoto Pyramid, resembling the IED method, modified from (Kongebro, 2012; Nielsen, 2012; Strømann-Andersen, 2012).

1.3.6 DGNB

The DGNB system was chosen as the most preferable sustainability system in Denmark in 2010 by the DK-GBC, based on a comparison of existing sustainability certification systems. The DGNB system was selected to increase the general level of sustainable buildings in Denmark, guided by the DK-GBC (Birgisdottir, 2012). In 2011 the first DGNB system adapted to the Danish building regulations was presented for use and has since then been updated regularly (Green Building Council Denmark, 2012).

A new report from DK-GBC shows that only 16,8% of the DGNB criteria are fulfilled if solely focusing upon fulfilling the new Danish building regulation for 2018 (BR18) (DK-GBC, 2018a). The level of sustainability is thus very limited if only the legal requirements of BR18 in a building project are considered, so it is important to focus on sustainability in a broader perspective by using the DGNB system (DK-GBC, 2018a).
Sustainability certifications has become an accepted concept that creates a kind of seal of approval for a building project, which make them more attractive and creates economic benefits for the building owner. Certification is a method for measuring and quantifying sustainability in a project. Through a systematic approach the certification proves the sustainability in the choices of the design, and in this way makes it possible to compare the level of sustainability between different projects (DK-GBC, 2014).
For economic, organizational and temporal reasons, it may not always be desirable for a project to obtain a fully implemented certification, but it may still be desirable to ensure a certain level of sustainability. Even when the construction company and the architects offer DGNB sustainability certification to its customers, many customers choose to go only part of the way towards formal certification so that there are systematically documented qualities without the rigidity that certification entails and the related costs.
The DGNB certification system exists in many versions, with the building typology as the starting point for selecting the correct version. Among these building typologies are (DK-GBC, 2018b):

- New office buildings

- Residential story houses and terrace houses
- Hospitals
- Educational and childcare facilities
- Urban areas
- Existing office buildings
- Diamond for architectural quality

Table 6 shows the DGNB criteria for 'New office buildings' as a reference for all typologies, hence the limited difference (DK-GBC, 2014).

Table 6 - DGNB criteria for 'New office buildings' (DK-GBC, 2014).

Theme	Criteria group	Number	Criteria	Weighting factor	Group weight
Environment	Life cycle assessment	ENV 1.1	Life cycle impact assessment	7	22,5%
	Global and local environment	ENV 1.2	Environmental risks related to building materials	3	
		ENV 1.3	Responsible procurement	1	
	Utilization of resources and arising waste	ENV 2.1	Life cycle impact assessment – Primary energy	5	
		ENV 2.2	Drinking water demand	2	
		ENV 2.3	Land use	2	
Economy	Life cycle cost	ECO 1.1	Life cycle cost	3	22,5%
	Value stability	ECO 2.1	Flexibility and adaptability	3	
		ECO 2.2	Commercial viability	1	
Social	Health, comfort and user satisfaction	SOC 1.1	Thermal comfort	5	22,5%
		SOC 1.2	Indoor air quality	3	
		SOC 1.3	Acoustic comfort	3	
		SOC 1.4	Visual comfort	3	
		SOC 1.5	User control	2	
		SOC 1.6	Quality of outdoor spaces	2	
		SOC 1.7	Safety and security	1	
	Functionality	SOC 2.1	Design for all	2	
		SOC 2.2	Public access	1	
		SOC 2.3	Cyclist facilities	1	
	Quality of design	SOC 3.1	Design and urban qualities	3	
		SOC 3.2	Integrated public art	1	
	Plan layout	SOC 3.3	Plan layout	1	
Technical	Quality of technical configuration	TEC 1.1	Fire safety	2	22,5%
		TEC 1.2	Sound insulation	2	
		TEC 1.3	Building envelope quality	2	
		TEC 1.4	Adaptability of technical systems	1	
		TEC 1.5	Cleaning and maintenance	2	
		TEC 1.6	Deconstruction and disassembly	2	
Process	Quality of planning	PRO 1.1	Comprehensive project brief	3	10%
		PRO 1.2	Integrated design	3	
		PRO 1.3	Design concept	3	
		PRO 1.4	Sustainability aspects in tender phase	2	
		PRO 1.5	Documentation for facility management	2	
		PRO 2.1	Environmental impact of construction	2	
	Quality of construction activities	PRO 2.2	Construction quality assurance	3	
		PRO 2.3	Systematic commissioning	3	
Site	Site	SITE 1.1	Local environment	3	0%
		SITE 1.2	Public image and social conditions	3	
		SITE 1.3	Transport access	3	
		SITE 1.4	Transport to amenities	2	

The intention of the DGNB certification system is to use it as a design tool during the process and a way to ensure a certain level of sustainability in the project from first visions and design concepts to the final constructed building (DK-GBC, 2018b). Certification systems make projects measurable and comparable, a way to describe and quantify sustainability which is otherwise a complex matter. However, the DGNB does not describe how to use it as a tool in the design process, despite the aim in the ‘Process criteria’.
Research has been conducted to investigate how the DGNB is actually included in design processes, and has found that DGNB tends to be more of a check-list that is used to document the points that have been reached (Brunsgaard, 2016).

The use of DGNB is becoming more and more widespread in Denmark and it is in constant development, to adapt to regional requirements such as BR18, but it also emphasises and supports global tendencies in sustainability, such as the UN 17 SDG’s (DK-GBC, 2017). The developers of the DGNB made a comparison of the DGNB and the 17 SDGs, and found that 13 out of 17 goals were addressed by the DGNB (DK-GBC, 2017). A master’s thesis, supervised as a part of this PhD study, documented the coherence between the two systems. The study identified the relevance of 93 out of the 169 SDG targets that are related to the DGNB system (Orfanidou, 2018).

2. METHODS

2.1 Quantitative and qualitative study

This PhD research used a twofold method – the quantitative and the qualitative approach – where both are equally important. The study was conducted in the field by means of case studies. The quantitative part of each case study took place when implementing and using technical simulation and calculation tools in the building design processes, while the active research approach that was taken and the researchers own influence, evaluations, analysis and handling of the design process constituted the qualitative approach, as seen in Figure 14. Mapping has elements that are both quantitative and qualitative but is primarily quantitative. Additionally, the use of the DGNB system was the basis of this research approach, and this system uses both qualitative and quantitative evaluation criteria.

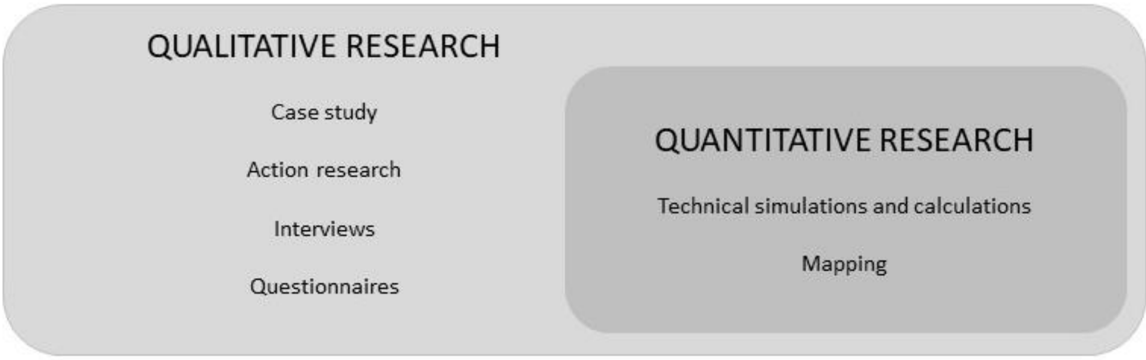


Figure 14 - Qualitative and quantitative setup in this PhD research.

The scientific method was applied to evaluation of the impact of the proposed design process and design method, using both qualitative and quantitative data. By analysing a number of design processes at JJW Architects, it was possible to compare and evaluate how different factors affected the design process in the case studies and in the final phase submission products.

Two kind of case studies were examined. One category consisted of case studies that were not affected by the PhD researcher's input. These case studies were available in the historical archive of the company from existing project briefs. These cases formed a baseline reference for the second category of case studies, in which the PhD researcher took an active part by introducing specific elements and observing and reflecting upon the effects this produced, and may thus have affected the design process.

In qualitative assessments the toolbox was taken from the humanistic science tradition (Glaser & Strauss, 1967; Kvale, 2007), while the quantitative assessments were based on the DGNB certification methodology (as described in previous section 1.3.6 DGNB) that is widely used in the building industry (Anders, 2013; Andrade & Bragança, 2016). However, it should be noted that the DGNB system uses both quantitative and qualitative indicators as criteria (DK-GBC, 2014)

The main points of comparison between qualitative and quantitative research in this research were those set out in Sharan's (1988) definitions as listed in Table 7 (Sharan B., 1988).

Table 7 - The point of comparison for qualitative and quantitative research, modified table to fit current research perspectives (Sharan B., 1988).

Point of comparison	**Qualitative Research**	**Quantitative Research**
Focus of research	Quality (the essence)	Quantity (the amount)
Associated phrases	Fieldwork, subjective	Experimental, empirical
Goal of investigation	Understanding, description, hypothesis generating,	Hypothesis testing, control
Design characteristics	Flexible, evolving	Predetermined, structured
Data collection	Researcher as primary instrument, interviews, observations	Physical instruments (scales, questionnaires)
Mode of analysis	Inductive (by the researcher)	Deductive (by statistical methods)
Findings	Comprehensive, holistic	Precise, narrow

Most qualitative research methods in current research focus upon the design process rather than the final design of the building, and seek to understand the reasons for the design decisions made by the design team (Kvale, 2007). Case study research, in which the researcher takes an active part while also observing and reflecting on the impact this has, is a classic case study approach. As this research was conducted by me as a researcher and PhD student the findings must inevitably be mediated by my subjective perceptions (Sharan B., 1988).

2.2 Mapping sustainability in practice

The central part of the research method of this PhD research was based upon mapping of:

- design process flow,
- design team structure,
- design decisions,
- level of sustainability,
- implementation of technical knowledge,
- level of Integrated Energy Design (IED) parameters, and
- level of DGNB parameters.

Figure 15 illustrates the process of the mapping. The mapping was conducted in two main categories. The first category was based on available material in the literature and in the records of cases conducted at JJW one year prior to the start of the PhD research. The second category was based on active research in case studies involving the participation of the researcher, supported by interviews and questionnaires mainly at JJW but also including other companies and specialists in the building industry. Both approaches to mapping the state of the art of sustainability in building design projects and processes formed the basis for the development of Integrated Sustainable Design (ISD) in this PhD research project.

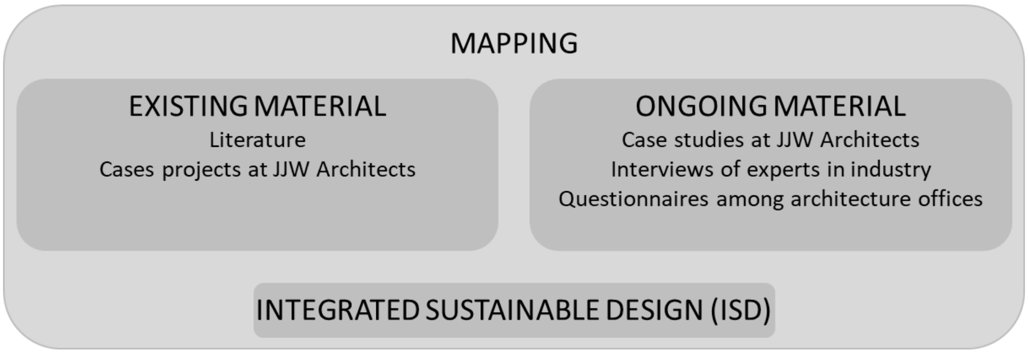


Figure 15 - Mapping as method for the research process.

This section describes the mapping methodology and how it was developed to obtain an overview of the state of art for implementing sustainability at an architectural office in the framework of the IED method and the DGNB system.

Mapping is used as a tool to document data in defined matrices for easier comparison and analysis. This is a method that has been used in previous research, e.g. by Schröpfer et al. (2017) to map the complexity of sustainable building projects as well as by Macmillan et al. (2002), who compared process maps from architecture and engineering (Macmillan et al., 2002; Schröpfer, Tah, & Kurul, 2017).

The mapping represents architectural practice as the topic of research and the focus of this sub-section, which reports research that was conducted in the setting of an architectural office (JJW). The mapping was performed in a Danish context, using the Danish Description of Service as the framework for the common terminology and for the setup of the design phases (DANSKE ARK and FRI, 2017).

2.2.1 The Danish Description of Service

The Danish Description of Service is a driving factor for design processes in the Danish building industry (Brunsgaard, 2009; DANSKE ARK and FRI, 2012; Urup, 2016). It specifies the specific design phases, milestones and requirement for submission (DANSKE ARK and FRI, 2012). In that sense it provides an economic framework for most building design projects. Table 8 explain the milestones and phases of the Danish Description of Services compared to the American phases for the building design process.

Table 8 - The Danish Description of Service, see the Danish terms in GLOSSARY (DANSKE ARK and FRI, 2012).

American phases	Milestones in the Danish Description of Services	Phases in the Danish Description of Services
Project Brief	Pre-design	Initial design
Concept design	Concept design	
Schematic design	Schematic design	
Design development	Outline proposal	Design proposal
	Project proposal	
	Preliminary project	Detailed design
Construction documents	Main project	
Construction	Construction	Construction
Commissioning	Operation	In use

In 2017 a beta version of an addition to the Description of Service concerning ‘Counselling about sustainability in the building industry’ was launched. It can be used as a more detailed description or guide for consultants about how to define their roles, goals, how to manage sustainability or sustainability certification as well as in single sustainability tasks (DANSKE ARK and FRI, 2017). Due to the timing of this PhD study, the beta version could not be used as a tool in the research. However, the beta version contributed indirectly to the PhD research, as it is also based on the DGNB system. The diagram in Figure 16 is based upon Table 8 and ensures a common graphic background for the studies performed in the PhD research.

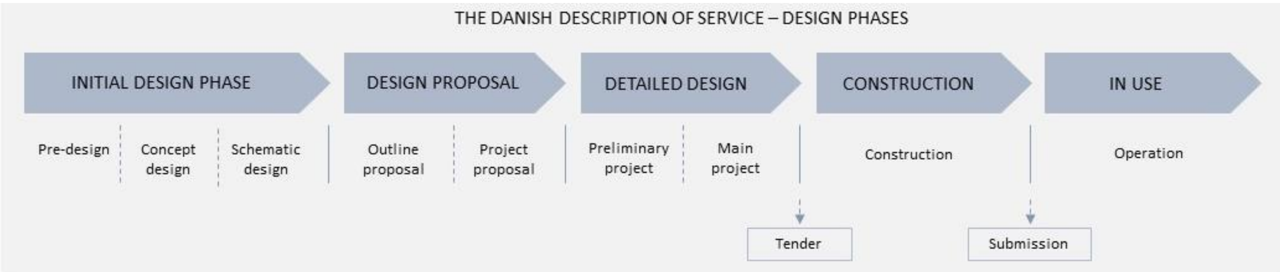


Figure 16 - The Danish Description of Service illustrated as a timeline based on design phases and milestones (DANSKE ARK and FRI, 2012).

The Danish Description of Service plays an important role in the present PhD study. It was used as the basis and definition of the building design process in practice, including design phases and milestones. In that sense it functions as a template that reveals any deviations and any new design processes. Mapping of the simulation tools and design methods used in architectural and engineering practice was conducted by means of case studies, interviews and questionnaires.

Figure 16 illustrates the process and may be regarded as the basic diagram for the mapping, case studies, interviews and questionnaires. The topics which are included in these studies are the IED method and DGNB certification system as previously described, as well as various digital simulation tools dealing with energy, indoor climate, LCC, and LCA.

Mapping of the different sustainability criteria and the related simulation tools was based on Figure 16, where practitioners evaluated their use of the different tools related to the level of sustainability, based on the DGNB criteria. A mapping was conducted of the most optimal use of the tools according to the different design phases to be able to see how far the state-of-art in practical use is from the most optimal use of the tools and to define an ideal, optimized design process.

2.2.2 Mapping of Integrated Energy Design and DGNB

The method was based on the state-of-the-art within the research area of Integrated Energy Design (IED) and the DGNB certification criteria. The use of the IED method and the DGNB system was documented in this research.

The IED method is based upon the existing Kyoto Pyramid, as seen in Figure 13, which has been developed throughout the past decade, starting in Norway and the Nordic countries and further developed and used by practitioners and PhD students (Nielsen, 2012; Strømann-Andersen, 2012). Figure 13 should be read from the bottom and up, when designing buildings from the initial design phase, by firstly altering the building geometry to achieve reduced energy consumption, good indoor thermal, and daylight conditions through passive strategies, secondly by optimising the building envelope by altering the thermal properties of the building materials and components to fulfil the visions of the project e.g. to fulfil the building energy requirements, and finally by adding renewable energy sources to the building. In short: Reduce – Optimise – Produce.

The matrix shown in Table 9 for mapping IED was developed from the three parts of IED; Reduce, Optimize and Produce from earlier PhD research at DTU (Kongebro, 2012). For the purpose of the mapping in this research the matrix has a third column for the data collection from each case study, which can be marked as the scale on the right in Table 9: XXX = High focus, XX = Middle focus and the X = General focus.
The mapping tool was developed in late 2015 and early 2016 for the mapping of IED parameters in the existing project briefs and a logbook was used to acquire all ongoing information about each case. It was thus possible to ensure the data acquired in all of the case studies was comparable.

Table 9 - Matrix for IED mapping (Kongebro, 2012).

IED-Process	**IED-criteria**	**Case No.**
Reduce	Context	
	Orientation/placement	
	Geometry	
	Daylight	
	Facade design	
	Zone/ programming	
	Structural concept	
	Energy concept	
	Use of roof area	
Optimise	Windows	
	Lighting	
	Ventilation	
	Cooling/heating system	
	Automation/ controlling	
Produce	Renewable energy	
	Passive cooling	

XXX	High focus
XX	Middle focus
X	General focus

The matrix for mapping DGNB was developed from the existing criteria and indicators used in the Danish certification scheme for 'New office buildings' (DK-GBC, 2014). Here the five main categories are: Environmental, Economic, Social, Technical and Process, where the sub-criteria are listed with a description for each, as seen in Figure 17 (DK-GBC, 2014). The diagram shows all the DGNB criteria and the weighted points given by the system for each indicator. The indicators are coloured in dashed colours to identify the indirectly affected indicators and fully coloured to identify the directly affected indicators for each criterion. The space allocated to each criterion was defined by the percentage of points given by the DGNB system and thus its importance.

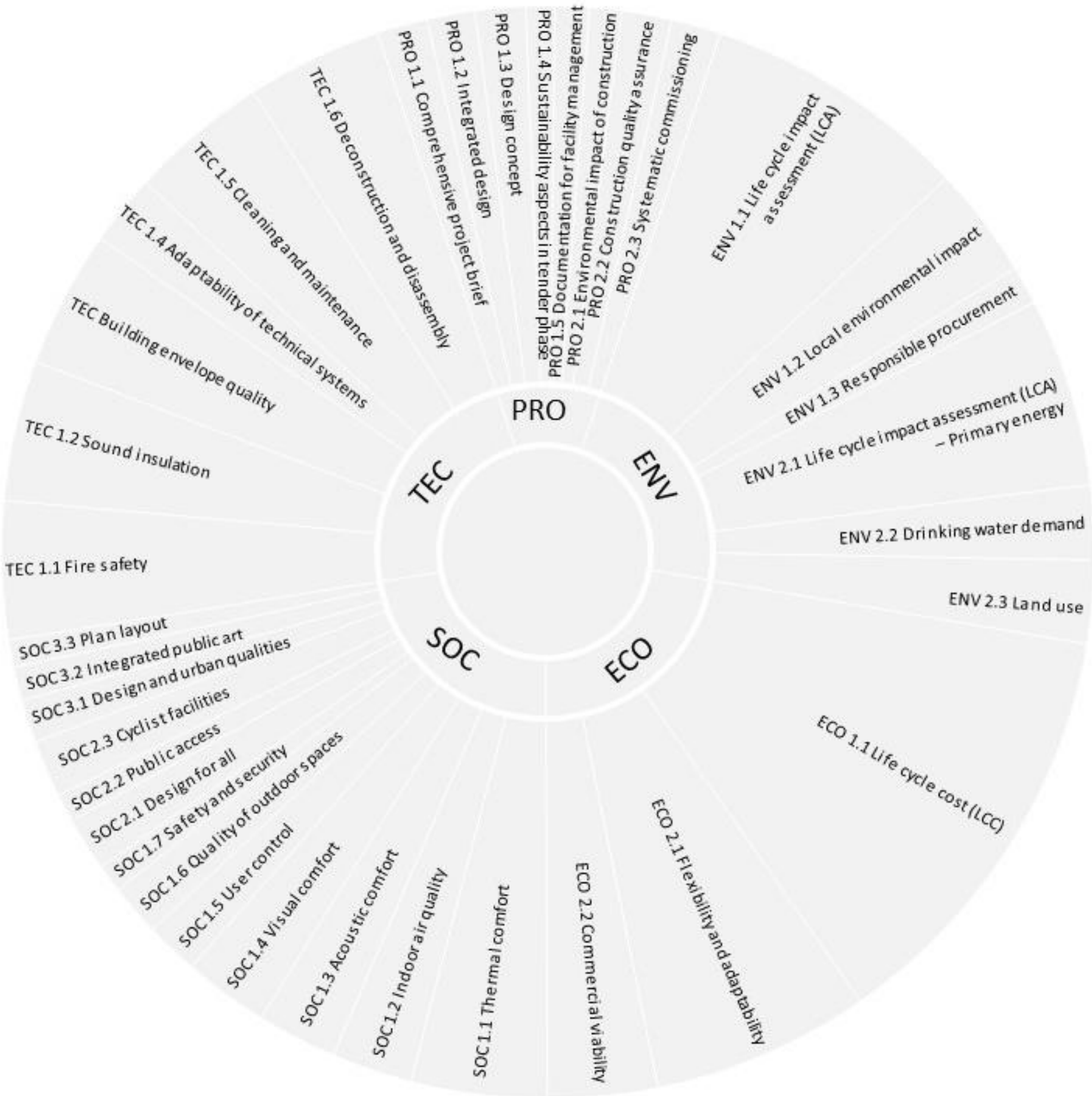


Figure 17 - The DGNB wheel, with the list of criteria for 'New office Buildings' (DK-GBC, 2014). Updated to English and correct weighting according to the mentioned manual.

2.3 Case studies of design processes in practice

Case studies were the main method used in this research and the design processes used in architectural practice were the main research object. The case studies were conducted from October 2015 to May 2018. They were a central part of the current research project and were undertaken to obtain an insight into the design processes used at an architectural office. The researcher took part in various design teams as a sustainability expert and introduced topics and tools to improve the level of sustainability and quantify it by informing the design processes with technical knowledge and analysis. The adaption and inclusion of the efforts of the researcher and thus the implementation of engineering calculations in the design processes were mapped as well as how it was received by the design team and how the technical analysis was used in practice. The technical inputs included daylight simulations, thermal indoor climate considerations, LCC calculations, and LCA, as well as overall sustainability considerations. The mapping was performed continuously as an iterative process to enable a stepwise development of the methodology and to identify and differentiate the impact of these steps on the resulting building performance.

The case studies conducted varied in size, design phase, building typology and design team, however common to all projects were the explicit goal of designing more sustainable buildings. Sustainability is a complex matter, when considering the holistic approach introduced by Brundtland, which states that the social, economic and environmental aspects are equally important. As previously described in the introduction section '1.3.6 DGNB' the DGNB certification system is used as a template for the sustainability approach at an architectural office as well as in the current study.

The following sub-section provides an overview of the case studies that were conducted in the course of the PhD research at JJW. The data were collected according to a design protocol and archived in a database to ensure a secure chain of evidence that would make it possible to trace the evidence relevant to a given research question throughout each case study, as advised by Yin for conducting case studies (K. Yin, 1998). The data collection was divided into two main steps. The first step focused upon the individual case and the second step was a comparison of different cases. For each case the focus was upon sustainability and how it was implemented in the design process and project as well as the degree to which it was achieved.

<u>STEP 1 – Case specific data – Design protocol</u>

The first step focused upon an individual case study and included the topics: Design team, Project info, Design Process and Sustainability Focus. This data collection is based upon '2.2.1 The Danish Description of Service', when defining the building design phases and the timeframe for the projects. Furthermore, to measure the impacts of the contribution and implementations the mapping tools for IED and DGNB were used to follow the process described by '2.2.2 Mapping of Integrated Energy Design and DGNB'.

The data concerning the degree of sustainability was collected in various ways. For a number of projects with available data, a screening was conducted to visualize the clients' wishes for implementation of the various sustainability criteria, as well as the focus upon sustainability recommended by JJW. To measure the impact of my implementations the mapping tools for IED and DGNB were used to follow the process.

<u>STEP 2 – Analysis and comparison of the different case studies</u>

All the case studies were compared in a general analysis. The analysis was conducted in four steps: Categorizing, summarizing, condensing and recombining the data, to ensure the use of all relevant evidence and to identify the alternative interpretations (K. Yin, 1998). The results of the data analysis were compared to those reported in the literature. The graphical timelines were compared and evaluated and then transformed into a general visualisation and the individual mappings were compared by using standardised graphics.

2.3.1 Case study research

There has been a tendency in published research to equate case study research with participant observation, qualitative research, grounded theory, and exploratory research, although some researchers define case study research as a quite different research approach (Sharan B., 1988). Sharan (1988) defines the use of case studies as a research design method, as "*a plan for assembling, organizing, and integrating information (data) and it results in a specific end product (research findings)*" based upon Yins paper from 1984 (Sharan B., 1988). In case studies the output is defined by the process and it is therefore impossible to distinguish the product from their context (Sharan B., 1988). The case studies conducted in this research include both quantitative (numeric) and qualitative (non-numeric) data, as Yin concludes is possible in his definition (K. Yin, 1998).

Iterations among design data collection, and analysis were necessary to ensure successive redefinitions of the applied problem as the project was being planned and implemented. New knowledge could thus be gained during the case studies, as unanticipated obstacles could be included in the process, and there might be some contextual changes, which might challenge and affect the overall research setup (K. Yin, 1998). Each case study conducted in the course of this PhD research therefore collected data in the same two steps as described in '2.3 Case studies of design processes in practice' to ensure the same replication logic and comparability between the case studies.

As the data were collected during the design development throughout the design process it was possible to continue to measure the development of methods, collaboration and specific design decisions and the reasons behind them. The nature of the evidence used in the present research project corresponds to the general most commonly used evidence in case study research, according to (K. Yin, 1998). Table 10 shows the sources of different kinds of evidence and their strengths and weaknesses:

Table 10 - Strength and weaknesses from source of evidence, (K. Yin, 1998).

Source of Evidence	**Strengths**	**Weaknesses**
Documentation	Stable – can be reviewed repeatedly Broad coverage- long span of time, many events and many settings	Retrievability – can be low Biased selectivity, if collection is possible
Archival records	Same	Same
Interviews	Targeted – focuses directly on case study topic Insightful – provides perceived casual inferences	Bias due to poorly constructed questions Reflexivity – interviewee gives what interviewer wants to hear
Direct observations	Reality – covers events in real time Contextual – covers context of event	Selectivity – unless broad coverage Reflexivity – event may proceed differently because it is being observed
Participant observation	Same Insightful into interpersonal behaviour and motives	Same Bias due to investigator's manipulation of events
Physical artefacts	Insightful into cultural features Insightful into technical operations	Selectivity Availability

The case study used the evidence in a converging manner, to define the 'facts' of the case by applying the concept of triangulation as used in geometry when defining a point in space with three vectors. The result is considered a robust fact if evidence from at least three different sources converge. To achieve this convergence the same questions must be asked of all the different sources of evidence. Furthermore, this must be contrasted with another type of study with a diverse array of evidence to converge on the facts of a case study as shown in Figure 18. In the present study ‘documents’ represent the literature study, ‘open-ended interviews’ were conducted with professionals to obtain their point of view without guiding them in a predetermined direction, ‘observations’ were performed both directly and as a participant in the design team, ‘physical artefacts’ represent the calculations, simulations and visual communication conducted in the case studies, and ‘focused interviews’ were conducted to obtain feedback on specific aspects of the design process. In the present research, ‘participant observation’ was a key method as the PhD researcher participated in the design teams that were being studied, and thereby actively contributed at the same time as observing; this is a widely used approach in anthropological studies (Glaser & Strauss, 1967; K. Yin, 1998).

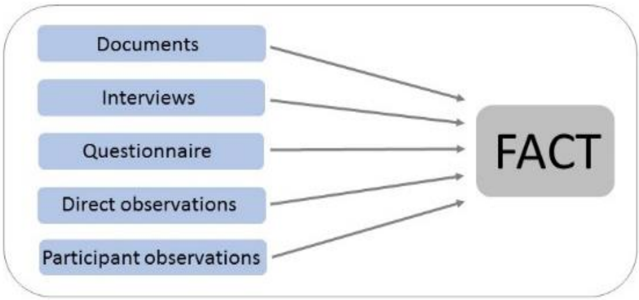


Figure 18 – Definition of facts, modified figure (K. Yin, 1998).

Another relevant approach when conducting case studies is to subject multiple sources of evidence to separate sub-studies as seen in Figure 19. Important conclusions can be made through this type of study.

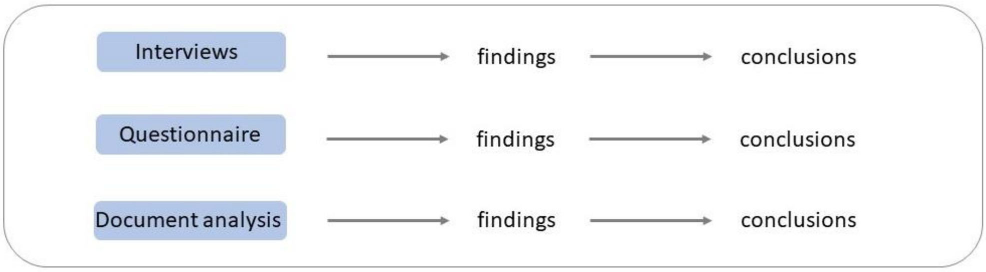


Figure 19 – Separate sub-studies (K. Yin, 1998).

The design of the case studies from the very beginning as described in ‘2.3 Case studies of design processes in practice’ is of great importance to ensure that the evidence addresses the initial research questions (K. Yin, 1998). According to Yin, it is important to define the units used in the analysis to create well-defined boundaries for the case study from the very beginning, however an important advantage of case studies is also the fact that some boundaries are unknown from the beginning of the case study but emerge progressively in the context of the individual case study. (K. Yin, 1998). In the current research the based on IED and DGNB constitute the planned case study approach and boundaries in the research field. Using the timeline of design phases from the Danish Description of Service to map the design process includes time as a unit in the case studies and the analysis. As each case study was mapped quantitatively followed by a qualitative analysis by the PhD researcher, the analysis was both quantitative and qualitative.

The number of replications depends upon the certainty required in the results and as a general rule of thumb; as more questions are investigated, the more relevant the case study method becomes (K. Yin, 1998). The

questionnaire data are part of the findings and conclusions for each individual design project and not universal. This is because all design projects are unique, even if the same questionnaire layout was used.
The benefit of multiple case studies compared to single case studies is that they can strengthen or broaden the analytic generalizations and the evidence for a general conclusion about case studies, which will be stronger if the same results are obtained in more cases. (K. Yin, 1998). In my research there are no direct replications, since each project was unique. However, the approach of actively contributing to the work of the design team was the same, as was the mapping according to IED, DGNB and Description of Service.
According to Yin, the quality of empirical social research as well as of the case study can be evaluated via four tests: whether it has construct validity, internal validity, external validity, and reliability. In this PhD study these four tests were made as recommended by Yin (1998), as illustrated in Table 11 (K. Yin, 1998).

Table 11 – Validity and reliability in relation to case study tactics and phase of research of which the tactics are used (K. Yin, 1998).

Tests	Case study tactics	Phase of research of which the tactics are used
Construct validity	Use of multiple sources of evidence	Data collection
Internal validity	Pattern matching Time series analysis	Data collection Data collection
External validity	Use replication logic in multiple-case studies	Research design
Reliability	Use of case study protocol Development of case study database	Data collection Data collection

2.3.2 Action research

Case studies use several approaches to data collection, as previously described, where 'participant observations' is one of them. This is closely related to action research, which is mentioned by Swann (2002) as an iterative process having four main steps: Plan, action, observe, and reflect, as seen in Figure 20 (Swann, 2002). Plan resembles the planning process of research question and the process strategy, Action is where the plan is implemented in practice, Observation is where the action is monitored and evaluated using selected methods, and Reflection is the post processing, where the results are analysed, synthesized and interpreted to see how they the action changed the design practice, then evaluated in relation to the plan and research question, which leads to an iteration of the four steps. The data collected from the action research iterations are evidence for a claim that practice was improved. Action research arises from a specific situation and problem of which the practitioner is an integral part and it is a practical research methodology since the researcher is a part if the situation and process (McNiff, 2002; Swann, 2002).

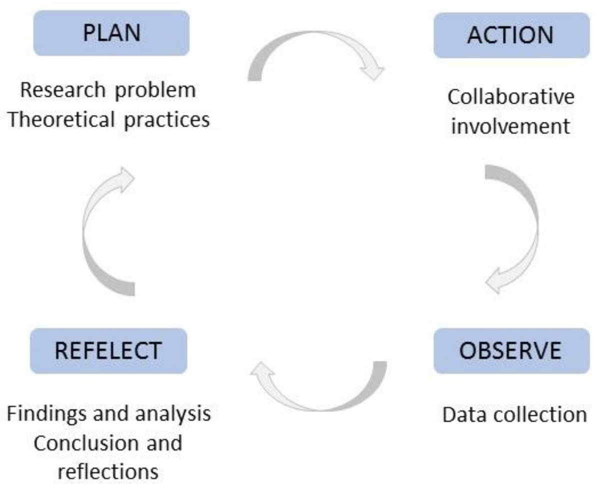


Figure 20 - Action research process (Swann, 2002).

2.3.3 Interviews

Interviews were conducted during the PhD study as previously mentioned in Section '2.3.1 Case study research'. Open-ended interviews were conducted with professionals to obtain their point of view without guiding them in a certain direction, focused interviews were conducted to obtain feedback upon specific aspects and can be equated with the conversation-interview in this case (Glaser & Strauss, 1967; Kvale, 2007). The interviews were conducted in three rounds. For each interview round an interview guide was constructed to structure the course and create a base line for the content of the interview and a systematic basis for assessment (Kvale, 2007).

The interviews were conducted by the researcher and a transcriptions was made after each interview. When transcribing an interview from records to text there are technical and interpretational issues and decisions must be made between a verbatim or formal style for transcription (Kvale, 2007). For this current research the transcription was conducted verbatim and word by word although this was more laborious to conduct in practice. The use of citations was transformed into a more formal style.

Reliability and validity are issues related to transcripts. Reliability can be decreased by poor recordings and the difficulty of hearing the start and of a sentence, which can lead to different interpretations of the same interview (Glaser & Strauss, 1967; Kvale, 2007). The validity of a transcript is a nuanced matter as they are interpretative constructions with no correct objective transformation from oral to written. The transcription can focus upon the aspects that are important for the research topic and in some cases, might clarify some nuances in the statements (Kvale, 2007). In the present research, the reliability and validity of a transcript is considered to be acceptable, as it is verbatim and word by word and provided as an appendix, making transparent the transfer of data from interview to transcription and to final analysis and citation in published papers and the thesis.

The three interview rounds were conducted:

a. Among experts in the building industry (IED and LCA in Design Processes for Refurbishment)
b. Among experts in the building industry in London (Sustainability and Software)
c. At JJW to round off each case study

a. The interviews with experts in the building industry was a part of a study investigating the use of LCA in the building industry that had a focus on building refurbishments and data transfer between different software tools and 3D modelling. These interviews were conducted to support the literature study and the case studies. They were about the state-of-the-art in implementing sustainability in the framework of the IED method and the DGNB certification system in the building design processes specified in the Danish Description of Service.

An interview guide was constructed to create a base line for the content of the interview, although an open-ended approach was taken so that any new perspective introduced by the interviewee could be added. The interview format was thus more like a conversation. Table 12 show the interview guide used for this round of interviews.

Table 12 - Interview Guide for round A - Experts in building industry focussing upon LCA and building refurbishments.

Interviewee
Interview date
Material used during the interview: - Process time line for the Danish Description of Service
Do you make LCA calculations? - At new buildings? - At refurbishment projects?
How do you collect the data required for conducting the LCA? - Via drawings? - Via 3D models? - Via Point-clouds for registration of existing buildings? - Via the use of drones for registration of existing buildings?
Do you always draw a 3D model? - Also for refurbishment projects? - Which calculation tools and 3D modelling tools do you use?
How do you transfer the data from the 3D model to the LCA calculation tool? - Manually - Though plugins between the tools
Is there a coherence between supply and demand for LCA calculations in the Danish building industry? - Or is it only via DGNB certifications there is a request for LCA?
What is the optimal scenario for the use of LCA in your point of view? - For new buildings? - For refurbishment?
Does an increased focus upon LCA require anything specific from the consultants/clients/industry in general/politics? - Any specific education for the consultants? - Specific data from the material and component producers? - Additional specific building requirements?
Is the use of IED implemented in practice design processes? - Indoor climate, energy consumption and daylight? - Will the use of LCA and LCC in design processes compromise the implementation of the IED parameters in practice?

b. The interviews of experts in the building industry in London was part of a study investigating the use of LCA and modelling tools outside Denmark, to put research in an international context. This was also part of an External Research Stay at the Architectural Association, Sustainable Environmental Design programme. These interviews were conducted to support the literature study and the case studies. An interview guide was constructed to create a base line for the content of the interview, but once again taking an open-ended approach as described in the previous subsection. Table 13 shows the interview guide used for this round of interviews.

Table 13 - Interview Guide for round B - Experts in building industry in London focussing upon LCA and modelling tools.

Interviewee
Interview date
Material used during the interview: - Process time line for the Danish Description of Service
Company
Professional background
What is your definition of environmental design?
Is environmental design equal to sustainable design? - If not, what is your definition of sustainable design?
How do you implement environmental design in practice? - Design method - Design process, when is what included - Collaboration, which professions are included when? Who do the different simulations and calculation into what detail level? Who do the design decisions? - Which tools do you use? In which design phases are they in use?
Do you work with BREEAM / LEAD / DGNB in your work?

c. The interviews at JJW were conducted with the project managers of the design projects which were selected as the case studies. Due to rotation of the employees at JJW to other companies, only a limited number of them were available for interview. Only thereof these interviews were conducted. The project managers were asked to reflect upon the technical inputs and the researcher's general presence and work in the design teams. This was a way to obtain more information about specific design decisions and whether they were made in collaboration with other professions and whether their focus was on sustainability. The interviews were conducted after completing the case studies. These interviews were made to supplement the evidence from the case studies about the state-of-of-the-art in implementing sustainability in the framework of the IED method and the DGNB certification system in the building design processes specified in the Danish Description of Service. An interview guide was constructed to create a base line for the content of the interview, but once again taking an open-ended approach as described in the previous subsection. Table 14 show the interview guide used for this round of interviews.

Table 14 - Interview Guide for round C - JJW project leaders included in case studies of the PhD

Interviewee
Interview date
Material used during the interview: - Process time line for the Danish Description of Service - IED mapping tool - DGNB wheel - The case specific work conducted by me in the process
Specific case at JJW Architects
What inputs did you get from me during the case study? - And at what design phase, based upon the Danish Description of Service?
How useful were these inputs? - Was the timing good related to the design process?
Which sustainability criteria were investigated in the project? - Were they implemented in the process? - How were they received by the architects and engineers of the design team?
Did my inputs add value to the design project?
How do you suggest implementing sustainability in the design process at JJW in the future? - Who should be responsible?

2.3.4 Questionnaires

Questionnaires represent another method that can supplement the other methods used in the present research. The questionnaires were applied in two parts. Q1 was intended to provide some overall profiles of the design process at architectural offices in Denmark and in one office that also operated in Sweden. Q2 was distributed only at JJW, to investigate the development of knowledge after one year. QJJW1+2 was a questionnaire that was distributed twice at JJW with a one-year interval.

<u>Q1: Technical knowledge used at architectural offices to develop a work profile</u>

In the spring of 2017 questionnaire Q1 was sent out to a large number of architectural offices of various sizes and specialisation, and seven offices provided feedback by completing the questionnaire. One of these companies maintained two offices in Sweden and one in Copenhagen, and all three asked for the questionnaire to evaluate whether their design methods differed from other Copenhagen offices and if there was any coherence between the Swedish offices. However, although the other companies had several other offices worldwide only their Copenhagen office was included since the interest of the present research was the state-of-the-art in Denmark. See APPENDIX Y. The offices requested that they should be anonymous in the published thesis, although all of their names are known to the author. The offices are designated Q1_A, Q1_B, etc. in the thesis Table 15 lists the companies involved in the research including the number of responds and the percentage of them providing full feedback.

Table 15 – Respond information of Q1.

Q1			
Name	**Responds**	**Full responds**	**Percentage**
Architectural Office A	11	9	82%
Architectural Office B	20	12	60%
Architectural Office C	17	10	59%
Architectural Office D	9	3	33%
Architectural Office E	31	14	45%
Architectural Office F	23	8	35%
Architectural Office G	14	6	43%

Q2 was the questionnaire conducted after a year (spring 2018) at JJW to investigate whether, during the researcher's participation in the various design teams and presentations, any difference in their level of knowledge occurred. The results may have been affected by the number of people leaving and joining the design teams in this period. Table 16 show the feedback from Q2. Results are available in APPENDIX Y.

Table 16 – Respond information of Q2.

Q2			
Name	**Responds**	**Full responds**	**Percentage**
02_Q2	18	11	61%

The questionnaire was developed in the online software tool called SurveyMonkey, so that the employees could answer directly online (SurveyMonkey, 2018). By using the online tool for the questionnaires, the feedback was automatically collected, providing easy and direct access to the answers. Another advantage of using an online questionnaire is that the contact person at each office was able to distribute the questionnaire via a link per email and thus target them all.
The questionnaire consisted of 8 pages, with one theme for each page, see APPENDIX Y. From the themes, it is possible to obtain knowledge about which technical aspects were considered for which building design phases. Furthermore, an idea of how the constellation of employees at the offices are arranged and how well the general collaboration with other professions worked. This describes a design process culture at each architectural office.

The overall themes for each page of the questionnaire were:

1. Which phase of the building design are they working with? (according to the Danish Description of Service)
2. Collaboration
3. Microclimate comfort
4. Daylight
5. Energy performance
6. Life Cycle Costing (LCC)
7. Life Cycle Assessment (LCA)
8. Who are you?

Furthermore, the questions were a mix of the following typologies:

- Multiple-choice (questions requiring one or more answers)
- Slider (questions requiring the selection of a value in range from 1-5)
- Descriptive (questions requiring written answers)

The SurveyMonkey software includes a standard analysis, but as the graphics and analysing setup was predefined, it was not used in the present research. Instead, an Excel spreadsheet was developed to fit the layout and data handling setup.

Q_JJW1+2: Investigating the knowledge about specifically LCA and LCC at JJW in one-year timespan
To investigate the influence of my presence in the office upon the general level of knowledge about LCC and LCA this additional questionnaire was used twice. Once in the spring 2017 and once in the spring 2018. In the duration between the two questionnaires (Table 17), I participated in various design teams, as further elaborated in '1.2.3 PhD setup', and contributed with a row of six short presentations; two about LCC and LCCByg, two about LCA and LCAByg and two about social sustainability and Integrated Energy Design (IED).

Table 17 - Reply percentage of Q_JJW1+2.

Q_JJW1+2				
Office	**Name**	**Employees included**	**Employees reply**	**Reply percentage**
JJW	Q_JJW1	60	34	57%
JJW	Q_JJW2	50	14	28%

This questionnaire consists of two pages in Word, with three main topics:

- Knowledge of JJW tools overall
- Knowledge and use of LCC
- Knowledge and use of LCA

The questionnaire consists of descriptive replies, sliders and tables in which values are to be selected. The full questionnaire can be found in APPENDIX Y.

2.4 Critique of method

This section discusses the methods used in the present PhD research, and identifies their limitations.

For the mapping of existing projects, only a limited number of projects were available, so there was limited data for generating a general evaluation of the state-of-the-art.

The interview studies were conducted in three parts, which ensured a specific focus upon each topic. To widen the feedback from the interviews, a generic design guide for all of them could have been developed.

The questionnaires had a very varying response rate, which makes the analysis of the state-of-the-art difficult. For the questionnaires some uncertainties are present due to the setup of the questions. Because it is possible to skip some questions, which might give an additional output, hence it is still included. To accommodate this uncertainty it is aimed at distinguishing between full responses and partly responses. However, this does not always include same partly responses and variations will occur. The questionnaires thereby give an indication of how state-of-art is in practice.

Despites these critiques and limitations, the methods used in this PhD research are considered to have covered the topic from a number of different angles.

3. RESULTS

This section includes analysis and sub-discussions for the topics included in the PhD research. With this structure the 5. RESULTS section is long and detailed and the 4.DISCUSSION AND CONCLUSION section is a short summary of all the topics.

This section is divided into five main sub-sections related to the main outcomes of the three years of PhD studies and the various methods described in section, as illustrated in Figure 21.

Firstly, a broad overview of the work profiles and processes as revealed by the questionnaires that were completed by seven architectural offices is presented with visualisation of the results and an analysis.

Secondly, the state-of-the-art of IED and DGNB in design processes in architectural practice is examined. This is mainly based on data from the case studies and mapping of these at JJW Architects, supplemented by interviews and questionnaires.

Thirdly these results are followed up by mapping of the state-of-the-art for LCA and LCC in design processes in architectural practice. The fourth theme is the state-of-the-art for collaborative processes in an interdisciplinary and integrated design perspective.

Finally, the fifth sub-section describes the Integrated Sustainable Design (ISD) method that uses the results from the four sub-sections to create one common method/guideline.

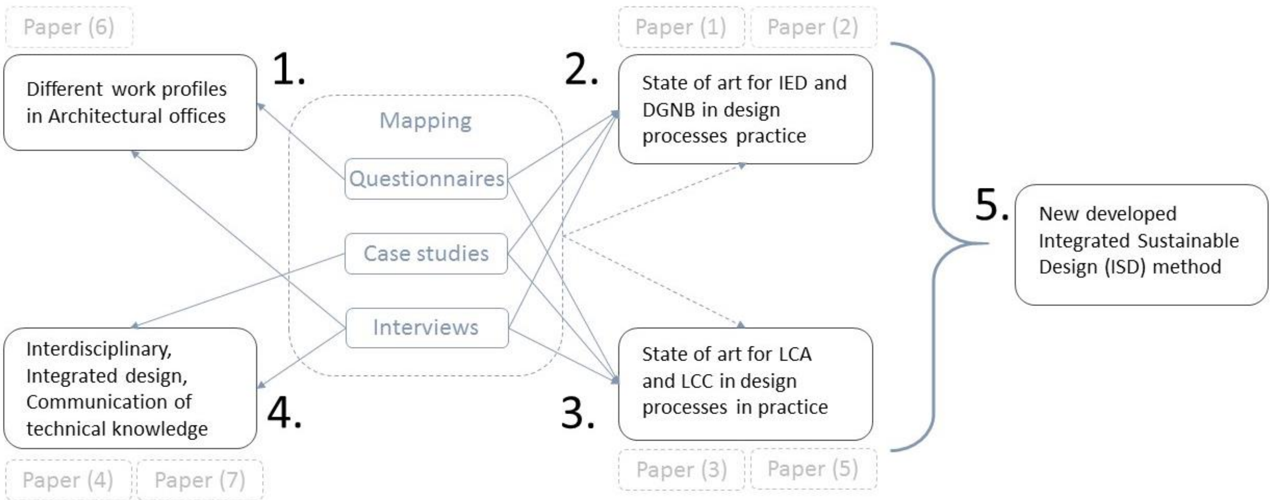


Figure 21 - The disposition of the Results section.

3.1 Work Profiles at Architectural Offices

In the period from March till June 2017 a questionnaire about architectural Engineering and Technical knowledge in design processes was distributed at a number of architectural offices, as described in 2.METHODS sub-section 2.3.4 Questionnaires. The questionnaires were distributed internally in the architectural offices by a sustainability expert, and this might have affected the responses of the employees. Seven architectural offices agreed to distribute the questionnaire and employees responded via SurveyMonkey. The architectural offices are anonymous in this, but their identities are known to the author. See APPENDIX Y. The results of this questionnaire are examined in this sub-section and an analysis of them has been presented in a conference paper (7), APPENDIX G. The respondents were asked questions about the following five topics: microclimate comfort, daylight, energy performance, LCC and LCA.

In this sub-section the results from all 7 offices are visualised in the same way to make it possible to compare the results from the seven offices, as seen in Figure 22 to Figure 40. An analysis of each diagram is made in direct relation to each diagram.

THE FIRST PART shows results concerning the number of respondents. This provides an overview of which design phases they mainly work with and their job title, however it have to be considered, that some had several titles yet considered equally in this analysis. This is followed by the respondent's perception of their own level of holistic thinking, how their design decisions are influenced by microclimate comfort, daylight and energy performance and by LCC and LCA. Finally, the respondents were asked to record their perception of the level of holistic thinking reached by the office as a whole in its design approach.

THE SECOND PART addresses the respondent's collaboration with other professions in each design phase, based upon six of the phases from the Danish Description of Services. The respondents were also asked to record their perception of the importance of integrating the five themes (microclimate comfort, daylight, energy performance, LCC, and LCA) into the design processes.

THE THIRD PART examines the use of the five themes, how much it influences different design phases and how the respondents work with the themes in practice.

A SUMMARY is provided for each questionnaire to emphasise certain aspects in each office.

FIRST PART

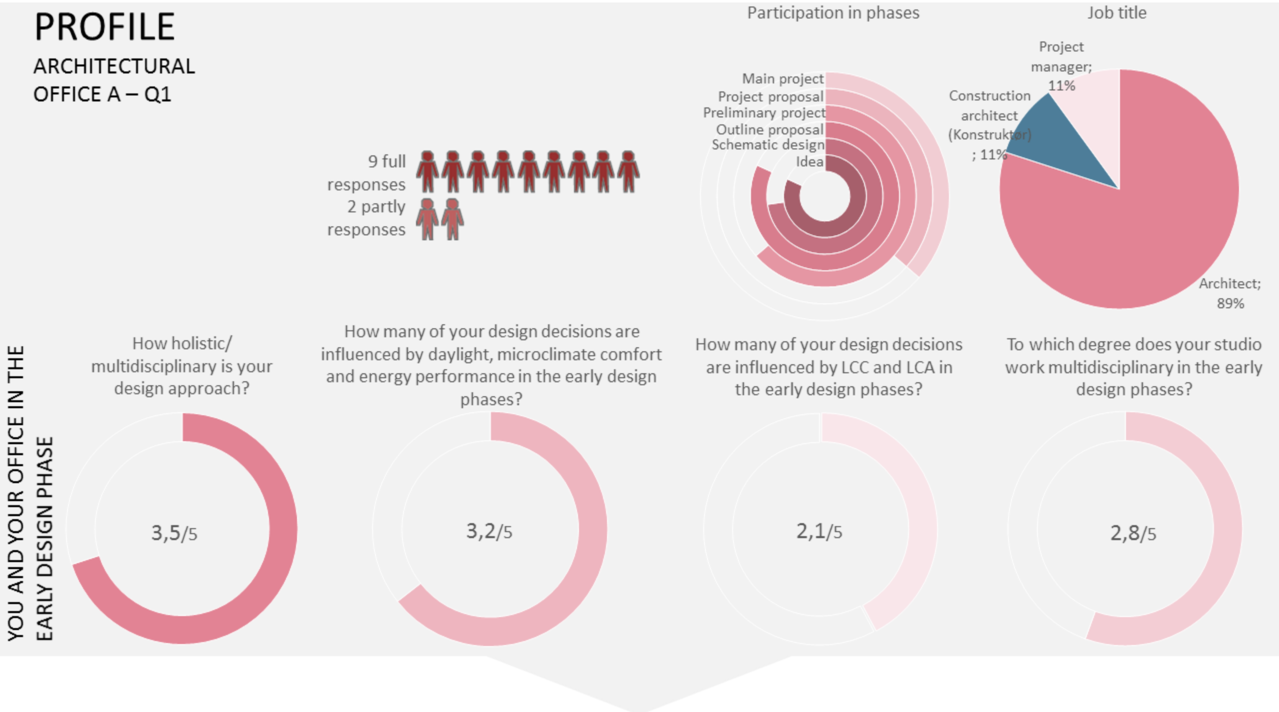


Figure 22 - Office A, first part, based on Q1.

For office A 9 respondents did the full questionnaire of a total of 11. The respondents' division of job title were 89% architects, 11% Construction Architects and 11% Project managers. These respondents participated mainly in the first four building design phases. The respondents rated their own level of holistic/multidisciplinary thinking in their design approach higher than the general level of holistic/multidisciplinary thinking in the architectural office. Furthermore, they rated the impact of microclimate comfort, daylight and energy performance on their own design processes as greater than the impact of LCC and LCA.

SECOND PART

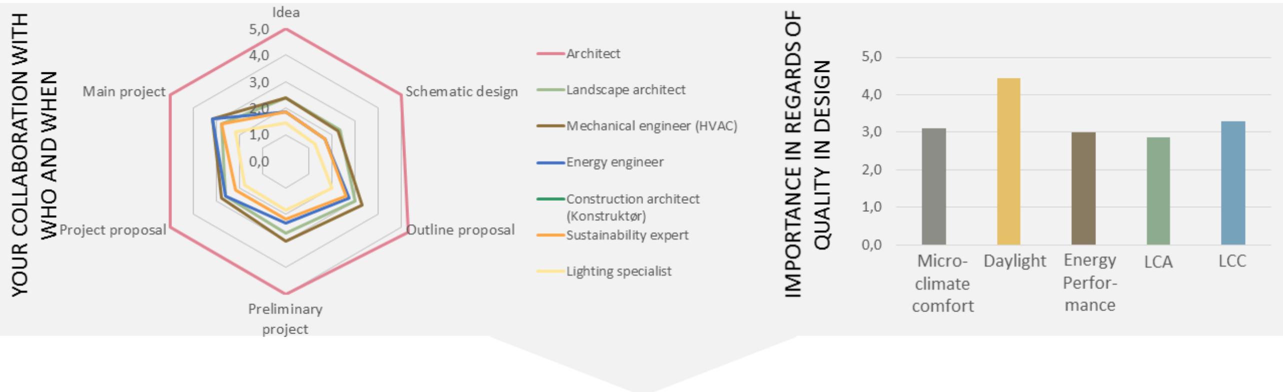


Figure 23 - Office A, second part, based on Q1.

When rating their own collaboration with various disciplines, they reported that they mainly worked with architects, and that the collaboration with different engineering disciplines was more limited in all building design phases, least in the initial design phase and more in the main project phase. Their collaboration with sustainability experts and daylight specialists was relatively low, and highest in the main project phase.

For the question regarding the importance of the five topics implementation in the design process and the resulting quality in design, daylight was considered most important. LCC was also considered of high importance, though not as high as daylight. Microclimate comfort, energy performance and LCA were considered to be equally important, but again not as important as daylight and LCC.

THIRD PART

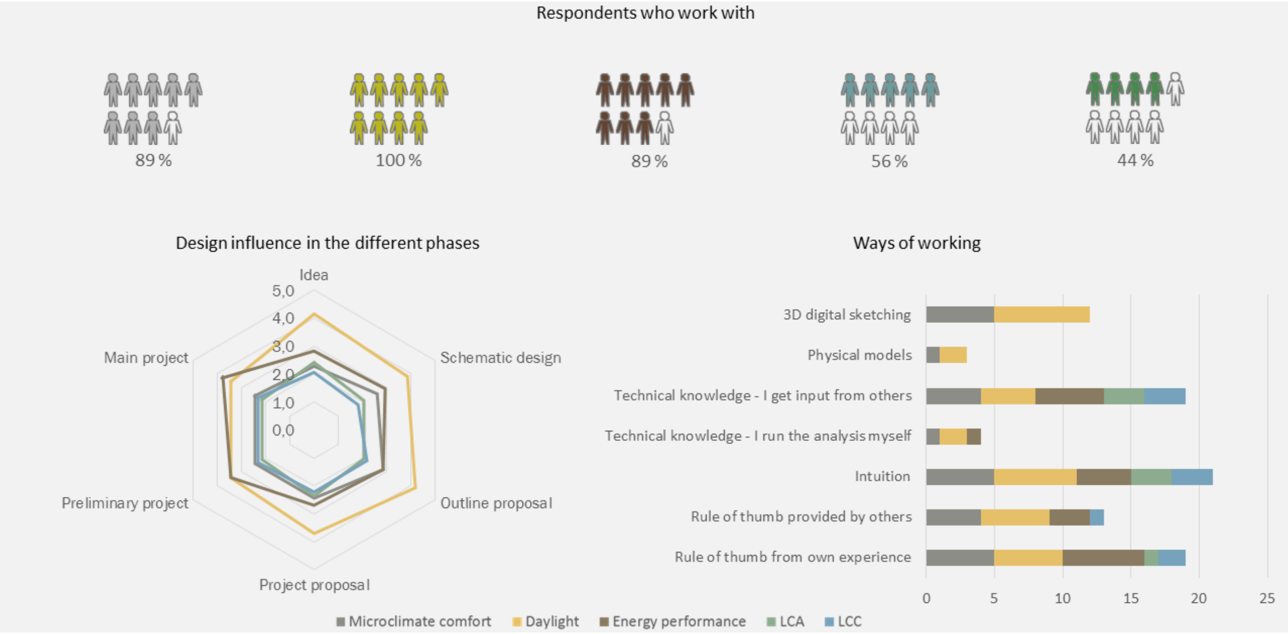


Figure 24 - Office A, third part, based on Q1.

For the third part the focus was on each of the five topics (microclimate comfort, daylight, energy performance, LCC, and LCA), how the respondents work with them and to what degree. Microclimate comfort was reportedly addressed by 89% of the respondents, although they only saw it as having a moderate influence on the design phases, and the way they worked with the topic was mainly using a rule of thumb from their own experience or that of others, by 3D digital sketching, or as technical inputs from others. All of the respondents reported that they worked with daylight, and that they considered it in all design phases, although mostly in the early design phases. Again, a rule of thumb was used, although many of the respondents use 3D digital sketching as a tool and obtained technical input from others. Energy performance and microclimate comfort were reportedly used mainly in the preliminary project phase and the main project phase. Also, here rule of thumb from their own experience was often used together with intuition and technical inputs from others. Only 56% of the respondents reported that they worked with LCC and they rated it as having a moderate impact upon the design process, especially limited in the schematic design phase. Mainly intuition and technical inputs from others were used. Only 44% of the respondents reported that they worked with LCA, and they also rated with a limited impact on the design process. Intuition and technical inputs from others were mainly used.

SUMMARY

The respondents from this office were mainly architects who participate in the ‘Idea’, ‘Schematic design’ and ‘Outline proposal’ design phases. Their collaboration was mainly with other architects and was limited with other professions. Daylight was the most prominent and most considered topic and LCA the least used. Overall they reportedly received technical inputs from others on all five topics but almost as often they relied on their intuition.

FIRST PART

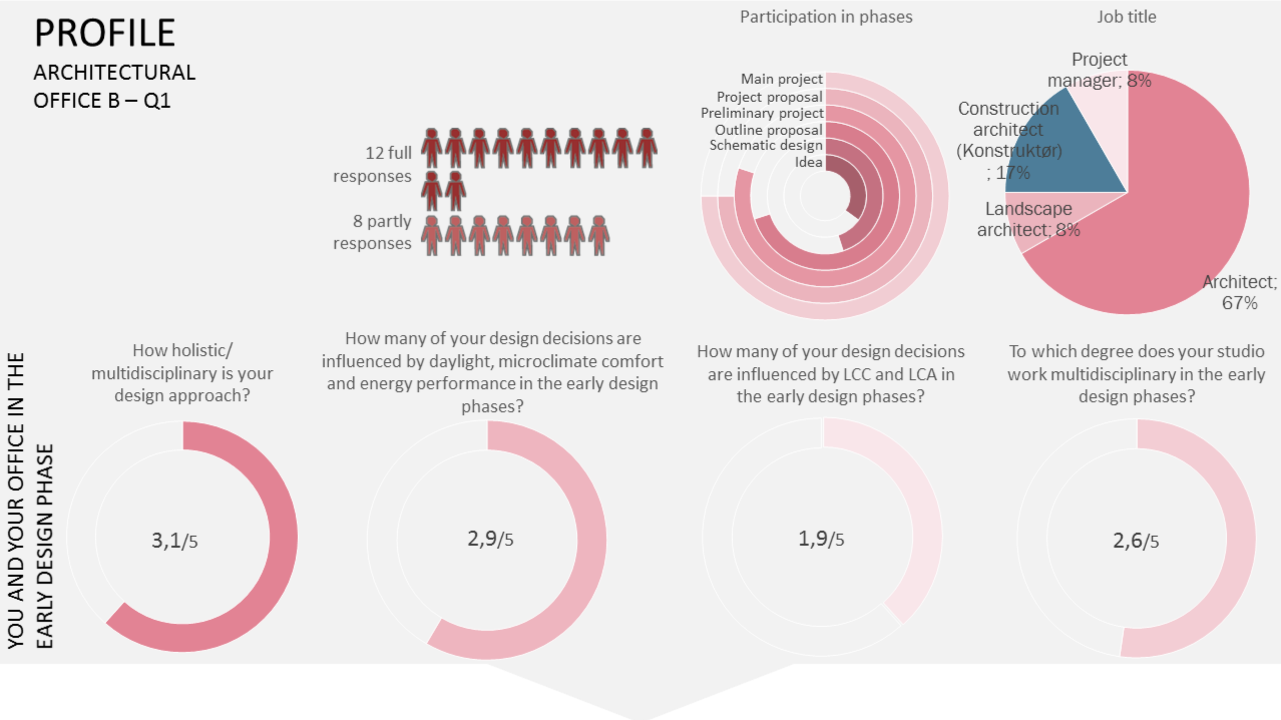


Figure 25 - Office B, first part based on Q1.

For office B 12 respondents did the full questionnaire of a total of 20. The respondents' division of job title were 67% architects, 17% Construction Architects, 8% Landscape architects and 8% Project managers. When considering their level of holistic/multidisciplinary thinking, the respondents rated their own approach as more holistic/multidisciplinary compared to the general approach by the architectural office. They rated design decisions based upon microclimate comfort, daylight and energy performance higher than design decisions based upon LCC and LCA.

SECOND PART

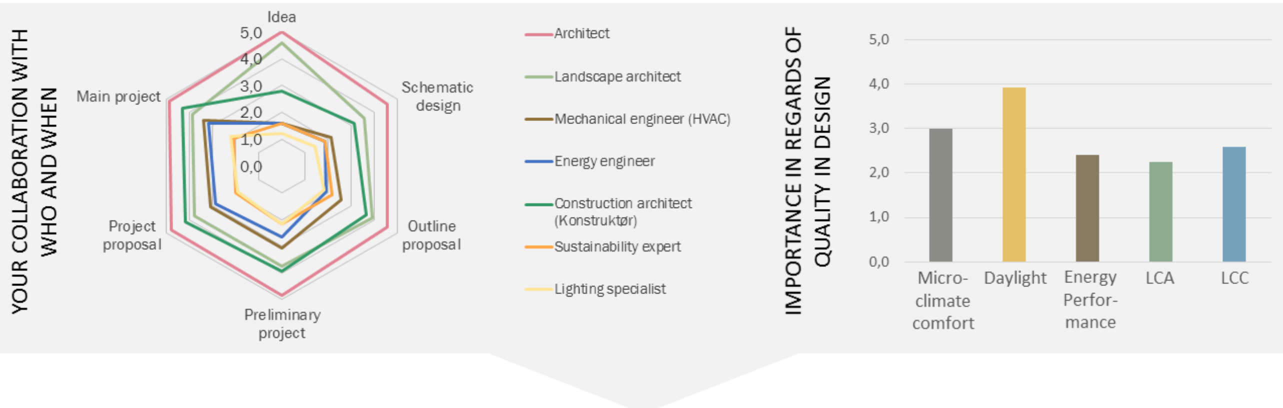


Figure 26 - Office B, second part based on Q1.

When considering collaboration with different professions, the responses show that most collaboration occurred with architects in all building design phases, followed by landscape architects and construction architects. The collaboration with the various engineering disciplines was rated moderate for the first design phases and relatively high from the project proposal to the main project. Collaboration with sustainability experts and daylight specialists was relatively low but was highest in the main project.

A graph illustrating the reported importance of the five topics for the quality of design, there is a clear tendency for daylight to be seen as the most important, followed by microclimate comfort. Energy performance was considered almost as important as LCC, and LCA was considered least important for design quality.

THIRD PART

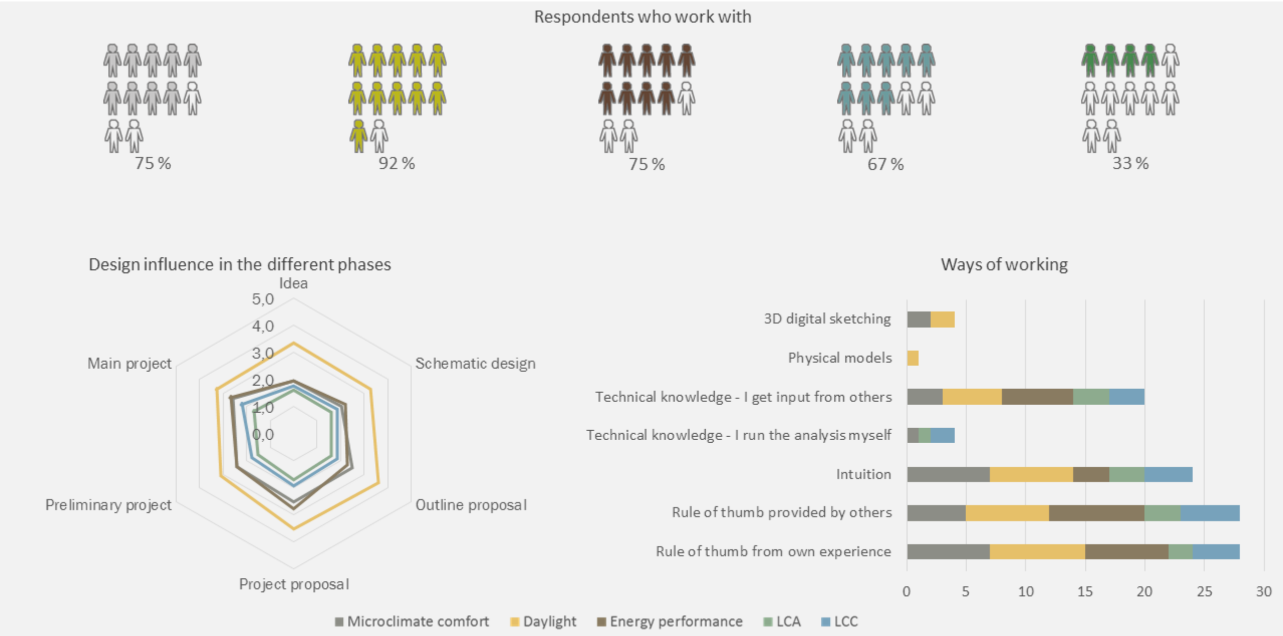


Figure 27 - Office B, third part based on Q1.

For the third part the focus was on each of the five topics, how the respondents worked with them and to what degree. Microclimate comfort was considered by 75% of the respondents but considered it to have only a moderate influence on the different design phases. It was mainly handled by rule of thumb from their own experience and that of others, and by intuition. Daylight was considered by 92% of the respondents. They found the topic relevant in all design phases, with special importance for the outline proposal and project proposal. As for microclimate, the method of working with daylight was mainly by rule of thumb from their own experience and that of others, and by intuition, but also by technical input from others. Energy performance, like microclimate comfort, was considered by 75% of the respondents rated as having only a moderate influence on the different design phases, although its influence on the project proposal and main project was rated as being higher than on the other phases. Energy was handled mainly by rule of thumb based on the experience of others and by technical input from others, followed by rule of thumb based on their own experience. LCC was considered by 67% of the respondents but its influence on the different design phases was rated as being low. Again, it was handled mainly by rule of thumb, intuition and by technical inputs from others. LCA was only considered by 33% of the respondents and its influence on the design phases was considered low. LCC was mainly handled by rule of thumb, intuition and technical inputs from others, although some reported that they ran technical calculations themselves.

SUMMARY

The respondents in this office were mainly architects but construction architects were also well represented. They were mainly working in the later design phases, from ‘Preliminary project’ to ‘Main project’. There was considerable variation in their collaboration with architects, construction architects and landscape architects, and less with other professions. Daylight was most commonly considered factor and LCA the least, and they worked with these factors mainly by rule of thumb from their own experience.

FIRST PART

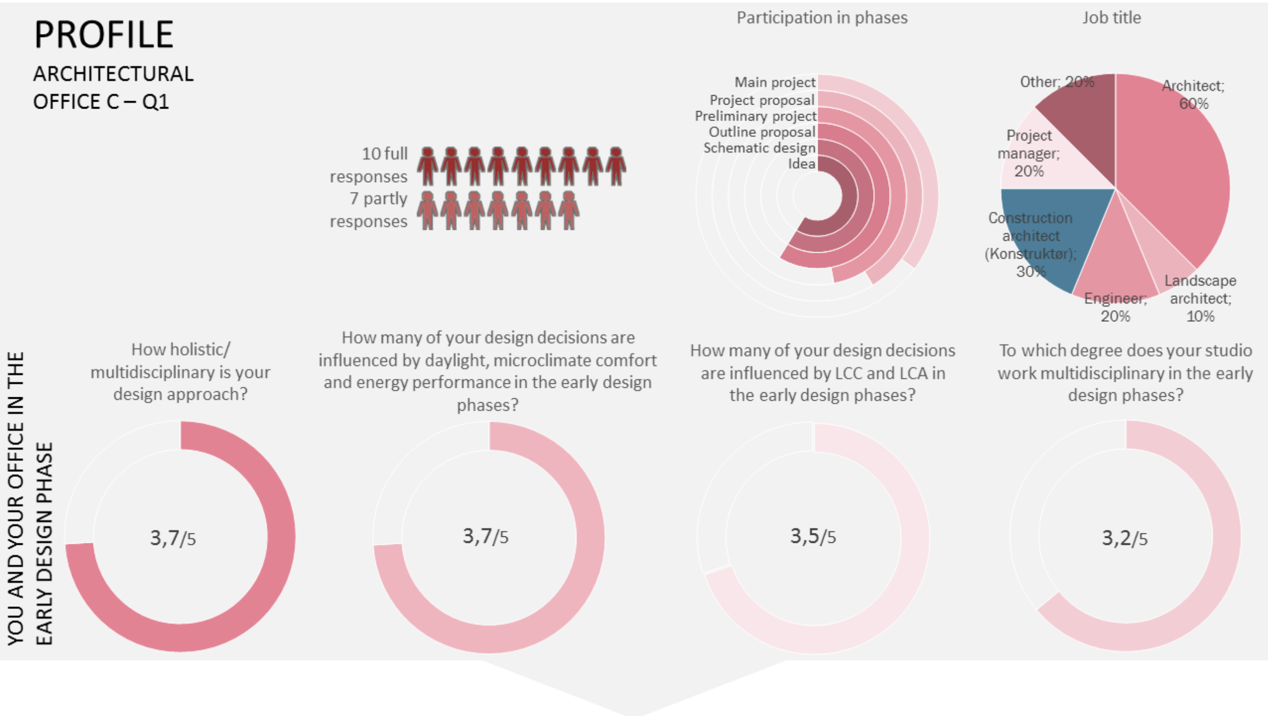


Figure 28 - Office C, first part based on Q1.

For office C 10 respondents did the full questionnaire of a total of 17. The respondents' division of job title were 60% architects, 30% Construction Architects, 10% Landscape architects, 20% Engineers, 20% Project managers and 20% Other. The respondents rated their own degree of holistic/multidisciplinary thinking as higher than that of the general level at the architectural office. There was a small tendency for the respondents to rate microclimate comfort, daylight and energy performance as having more influence on design decisions compared to LCC and LCA.

SECOND PART

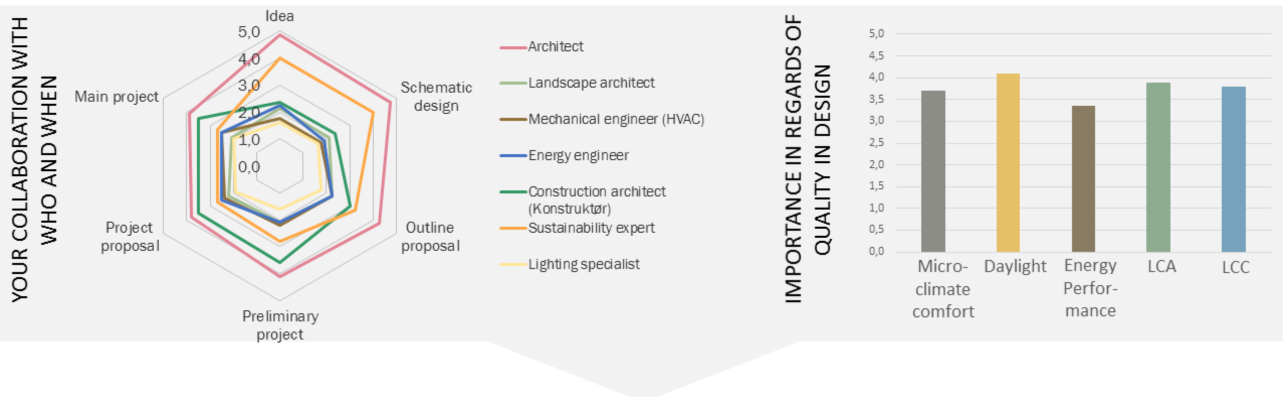


Figure 29 - Office C, second part based on Q1.

The respondents reported that they collaborated mainly with architects, especially in the idea and schematic design phases. Here the sustainability expert was also mentioned as included in the collaboration, and again, especially in the first two design phases. Collaboration with the construction architect was also relatively high but this was mainly from project proposal to main project. Collaboration with other professions was considered relatively low. The five topics and their relevance for the quality of design were rated equally. However, daylight was considered the most important and energy performance the least important.

THIRD PART

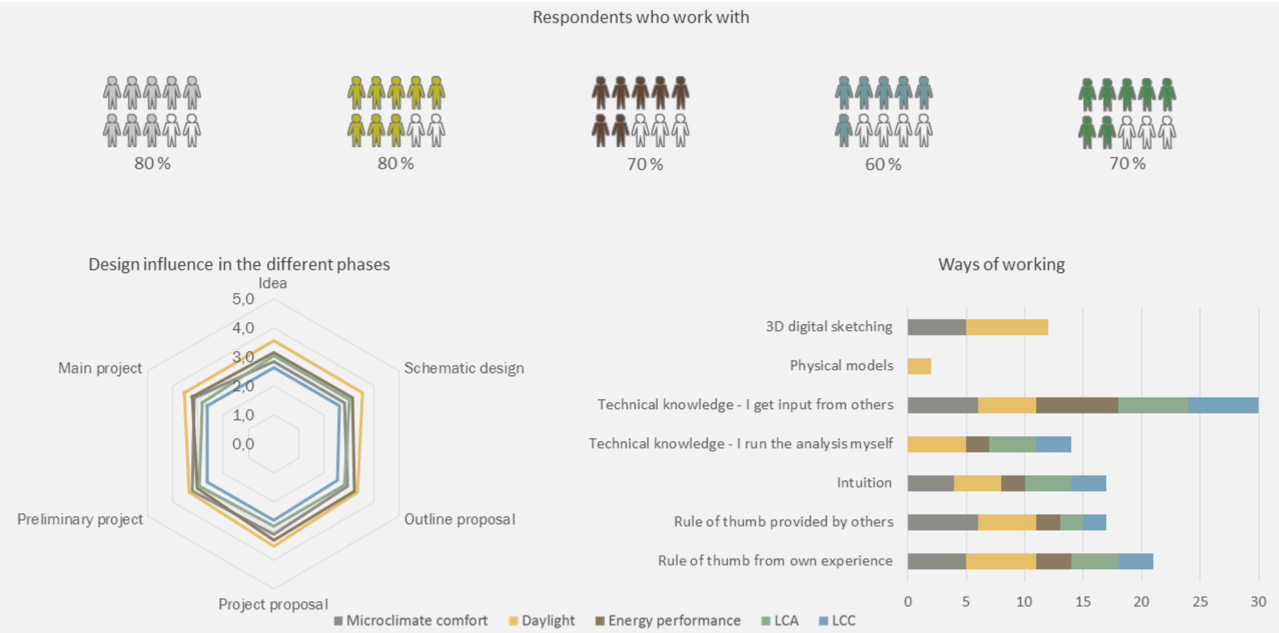


Figure 30 - Office C, third part based on Q1.

In the third part the focus was on each of the five topics, how the respondents worked with them and to what degree. Microclimate comfort was considered by 80% of the respondents and was considered to have moderate influence on the design process. The way of working with the topic was mainly by rule of thumb based on the experience of others and technical inputs from others, although rule of thumb based on their own experience, intuition and 3Ddigital sketching were also mentioned.

Daylight was reportedly considered by 80% of the respondents and was considered to have more influence on the design process than microclimate comfort. A variety of ways of working with the topic were reported but 3D digital sketching was the most commonly used. Energy performance was reportedly used by 70 % of the respondents and was considered as having almost the same impact on the design phase as daylight. Here technical input from others was by far the most common way of working. 60% of the respondent reportedly worked with LCC and they saw it as having moderate influence on the design process, as for microclimate comfort and energy performance. Also, here technical inputs from others was by far the most common way of working. LCA was reportedly used by 70% of the respondents, as for energy performance. Its influence on the design process was considered to be the same as for LCC and technical input from others was the most common way of working, although rule of thumb based on their own experience, intuition, and technical analyses they performed themselves was mentioned more for LCA than for LCC.

SUMMARY

The respondents from this office were mainly architects, but they included a number of engineers, construction architects, and project managers. They participated mainly in the early design phases 'Idea' to 'Outline proposal'. Their collaboration was mainly with architects, sustainability experts, and construction architects. They focused on all five topics, although daylight was considered most. For daylight, 3D digital sketching was their way of working but they also performed technical analyses themselves and received technical input from others. The other topics were handled by using technical input from others.

FIRST PART

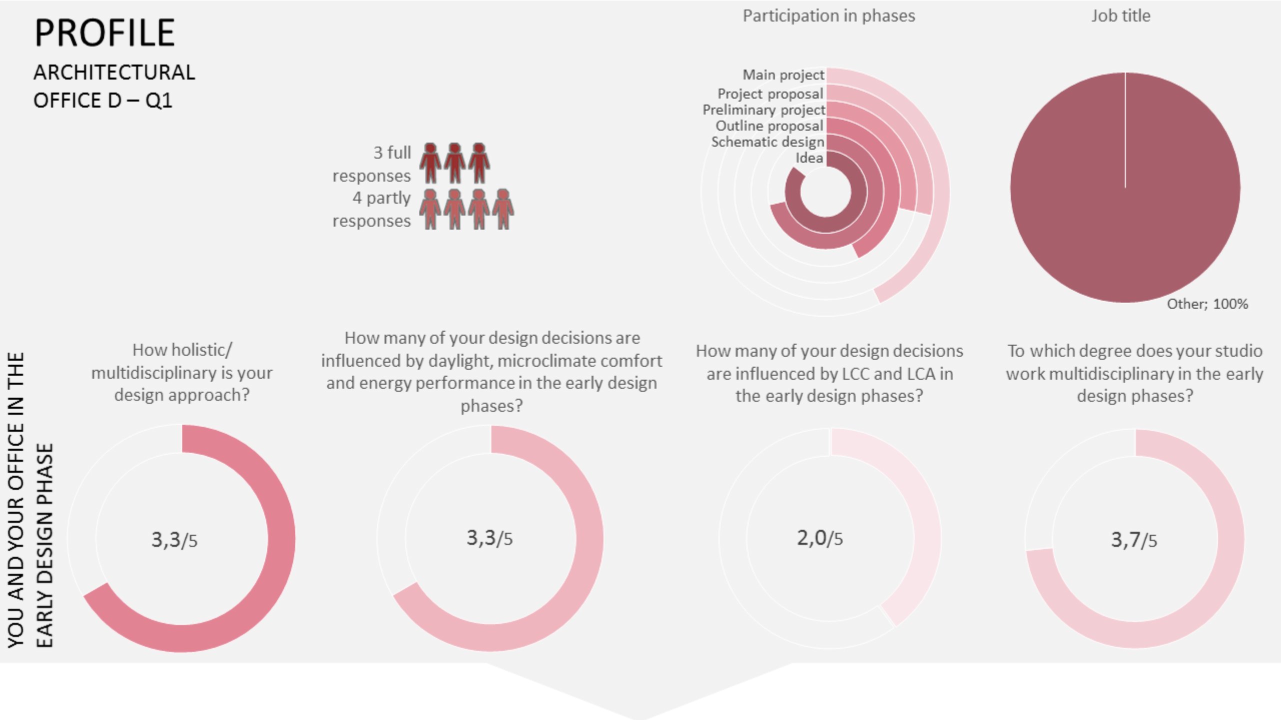


Figure 31 - Office D, first part based on Q1.

For office D 3 respondents did the full questionnaire of a total of 7. The respondents' division of job title were 100% Other. The respondents worked mainly with the idea and schematic design phases. The respondents rated the general office approach to have a more holistic/multidisciplinary approach than they did themselves. They considered microclimate comfort and daylight and energy performance to have a greater impact than LCC and LCA on the design process.

SECOND PART

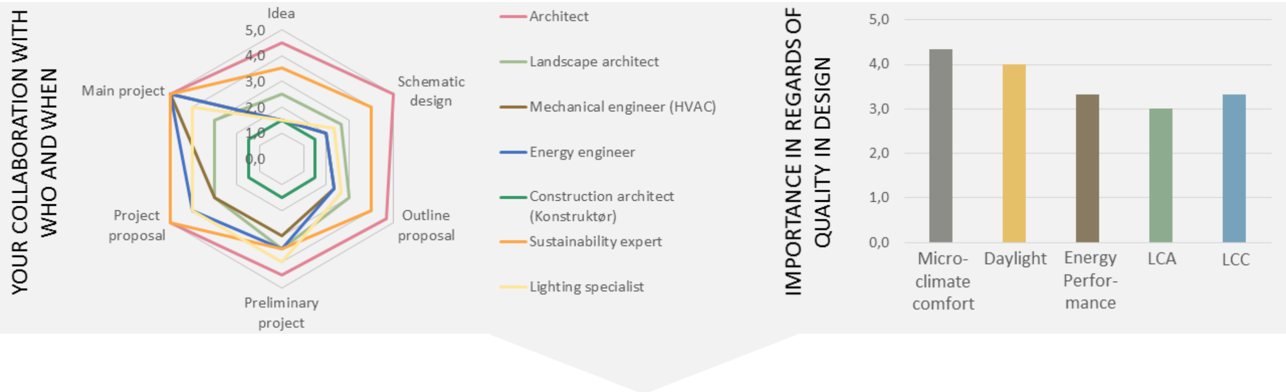


Figure 32 - Office D, second part based on Q1.

The respondents reported that they mainly worked with architects in all the building design phases, but also that they collaborated extensively with the sustainability expert, especially in the preliminary project and the main project. Collaboration with engineers and landscape architects was mainly in the main project phase. Of the 5 factors, microclimate comfort was considered to have the highest influence on the design process, followed by daylight. Next was energy performance and LCC equally and with least influence was LCA.

THIRD PART

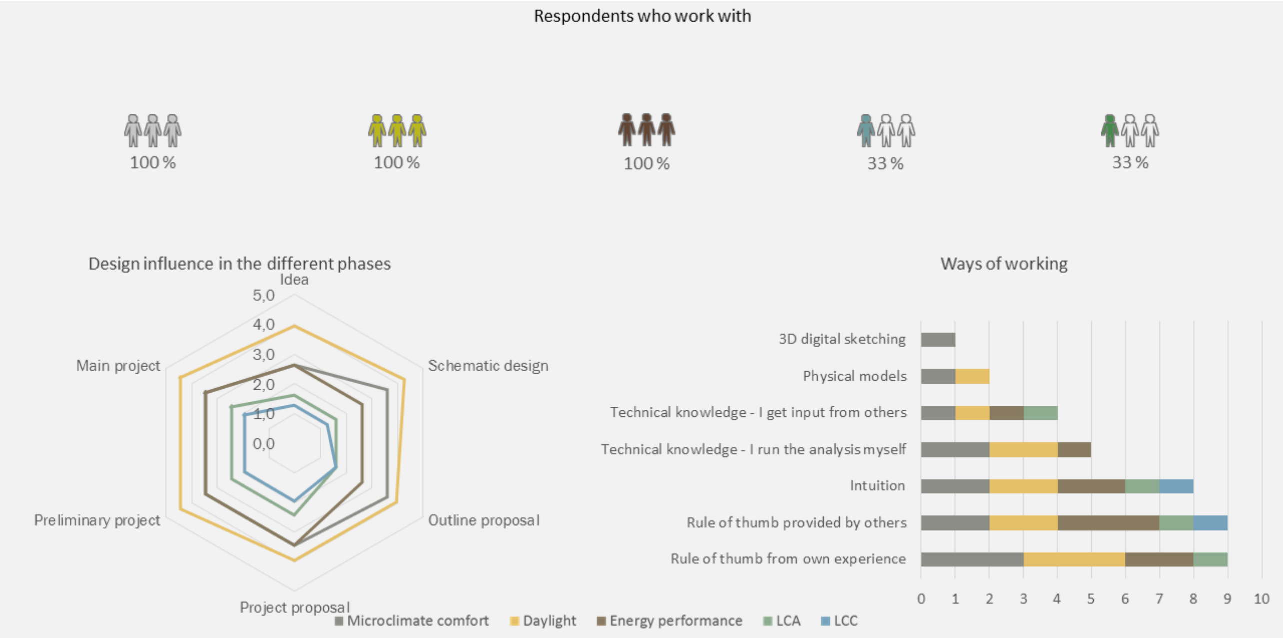


Figure 33 - Office D, third part based on Q1.

Microclimate comfort was reportedly considered by 100% of the respondents and was judged to have a relatively high impact on the design phases, although least upon the sketch phase. Rule of thumb based on their own experience was mostly used, followed by rule of thumb based on the experience of others, intuition and technical analyses they performed themselves. Daylight was also used by 100% of the respondents and was considered to have a greater impact on the design process than microclimate comfort. The way of working with the topic was the same as for microclimate comfort. Energy performance was also considered by 100% of the respondents and was judged to have a moderate impact on the design in the early design phases and more impact from the project proposal to the main project. LCC was considered by 33% and was reported to have little impact on the design process. Their use of LCC was limited to rule of thumb based on the experience of others and intuition. LCA was also considered by 33% and judged to have little impact on the early design phases, more from project proposal to main project. The way of working was equally rule of thumb, intuition and technical input from others.

SUMMARY

All the respondents had ‘Other’ as job title; this was the only office where this occurred, so their responses should be interpreted with caution. They participated mainly in the ‘Idea’ and ‘Schematic design’ phases. The respondents rated the holistic/multidisciplinary thinking of the office as higher than it was in their own work, a response that differs from most of the other offices except for Office F. Their collaboration was rather varied; mostly architects and sustainability experts in all design phases and then engineers and light specialists in the later design phases from ‘Project proposal’ to ‘Main project’. Microclimate comfort and daylight were considered most by the respondents followed by energy performance and LCC. For the first thee topics they performed technical analyses themselves. However, rule of thumb was their main way of working. These results indicate that this office has developed knowledge by performing technical analyses themselves which then provided a basis for using rules of thumb from own experience.

FIRST PART

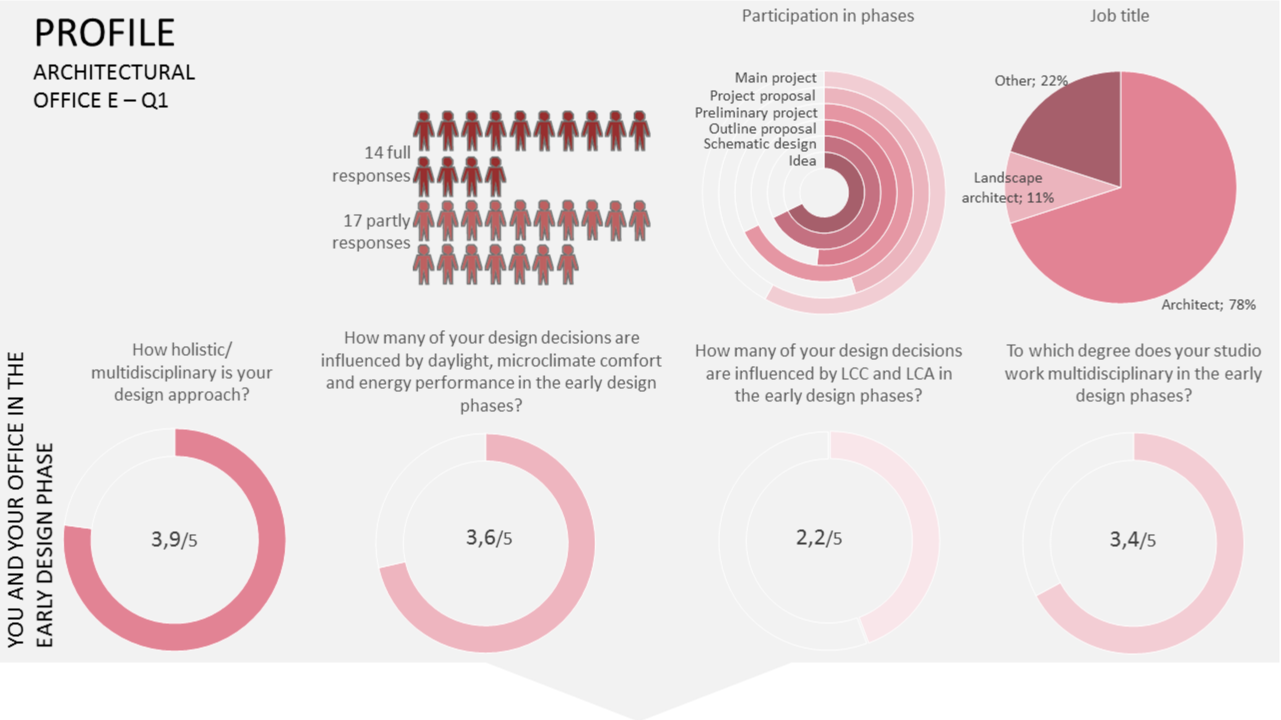


Figure 34 - Office E, first part based on Q1.

For office E 14 respondents did the full questionnaire of a total of 31. The respondents participated mainly in the Idea phase, schematic design phase, preliminary project and main project. The respondents included 78% architects, 11% landscape architects, and 22% other. The respondents considered their own level of holistic/multidisciplinary thinking to be higher than it was in the general office approach. They reported that microclimate comfort, daylight and energy performance had a higher impact on early phase design decision compared to LCC and LCA.

SECOND PART

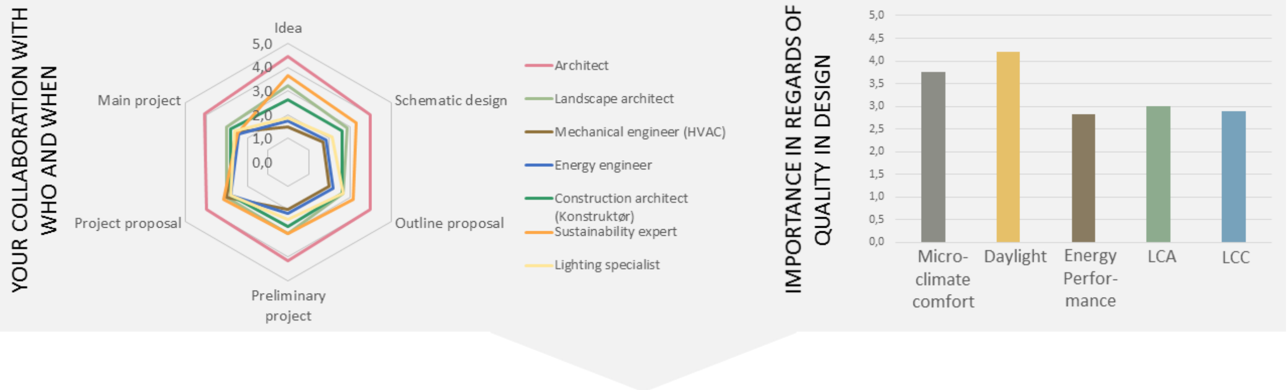


Figure 35 - Office E, second part based on Q1.

The respondents reported that they collaborated mainly with architects in all design phases and with sustainability experts in the idea, schematic design and outline proposal phases. They collaborated less with engineers and construction architects. They reported that daylight had the highest impact followed by microclimate comfort, LCA and LCC, and that energy performance had the least impact on the design process.

THIRD PART

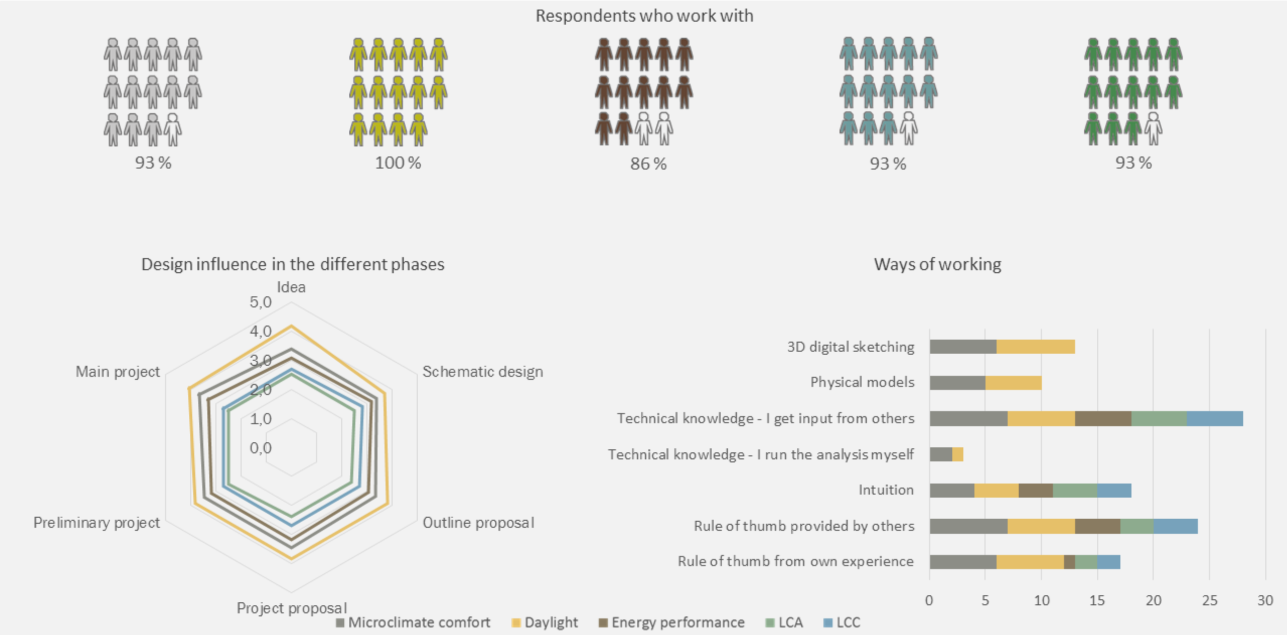


Figure 36 - Office E, third part based on Q1.

Microclimate comfort was considered by 93% of the respondents and was rated as having above middle influence upon design in the different phases. The main way of working with this topic was by rule of thumb based on the experience of others, 3D digital sketching and by technical input from others.
Daylight was considered by 100% of the respondents and was considered to have a relatively high impact upon design in all phases. The main way of working with this topic was by 3D digital sketching, by technical input from others and by rule of thumb based on the experience of others.
Energy performance was used by 86% of the respondents but the design influence was only considered to be moderate in all design phases. The main ways of working with this topic were by rule of thumb based on the experience of others and by technical input from others.
LCC was considered by 93% of the respondents and the design influence and way of working were the same as for energy performance.
LCA was also considered by 93% of the respondents but was rated as having the least impact upon design in all phases by the respondents. The main ways of working with the topic were by intuition and by technical input from others.

SUMMARY

The respondents from this office were mainly architects, who participated in the phases ‘Idea’, ‘Schematic design’, and ‘ Preliminary project’. They rated themselves as working in a more holistic/multidisciplinary way than their office in general. They collaborated mainly with architects and sustainability experts, more than with other professions. The participants reported that they considered all five topics, but again daylight was the most and LCA the least considered. For daylight, 3D digital sketching was the preferred approach.

FIRST PART

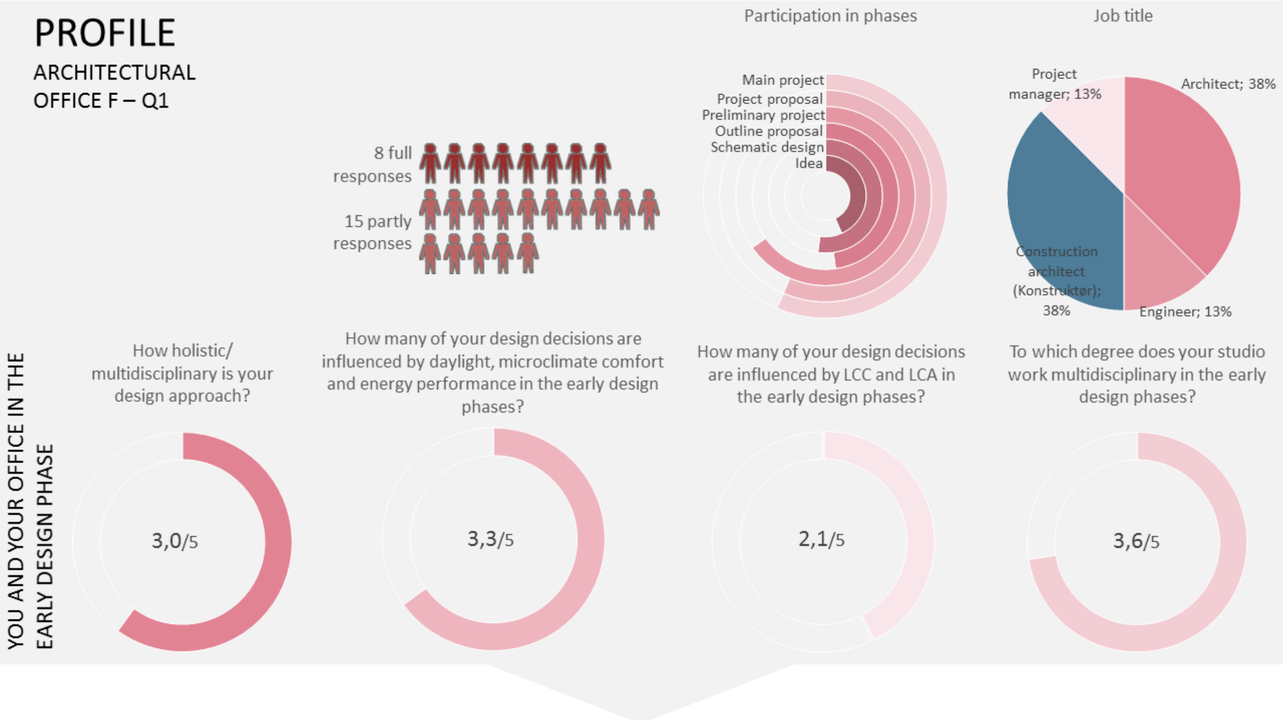


Figure 37 - Office F, first part based on Q1.

For office F 8 respondents did the full questionnaire of a total of 23. There were 38% architects, 13% engineers, 38% construction architects, and 13% project managers. They reported that the level of holistic/multidisciplinary thinking in the early design phases was higher in the architectural office than in their own work and that the design process was more often influenced by microclimate comfort, daylight and energy performance than by LCC and LCA.

SECOND PART

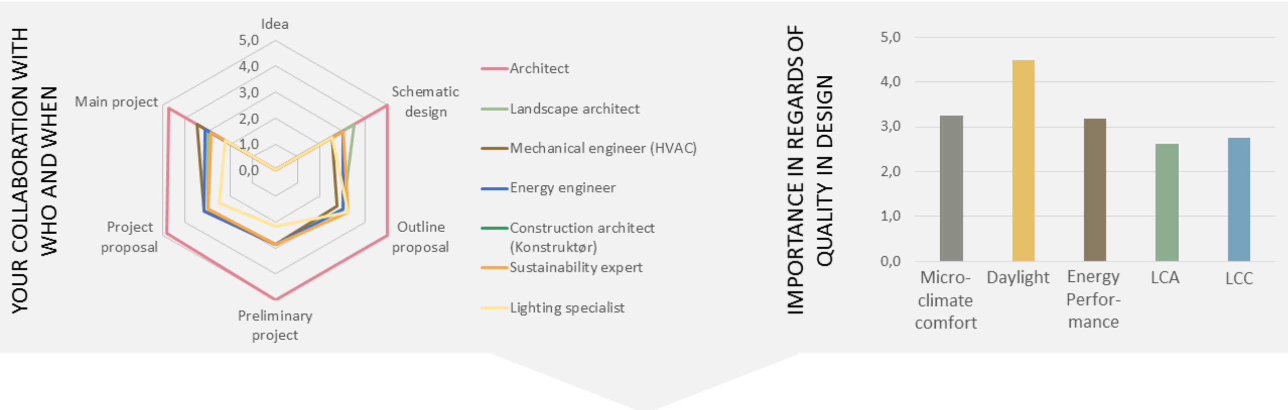


Figure 38 - Office F, second part based on Q1.

The graph of collaboration in the different design phases shows that there was no collaboration with other professions in the idea phase. And it shows no collaboration with construction architects. Otherwise they collaborated mainly with architects. Daylight was rated as having the greatest influence on design, followed by microclimate comfort and energy performance. LCC and LCA were considered to have the least influence.

THIRD PART

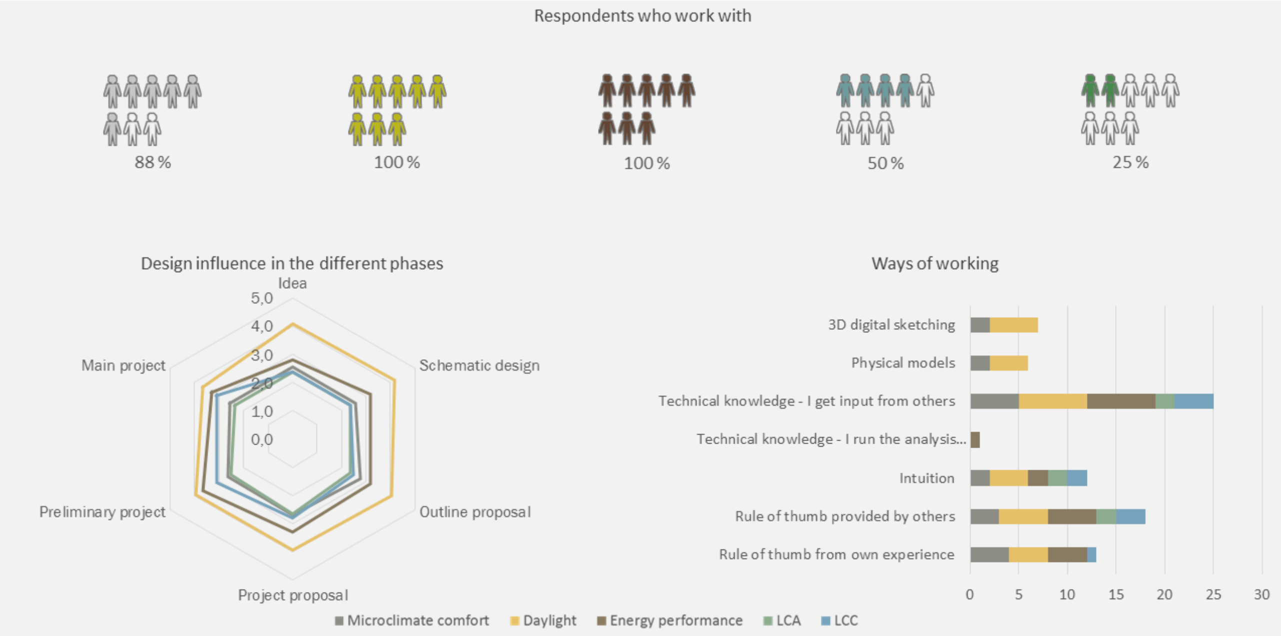


Figure 39 - Office F, third part based on Q1.

Microclimate comfort was considered by 88% of the respondents and was judged to have a moderate impact on the different design phases. The main way of working with the topic was by rule of thumb based on their own experience and by technical input from others.
100% of the respondents reported that they worked with daylight and that it had great influence in all design phases. Their main way of working with the topic was by technical input from others and none of them performed the technical analysis themselves.
Energy performance was considered by 100% of the respondents and it judged to have above average influence on design in all phases, with the greatest impact on the preliminary project. For this topic, the main way of working was by using technical input from others.
LCC was considered by 50% of the respondents and but judged to have a limited influence on the design phases and thus to have more influence from project proposal to main project. Rule of thumb by others and technical input from others were the main ways of working with this topic.
25% of the respondents reported that they considered LCA and it was considered to have relatively little influence in all design phases. Rule of thumb based on the experience of others, intuition and technical input from others were the main ways of working with this topic.

SUMMARY
The job division of the respondents in this office was unique in that there was an equal number of architects and construction architects, and one engineer, who reported that they mainly participated in the later design phases ‘Preliminary project’ to ‘Main project’. They mainly collaborated with architects and less with the other professions. Daylight and energy performance were the most often considered topics, based on technical input from others.

FIRST PART

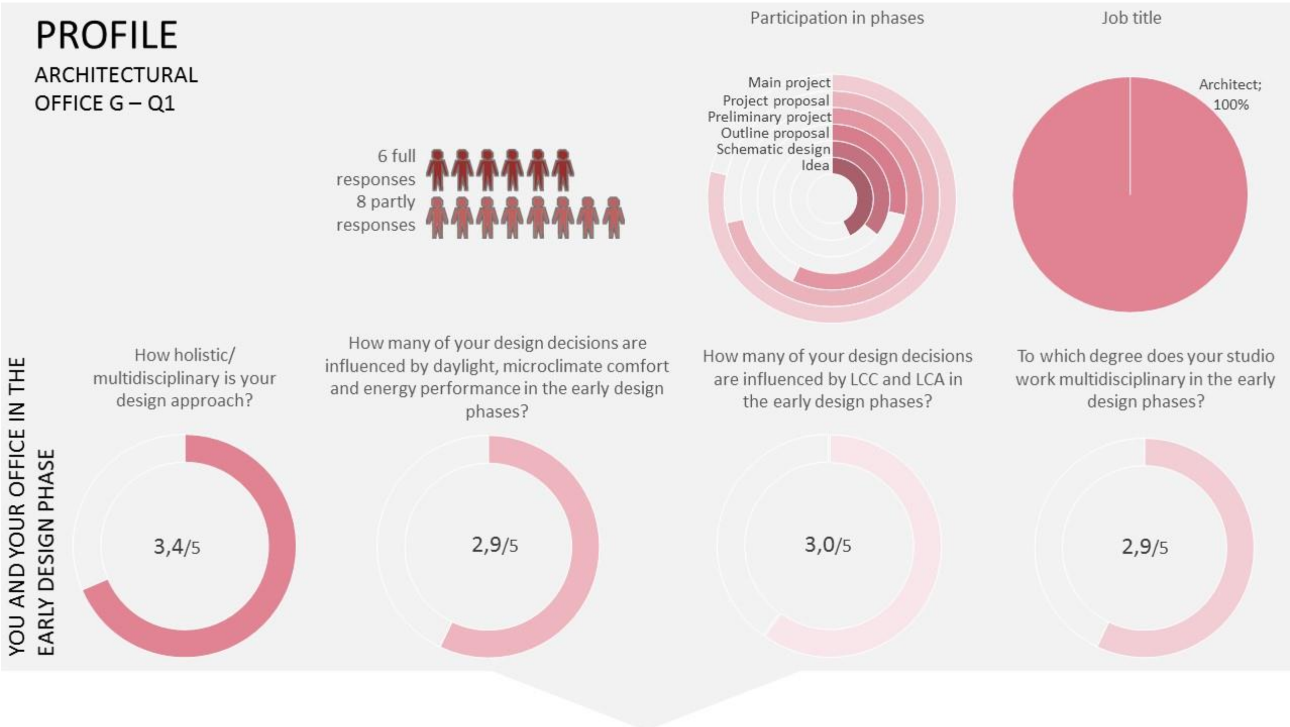


Figure 40 - Office G, first part based on Q1.

For office F 6 respondents did the full questionnaire of a total of 14. The respondents mainly worked in the preliminary project, project proposal and main project phase and they were all architects. The respondents considered that their own level of holistic/multidisciplinary thinking was higher than in the general approach taken by the architectural office. The influence on the early design phases was reported to be the same for microclimate comfort, daylight and energy performance as for LCC and LCA.

SECOND PART

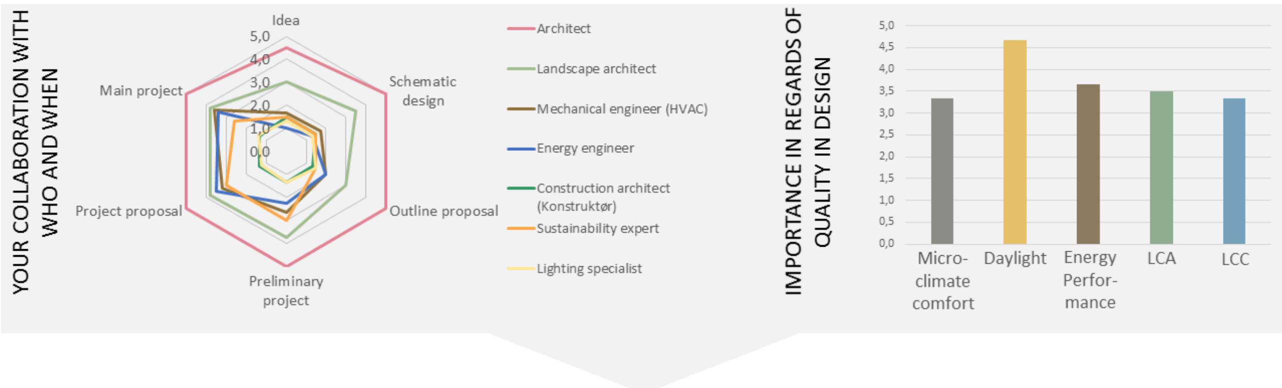


Figure 41 - Office G, second part based on Q1.

The respondents reported that they collaborated mainly with other architects in all design phases, followed by landscape architects. Their collaboration with engineers and sustainability experts took place mainly from the project proposal to the main project. Daylight was considered to have the greatest influence on the design process, followed by energy performance, LCA and LCC, and finally by micro climate which had the least influence.

THIRD PART

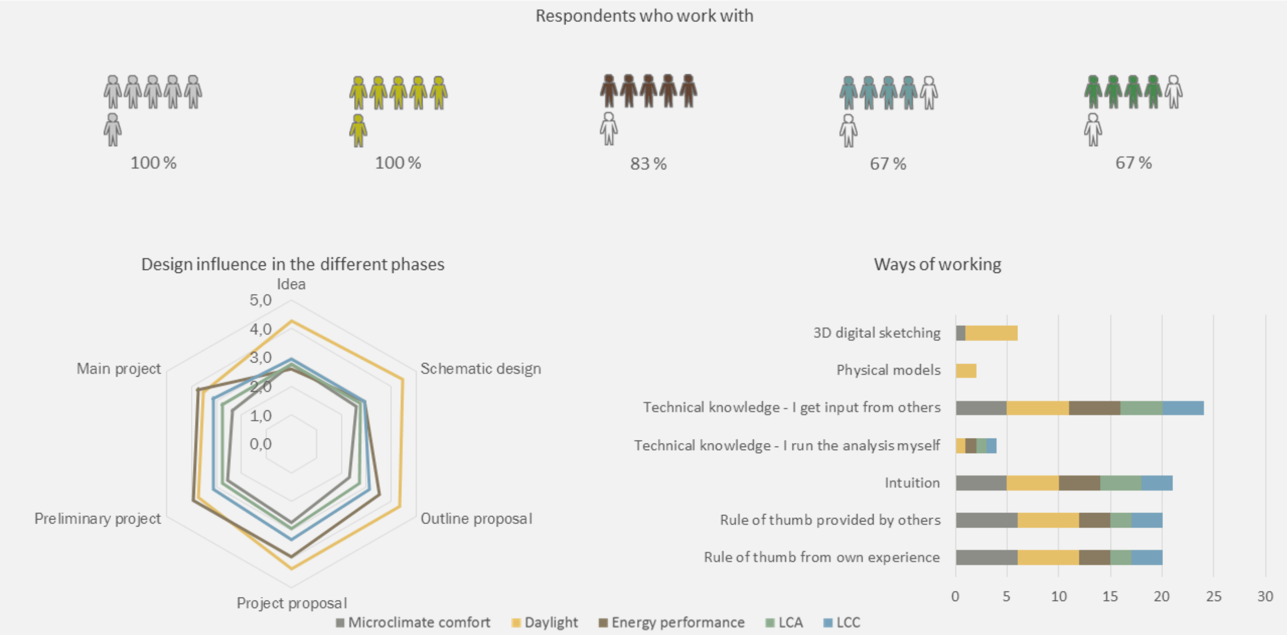


Figure 42 - Office G, third part based on Q1.

Microclimate comfort was considered by 100 % of the respondents but was judged to have a relatively low impact on design in all phases. Rule of thumb from own and others’ experiences, and technical inputs from others were the main ways of working with the topic.

Daylight was also considered by 100% of the respondents and was judged to have a great impact on design in all phases. The main ways of working were by rule of thumb from own and others’ experiences, 3D digital sketching and by technical input from others.

Energy performance was considered by 83% of the respondents and was judged to have a relatively large influence from project proposal phase till main project phase. The main ways of working with this topic were by intuition and by technical input from others.

67% of the respondents reported that they worked with LCC and they considered it to have moderate influence in all design phases. The main way of working with the topic was by technical input from others.

Also 67% of the respondents reported that they worked with LCA and they also considered it to have moderate influence in all design phases. The main ways of working with the topic were by intuition and by technical input from others.

SUMMARY

The respondents for this office were all architects and they mainly worked in the late design phases ‘Project proposal and in the ‘Main project’. They rated themselves as having a higher level of holistic/multidisciplinary thinking than was characteristic for the office. There was a tendency for them to collaborate more with architects and less with landscape architects, but they did collaborate with engineers and sustainability experts in the later design phases, from the ‘Preliminary project’ to the ‘Main project’. Again, microclimate comfort, daylight and energy performance were the most influential topics, with technical input from others and rule of thumb from own and others experiences, as the main working strategies.

3.1.1 Q2 as a follow-up to Q1 at JJW

For comparison with the first questionnaire Q1, an additional questionnaire Q2 was distributed after one year, but only at JJW. See APPENDIX Y. Q1 therefore represents a point in time for the state-of-the-art and at JJW comparison between Q1 and Q2 could reveal any development at JJW over the one-year period. A comparison of this questionnaire B-Q2 with B-Q1 from Figure 25, sows that they are very similar.

<u>FIRST PART</u>

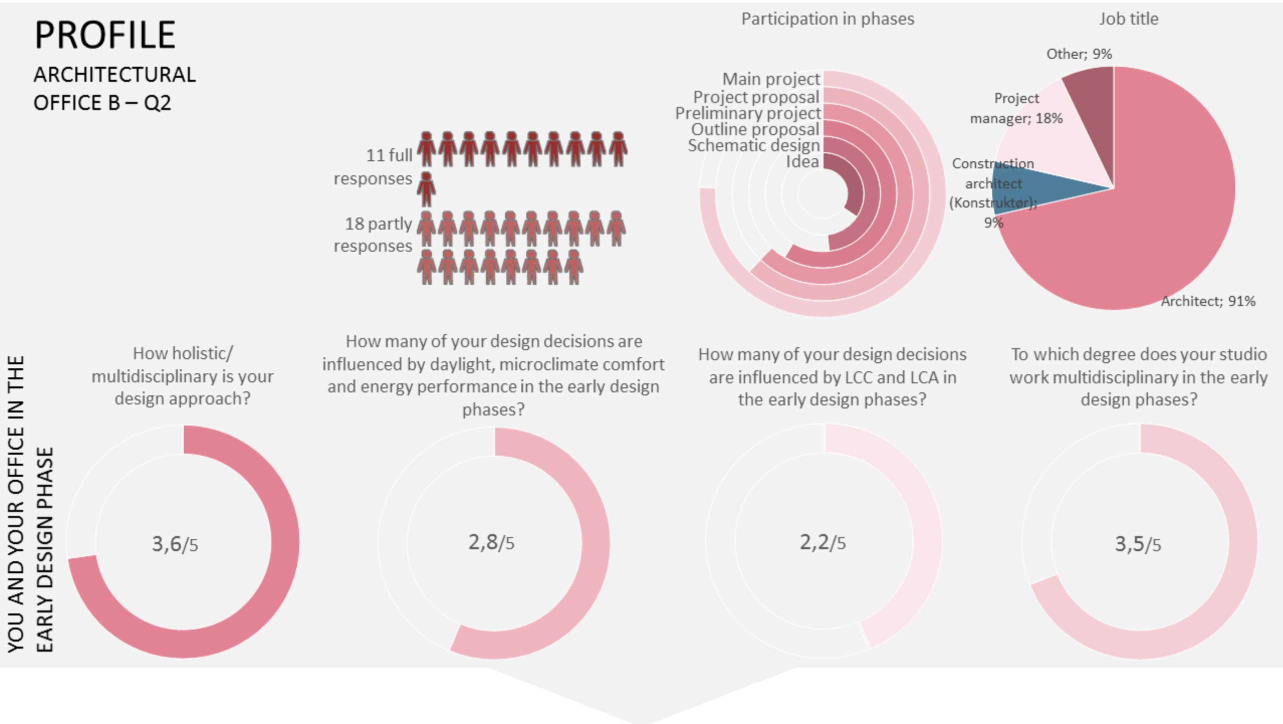


Figure 43 - First part of the results from Q2 at JJW.

Figure 43 shows the first part of the results from B-Q2, with 11 full responses of 29, almost equally divided between male and female respondents. There considerable differences between the respondents in terms of their participation in the various design phases. However, there was a tendency for most of the respondents to participate mainly in the Main project phase. The division of job titles between the respondents was architects 91%, followed by project manager 18%, and finally construction architects 9% and other 9%. The listed percentages are based on several jobs per respondent. There was a tendency for the respondents to find their own and the office's level of holistic/multidisciplinary thinking to be equal in the early design phases.

SECOND PART

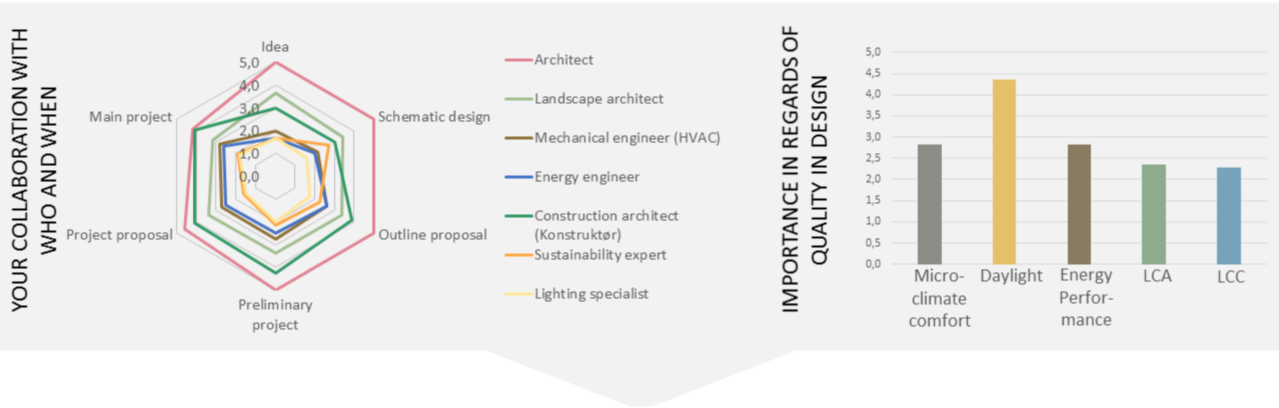


Figure 44 - Second part of the results from Q2 at JJW.

Figure 44 indicates a tendency for the respondents to report working mainly with architects in all design phases, followed by collaboration with construction architects and landscape architects. Their collaboration with the construction architects tended to take place in the design phases from Outline proposal to Main project, whereas their collaboration with the landscape architects took place equally in all design phases. Collaboration with engineers was not very common but was mainly in the design phases from the Outline proposal to the Main project, and finally their collaboration with experts was very limited. There is a clear tendency for daylight to be rated as the most important and next microclimate comfort and energy performance. LCA and LCC seems to have been considered the least important.

THIRD PART

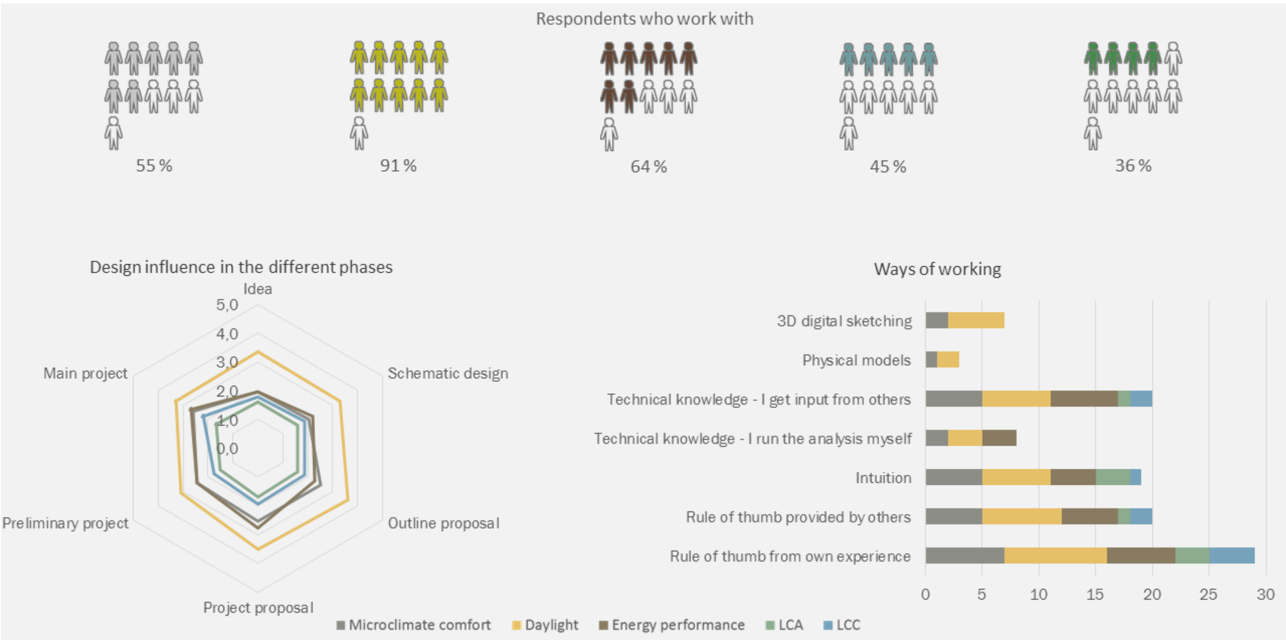


Figure 45 - Third part of the results from B-Q2 at JJW.

Figure 45 shows that daylight was the most commonly considered topic (91% of the respondents reported considering daylight). It was used in all design phases, though least in the Preliminary project and Main project phases. Their ways of working with daylight were mostly by rule of thumb based on their own experience and by rule of thumbs based on the experience of others. Energy performance was the second most commonly considered topic after daylight, and was considered by 64% of the respondents, reported to mainly influence the Project proposal and Main project phases. Microclimate comfort was used by 55%, LCC 45% and LCA 36%. The ways of working with this topic were mainly by rule of thumb based on their own experience and by receiving technical input from others. LCC and LCA were considered to influence the three last design phases the most. They dealt with these topics mainly by rule of thumb based on their own experience.

SUMMARY

As mentioned B-Q2 and B-Q1 from Figure 25 are very similar. However there had been some development over the one-year period between them. The responses from the early design phases indicate that the holistic/multidisciplinary approach had changed in that it became more equal between the individual respondent and the general approach by the architectural office. Hence for B-Q1, the respondents claimed that their own level of individual holistic/multidisciplinary thinking was higher than that of the office in general, while in B-Q2 they reported that the two were more equal. More of the respondents reported that LCC and LCA affected the early design phase, from 1,9/5 in Q1 to 2,2/5 in Q2. The percentage of respondents working with LCC is 67% for Q1-B and 45% for Q2-B. The number of respondents who reported working with LCA increased from 33% in Q1 to 36% in Q2. In Q2, daylight was still reported to have the most influence on the quality of design. Microclimate comfort was ranked higher in Q1 than in Q2.

3.1.2 Sub-discussion

The Q1 questionnaires from the seven architectural offices reveal that they all had different work profiles for architectural engineering topics and collaboration. All the offices had their own work cultures and design processes, and some were more fixed than others. This is not necessarily seen from the questionnaires, so the focus has been more upon the interface between different kinds of technical knowledge within each architectural office. These design process cultures might have influence on the possibility of creating new design processes that lead to a quantifiably higher level of sustainability. To highlight a few standouts for the office profile tendencies:

Office A – Rated themselves as more holistic/multidisciplinary than they rate their office.
Office B – Collaborated extensively with different professions.
Office C – Mixed job profiles of the respondents.
Office D – Collaborated with sustainability experts in all design phases.
Office F – Rated their office as having a more holistic/multidisciplinary approach than they did themselves.
Office G – LCA was reported to have considerable influence on quality in design.

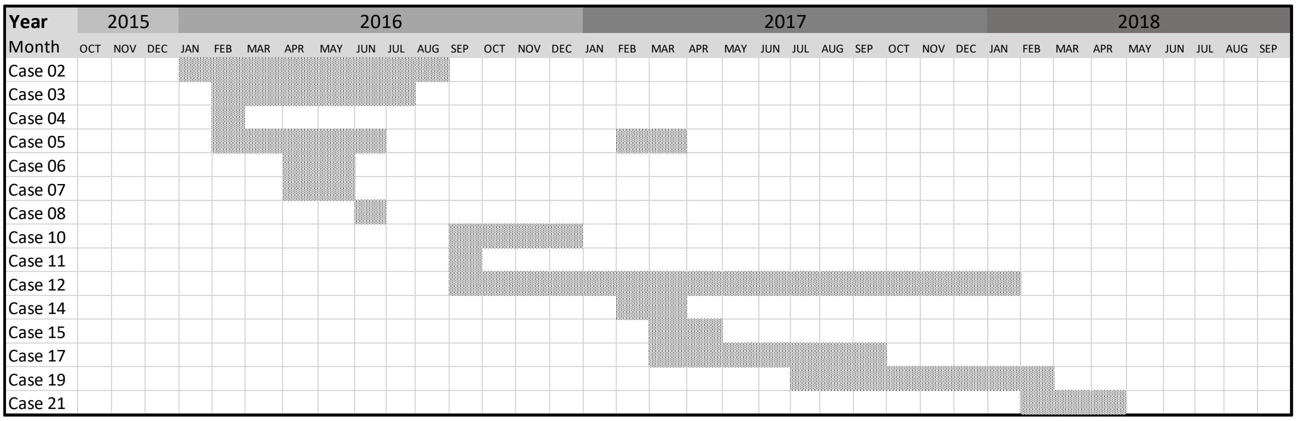
Despite the unique work cultures at the offices and the above-listed profile tendencies there were many similarities between the offices. There was a tendency for the respondents to be mainly architects and they ranked their own holistic/multidisciplinary thinking higher as than average for their office and they mainly collaborated with other architects. There were some commonalities in their work with the five topics; microclimate comfort, daylight, energy performance, LCC, and LCA: There was a tendency for daylight to be the most considered factor in all the offices, followed by energy performance and microclimate comfort. Although LCC and LCA were the least considered, many reported that it influenced the early design phases as much as energy performance and microclimate comfort.

From Q1_B to Q2_B one year had passed but many answers were the same. However, there was a tendency for LCC and LCA to have gained more value when ranking their influence in the early design phases. However, only LCA was reported to be more considered.

3.2 Overall mapping of case studies at JJW

This sub-section reports the case study research conducted through the three years of PhD study, from October 2015 till September 2018. Table 18 is a table of the 15 case study design processes at JJW. They varied in building typology, building design phase, sustainability focus, setting of design team etc. However, common to all cases selected for the case study was an intention to achieve some degree of sustainability, based on the project requirements or requested additionally by JJW themselves. All cases have been anonymized to protect the clients as well as the design team, however their identities are known by the PhD researcher and the university.

Table 18 - Overview of case studies in the timeframe of the PhD research.



The case studies were conducted as active research, as previously described in 2.3.2 Action research, and shown in the matrix in Figure 46. Each case study consisted of an implementation part, observation part and reflection part. All case studies were collected, mapped and compared in the same way so as to be able to perform the analysis.

The selected case projects at JJW all had some initial vision for sustainability and they were chosen to cover most of the design phases from the Danish Description of Service, including end of life and afterlife phases, so as to achieve sustainability in the entire life cycle.

The case studies were divided into four sub-categories, as seen in matrix of the case study mapping in Figure 46: one category focused on DGNB as the overall guideline, another solely on some of the social sustainability criteria (SOC), a third on environmental criteria (ENV) and lastly the fourth category focused on economic criteria (ECO).
The mapping of the case study design processes has patterns through the matrix, which may be seen in Figure 46. The colours in the matrix indicate respectively: Yellow indicates social sustainability topics, Blue indicates economic sustainability topics, Green indicates environmental sustainability topics and Orange indicates the overall DGNB certification topics.

Figure 46 shows the matrix of the overall mapping of the case studies at JJW. The matrix includes the following data:

- A case number, which is defined by the PhD researcher to ensure anonymised projects.

- A description of JJW’s role in the overall project.
- The design phase(s) in which JJW was involved (defined by the Danish Description of Service).
- Sustainability focus of the current case - combined for both client and JJW.
- A description of who requested the technical inputs to the project (inputs from the PhD researcher).
- List of technical inputs in the design process (inputs from the PhD researcher).
- Technical tool(s) used to conduct the technical inputs.
- A definition of tasks that required technical input.
- A list of design variations within the given task (that required the technical input).
- Short description of the design decision made for the task.
- The reason for the design decision.
- Who made the design decision
- A description of whether the technical inputs were implemented in the design decision.
- Level of sustainability ranking from 1-4. The development and results of this ranking are further described in sub-section ‘3.2.9 Level of sustainability reached’.

  1 = Mentioned
  2 = Investigated
  3 = Partly implemented
  4 = Fully implemented

Figure 46 is complex in its format and rather difficult to read, so is mainly used as the reference that might help the reader navigate through the elaboration of the cases in the following sections. Each case is elaborated, with a focus on the design team, project information, sustainability focus, technical inputs, design decision loops, mapping of IED and DGNB etc., to ensure a basis for comparison. Case 02, 03, 05, 12, 15, and 17 are included in the following sections and Cases 04, 06, 07, 08, 10, 14, 19, and 21 are available in APPENDIX I.

Case No.	JJWs role	JJW included design phase(s) (Description of Service)	Sustainability focus	Technical inputs -Requested by	Technical inputs	Technical tool(s)	Definition of tasks	Design variations	Design decision	Reason for design decision	Decision made by	Implement of inputs	Level of sustainability
Case 02	Sub-consultant architect	Detailed design	BR15/LEED	Client / to fulfil BR15	Daylight simulations	Velux Daylight Visualizer	Selection of glazing	2-layers 3-layers 4-layers	3-layers	Energy	Main architect	Y	3
						Velux Daylight Visualizer	Selection of solar shading	Coating Lamellas					
						Velux Daylight Visualizer	Design of balcony	Overhang balcony Depth Structure Material	Overhang balcony Depth Open Steel	Design Daylight Design Design	Main architect Sub-consultant architect Main architect Main architect	Y Y Y Y	
						Velux Daylight Visualizer	Ceiling surface	Plane surface Lamellas Color	Plane surface Lamellas	Daylight Design	Sub-consultant architect Main architect	N Y	
Case 03	DGNB Auditor	In use	DGNB Existing office building	Client / Building owner	DGNB certification	DGNB tool	Data collection - Economic	Energy consumption Water consumption Waste treatment	Gold	DGNB	DGNB Auditor	Y	4
						DGNB tool	Data collection - Environmental	Energy consumption Water consumption Waste treatment Material specification Test for VOC's documentation	Gold	DGNB	DGNB Auditor	Y	
						DGNB tool IC-meter measurements Velux Daylight Visualizer User Satisfaction Survey Floorplan studies	Datacollection - Social	Indoor temperature documentation Daylight documentation Indoor climate documentation Flexibility documentation	Gold	DGNB	DGNB Auditor	Y	
						DGNB tool	Technical	Catalouge for technical systems	Gold	DGNB	DGNB Auditor	Y	
						DGNB tool	Process	Management plan	Gold	DGNB	DGNB Auditor	Y	
Case 04	Consultant architect	Design proposal	BR15 and minimal maintenance and cleaning	Design team	Sustainability screening	DGNB manual	Defining economic criteria in competition program	On budget	Reccomendations	Competition strategy	Design team	Y	1
							Defining environmental criteria in competition program	Compact buildingmass to reduce ressources for construction and maintenance	Reccomendations	Competition strategy	Design team	Y	
								Minimize building envelope to reduce thermal transmissions	Reccomendations	Competition strategy	Design team		
								Limited material use	Reccomendations	Competition strategy	Design team		
								Minimize water use for cleaning and maintenance by material selection	Reccomendations	Competition strategy	Design team		
							Defining social criteria in competition program	Life between buildings to emphasize social meetings	Reccomendations	Competition strategy	Design team		
								Accessability for all - a knock-out criteria in the DGNB	Reccomendations	Competition strategy	Design team		
					Sustainability diagram	Illustrator	Sustainability diagram	Visualizing the sustainability concepts in building section		Competition strategy	Design team	Y	
Case 05	Project leader	In use	Economy	Design team	Economic estimates	Excel	Economic estimates for renovation	Planning the management of renovation process Comparing the existing remidiation strategies on the market Handeling of hazadous waste Timeframe for the entire process to limit re-housing costs	Reccomendations Reccomendations Reccomendations Reccomendations	Economy Economy Economy Economy	Client Client Client Client	Y Y Y Y	2
			LCC	Design team	LCC calculations	LCCByg	Comparing the existing remidiation strategies on the market	Thermal desorption Steel blasting Sealing Sand blasting	Reccomendations Reccomendations Reccomendations Reccomendations	Economy Economy Economy Economy	Design team Design team Design team Design team	N N N N	
			LCA	Design team	LCA calculations	LCAByg	Comparing the existing remidiation strategies on the market	Thermal desorption Steel blasting Sealing Sand blasting	Reccomendations Reccomendations Reccomendations Reccomendations	Economy Economy Economy Economy	Design team Design team Design team Design team	N N N N	
Case 06	Consultant architect	Design proposal	BR15	Design team	Sustainability screening	DGNB manual	Functional Structural Energy Indoor climate	Required functions and rooms implimented in floorplan for building Definition of structural concept in design team Definition of energy concept in design team A goal for indoor climate is defined by the team	Definition of floor plan Structural concept BR15 BR15	Competition strategy Competition strategy Competition strategy Competition strategy	Design team Design team Design team Design team	Y Y Y Y	3
					Solar and daylight studies	Velux Daylight Visualizer	Solar radiation on surfaces Daylight studies of building mass	Solar studies influence building geometry and orientation Daylight studies influence building depth and geometry	Reccomendations Reccomendations	Competition strategy Competition strategy	Design team Design team	Y N	
					Wind studies	FlowDesign	Wind studies of urban space	Windstudie influence the geometry of the balconies and outdoor spaces	Reccomendations	Competition strategy	Design team	N	
Case 07	Consultant architect	Design proposal	BR15	Design team	Sustainability screening	DGNB manual	Functional Structural Energy Indoor climate	Required functions and rooms implimented in floorplan for building Definition of structural concept in design team Definition of energy concept in design team A goal for indoor climate is defined by the team	Definition of floor plan Structural concept BR15 BR15	Competition strategy Competition strategy Competition strategy Competition strategy	Design team Design team Design team Design team	Y Y Y Y	3
					Sustainability reccomendations	DGNB manual	Greening the city Social interaction Enrich liveability Selection of materials	Green roof and facades Life between buildings to emphasize social meetings Adding new functions to the city - Rooms and atteliers for artists Easy cleaning and maintenance to limit water consumption	Reccomendations Reccomendations Reccomendations Reccomendations	Competition strategy Competition strategy Competition strategy Competition strategy	Design team Design team Design team Design team	Y Y Y Y	
					Sustainability diagram	Illustrator	Sustainability diagram	Visualizing the sustainability concepts in building section		Competition strategy	Design team	Y	
Case 08	Project leader	Design proposal	BR15	Design team	Energy calculations	Be15	Selection of window typology	Ventilationsvinduet 2-layers 3-layers	Reccomendation Reccomendation	Less interventions in building mass Best energy consumption output	Design team Design team Design team	N Y	3
Case 10	Project leader	Detailed design	LCC	Design team	LCC calculations	LCCByg	Selection of roof	Asphalt roof Green roof	Asphalt roof Green roof	Economy Lifetime of product	Client Design team	Y N	2
						LCCByg	Selection of facade cladding	Wood cladding Concrete Aluminium plates	Concrete	Economy	Client	Y	
						LCCByg	Selection of floors	Linoleum Wood cladding Tiles	Wood cladding	Economy	Client	Y	
						LCCByg	Selection of ceiling	Mineral wool Wood lamellas	Mineral wool	Economy	Client	Y	
Case 11	Consultant architect	Initial design	Most value for money in renovation	Design team	Daylight simulations	Velux Daylight Visualizer	Officespace based on daylight conditions	Existing windows New windows	New windows	Daylight	Design team	Y	4
					Energy calculations	Be15	Windows based on energy calculations	Existing windows New windows	New windows	Energy	Design team	Y	
Case 12	Project leader	Initial deisgn	LCC	Project leader	LCC calculations	LCCByg	Economic estimates for renovation	Renovation of existing buildings Demolishing and built new	Demolishing and built new	Economy	Client	Y	4
	Consultant architect	Design proposal	BR15	Design team	Daylight simulations	Velux Daylight Visualizer	Sufficient daylight in current geometry and layout?	30% glazing 30% glazing + 1 m2 rooflight 30% glazing + 2 m2 rooflight	 No selection yet No selection yet	 Daylight Daylight	 Design team Design team	 N N	2
			BR2020	Design team	Energy calculations	Be15	Study of nessessity of PV's	Increasing PV' angle - 3m2 less PV's Considering the efficiency of the mechanical ventilation - 9 m2 less PV's	No selection yet No selection yet	m2 PV's m2 PV's	Design team Design team	N N	
			Low environmental footprint	Design team	Material considerations		Study of CLT vs. Other materials	CLT Woodframe structure Aerated concrete blocks Concrete	First selected, but later rejected Aerated concrete blocks	Higher costs for projecting and material Economy	 Design team	N Y	
Case 14	Consultant architect	Design proposal	BR15	Design team	Sustainability screening	DGNB manual	Functional Structural Energy Indoor climate	Required functions and rooms implimented in floorplan for building Definition of structural concept in design team Definition of energy concept in design team A goal for indoor climate is defined by the team	Definition of floor plan Structural concept BR15 BR15	Competition strategy Competition strategy Competition strategy Competition strategy	Design team Design team Design team Design team	Y Y Y Y	1
					Sustainability reccomendations		Limit cleaning and maintenance	Robuste materials Robuste surfaces	No selection yet No selection yet	Competition strategy Competition strategy	Design team Design team	Y Y	
							Support social interaction	Few elevators and staircases Common functionalities	No selection yet No selection yet	Competition strategy Competition strategy	Design team Design team	Y Y	
							Flexibility	Residential units with low room dept Residential units with full room dept Planning of units for flexibility of future functions and needs	No selection yet No selection yet No selection yet	Better daylight conditions Good condition for natural ventilation Competition strategy	Design team Design team Design team	Y Y Y	
							Economic benefits	Maximize residential areas and limit passages	No selection yet	Competition strategy	Design team	Y	
Case 15	Consultant architect	In use	LCC	Design team	LCC calculations	LCCByg	Economic estimates for type of window	Wood-wood, frame and 2-layer glazing - Supplyer 1 Wood-wood, frame and 2-layer glazing - Supplyer 2 Wood-aluminium, frame and 2-layer glazing - Supplyer 2	Reccomendations	Less maintenance and suficient energy perforr	Design team	Y	3
			LCA	Design team	LCA calculations	LCAByg	Environmental estimates for type of window	Wood-wood, frame and 2-layer glazing - Supplyer 1 Wood-wood, frame and 2-layer glazing - Supplyer 2 Wood-aluminium, frame and 2-layer glazing - Supplyer 2	Reccomendations	Less maintenance and suficient energy perforr	Design team	Y	
Case 17	Consultant architect	In use	LCC	Design team	LCC calculations	LCCByg LCCByg	Building components Building materials	Supervision to the tool and setup Supervision to the tool and setup	Use of Excel tool Use of Excel tool	It is not requred by the client It is not requred by the client	Design team Design team	N N	2
Case 19	Project leader	Initial deisgn	Low environmental footprint	Design team	Material considerations		Study of CLT vs. Other materials	CLT Woodframe structure Aerated concrete blocks Concrete	CLT	Innovation project internal to work with CLT	Design team	Y	2
Case 21	DGNB Auditor	Design proposal	DGNB New residential buildings	Design team	DGNB certification	LCAByg	Building components Building materials	Supervision to the tool and setup Supervision to the tool and setup	Use of LCAByg Use of LCAByg	DGNB DGNB	DGNB Auditor DGNB Auditor	Y Y	4

Figure 46 - Matrix of the mapping, based on case studies at JJW. The complexity is high and is therefore used as an icon. Sustainability focus is indicated by colours: Orange = DGNB overall, ENV = Environmental criteria, ECO = Economic criteria, and SOC = Social criteria.

3.2.1 CASE 02

This case study was a project for a new headquarters office building in Copenhagen. The data from the case study are elaborated in the following. The data are based on specifications from the project brief, mapping of the inputs of technical information, observations of how the inputs were received and implemented in the process.

PROJECT INFORMATION

Location:

- Copenhagen, with a unique location at the coast surrounded by the sea.
- Close to the airport.

Main design focus:

- State of the art workplace. Up-to-date work facilities for the employees.
- Best possible view and relation to the sea.
- An architectural landmark. Both from the sea, mainland and from the plains around the airport.

DESIGN TEAM

Unusual team composition. JJW sub-consultants with direct contact to the main engineering consultancy, who have individual contact to all parties involved, as seen in Figure 47.

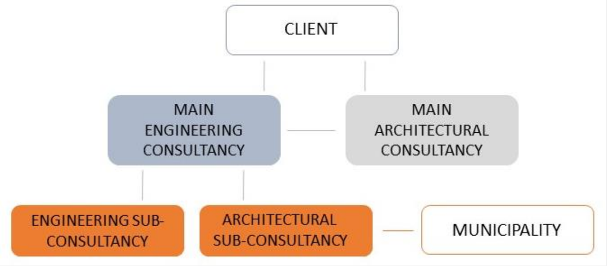


Figure 47 - Case 02 design team setup.

From JJW:

- Architect 1: Project leader, interest in sustainability
- Architect 2: Sustainability expert, DGNB auditor
- Landscape Architect: Education in accessibility
- Intern: BEng Architectural Engineering in Energy Design
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

- LEED Gold certification
- Best indoor climate conditions

Task specific sustainability:

- Visual comfort (DGNB: SOC1.4)
  - Proof of min. 2% Daylight factor for all permanent workplaces, according to the client's brief.
  - Optimal design solution to ensure an undisturbed view of the sea, good daylight conditions, well-designed facades.
  - Solar shading by overhanging balconies, low maintenance.
- Comparison for the LEED and DGNB certification systems:
  - DGNB screening of the project to inform the client in choosing a suitable system that is related to the company profile.

TECHNICAL INPUTS

- Daylight simulations
  - Tool: Velux Daylight Visualizer
- DGNB screening
  - Tool: DGNB Office buildings 2014 TLP score board

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops are mapped and illustrated in Figure 48. Here the dark blue arrow illustrates in which design phase the project is at the time of the case study at JJW. The dark blue box contains the design decision loops and the orange dot indicate the phase where there was interaction with the PhD researcher and the technical inputs.

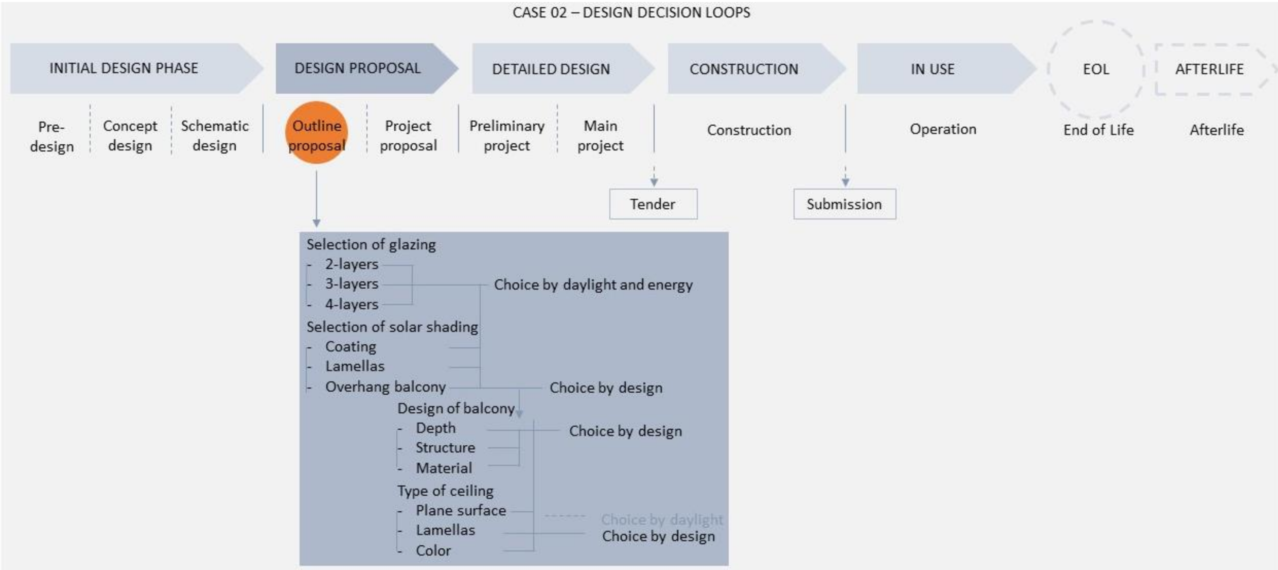


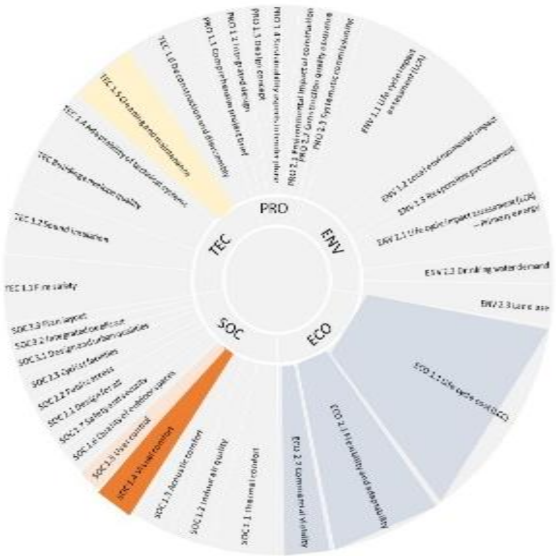
Figure 48 - Case 02 design decision loops, the dark blue arrow illustrates the design phase of which the project is at the time for case study at JJW, the dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

MAPPING IED

XXX	**High focus**
XX	Middle focus
X	General focus

IED-PROCESS	IED-CRITERIA	CASE 02
Reduce	Context	X
	Orientation/placement	X
	Geometry	X
	Daylight	XXX
	Facade design	XX
	Zone/ programming	X
	Structural concept	
	Energy concept	
	Use of roof area	X
Optimize	Windows	XX
	Lighting	X
	Ventilation	
	Cooling/heating system	
	Automation/ controlling	
Produce	Renewable energy	
	Passive cooling	

MAPPING DGNB



DGNB CRITERIA	CRITERIA DESCRIPTION	CASE 02	
		Directly affected	Indirectly affected
	Life cycle cost		
ECO 1.1	Life cycle cost (LCC)		X
	Economic guaranteed future		
ECO 2.1	Flexibility and adaptability		X
ECO 2.2	Robustness		
	Health, comfort and user satisfaction		
SOC 1.4	Visual Comfort	X	X
SOC 1.5	User Control		X
	Technical completion		
TEC 1.5	Maintenance and cleaning		X

The mapping of IED and DGNB are solely related to the JJW tasks in a holistic perspective, and not the entire project setup.

KNOWLEDGE BASED DESIGN

The final decisions based on the design loops for daylight studies are listed below:

- External solar shading rejected
  - Low lifetime in weather conditions near the sea, high maintenance
  - Shade for view from workplaces
- 3-layer glazing chosen
- Solar shading by overhang from balcony
- Design of the balcony based upon depth
- Investigating the effect of the light distribution when the ceiling surface consists of lamellas instead of a plane surface
  - Decision based on aesthetics and not simulations

KNOWLEDGE DEVELOPMENT

- New competence was developed within daylight consultancy for JJW
  - A simple report tool developed for visual communication to client. The tool includes plan drawings with daylight factor marked to illustrate the number of work places with optimal daylight conditions.

REFLECTIONS

The team composition limited the collaboration between JJW and the Danish engineering sub consultancy and led to some frustrations. The frustrations were due to missing direct communication with the engineers to make them see the holistic perspective of the window design. Many considerations related to the design of shading, and selection of glazing impact the indoor thermal comfort and energy performance. This was taken into consideration by the architects but could have been better included if there had been closer collaboration between the sub-consultants.

3.2.2 CASE 03

This case study was a part of the pilot phase for DGNB Existing office buildings. Here JJW's own office building, known as the 'JJW Workshop', was used as a test-bed and laboratory to gain more knowledge about the topics related to DGNB certification.

PROJECT INFORMATION

- Pilot project for DGNB Existing office buildings, aiming at a Gold certification.
  - The JJW Workshop was used as a testbed

DESIGN TEAM

The design team was mainly in-house, however external specialists were used to test 'SOC1.2 Indoor air quality'.

Figure 49 - Case 03 design team setup.

From JJW:

- Architect 1: Sustainability expert, DGNB auditor
- Intern: BEng Architectural Engineering in Energy Design
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

- DGNB Certification of Existing office buildings pilot phase 2016.

TECHNICAL INPUTS

- Daylight simulations
  - Tool: Velux Daylight Visualizer
- DGNB Certification
  - Tool: DGNB Existing Office buildings pilot phase 2016, TLP score board
  - LCC, LCA, Bio factor, IC-meter, MTU internal questionnaire.

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops were mapped as illustrated in Figure 50. Here the dark blue arrow illustrates in which design phase the project was at the time of the case study at JJW. The dark blue box contains the design decision loops and the orange dot indicate the phase where there was interaction with the PhD researcher and the technical inputs.

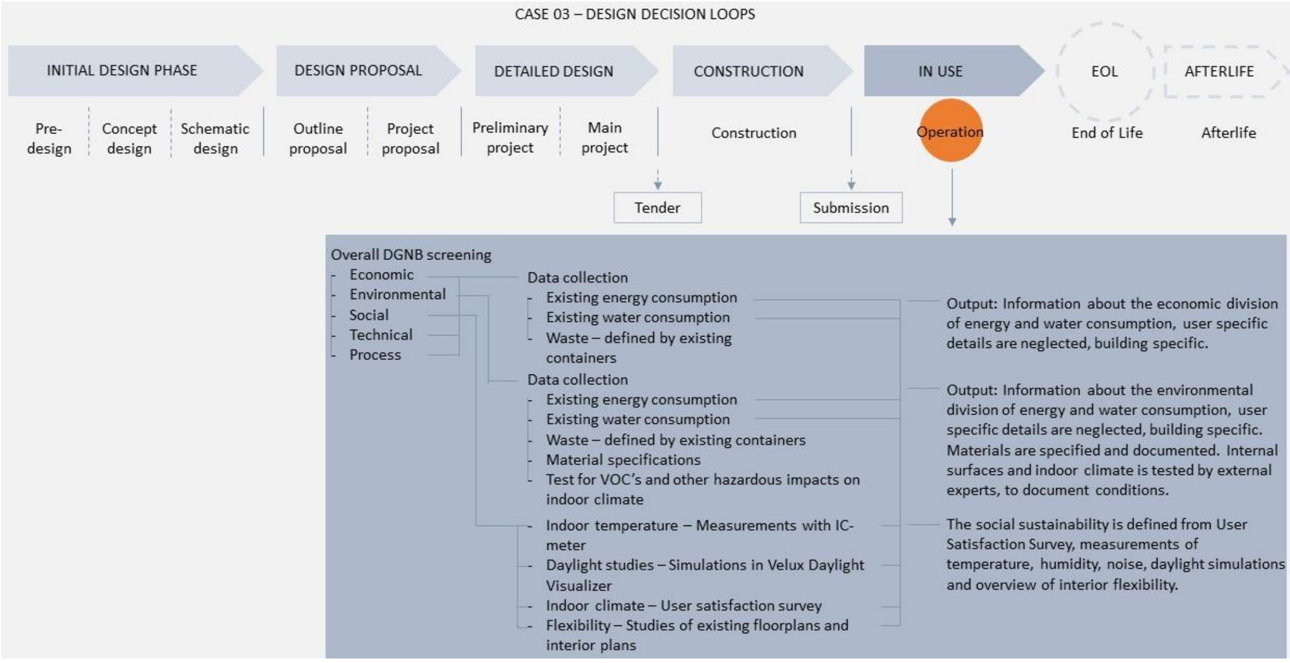


Figure 50 - Case 03 design decision loops, the dark blue arrow illustrates the design phase of the project at the time of the case study at JJW, the dark blue box contains the design decision loops and the orange dot indicate the phase where interaction with the PhD researcher and the technical inputs occurred.

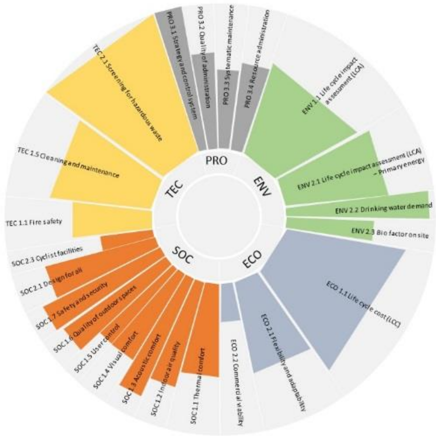
MAPPING IED

XXX	**High focus**
XX	Middle focus
X	General focus

IED-PROCESS	IED-CRITERIA	CASE 03
Reduce	Context	X
	Orientation/placement	XX
	Geometry	X
	Daylight	XXX
	Facade design	XXX
	Zone/ programming	XXX
	Structural concept	XX
	Energy concept	XX
	Use of roof area	XXX
Optimize	Windows	X
	Lighting	X
	Ventilation	X
	Cooling/heating system	
	Automation/ controlling	
Produce	Renewable energy	
	Passive heating/cooling	XXX

The mapping of IED and DGNB in the JJW tasks were from a holistic perspective. The DGNB was mapped according to the final total point score. The total points are thus shown instead of just a X.

MAPPING DGNB



DGNB CRITERIA	CRITERIA DESCRIPTION	CASE 03 TLP (criteria)
	Global and local environment	
ENV 1.1	Life Cycle Impact Assessment (LCA) - Environmental impacts	64,43
	Resources and waste	
ENV 2.1	Life Cycle Impact Assessment - Primary Energy (LCA)	69,58
ENV 2.2	Drinking Water Demand and Waste Water Volume	97
ENV 2.3	Bio factor on site	54
	Total life cycle costs	
ECO 1.1	Life Cycle Cost (LCC)	84,4
	Economic guaranteed future	
ECO 2.1	Flexibility and adaptability	62,5
ECO 3.1	Architectural value SAVE	35
	Health, comfort and user satisfaction	
SOC 1.1	Thermal Comfort	64,5
SOC 1.2	Indoor Air Quality	75
SOC 1.3	Acoustic Comfort	87
SOC 1.4	Visual Comfort	62
SOC 1.5	User Control	63
SOC 1.6	Quality of outdoor spaces	86
SOC 1.7	Safety and Security	90
	Functionality	
SOC 2.1	Design for All / Accessibility	76
SOC 2.3	Cyclist Facilities	35
	Technical completion	
TEC 1.1	Fire Safety	58
TEC 1.5	Cleaning and Maintenance	77,5
TEC 2.1	Screening for hazardous materials	100
	Planning process	
PRO 3.1	Strategy and control system	100
PRO 3.2	Quality of administration	67,5
PRO 3.3	Systematic maintenance	51
PRO 3.4	Resource administration	60

KNOWLEDGE-BASED DESIGN

- Value based design at JJW – office profile
    - Office work environment and social interaction in common areas
    - North-facing window façade to optimise good daylight conditions and avoid overheating.
    - Selection of materials – Robust materials, natural materials, limited surface treatments
    - Natural ventilation

KNOWLEDGE DEVELOPMENT

- Certification process for DGNB Existing office buildings in house
- Data collection from questionnaires
- Thermal indoor climate, data collection IC-meter
- Facility management report for further use in practice

REFLECTIONS

- Previously JJW had used the office as a laboratory to investigate acoustics in an open office landscape. With this project they continued the learning process by using the ‘JJW Workshop’ as a laboratory.
- Increased knowledge about the use phase, which normally takes place after the architects have left the project.
- The MTU (employee satisfaction survey) was used as a tool to gain knowledge about the indoor thermal comfort and work environment. It has some limitations regarding the thermal indoor comfort studies, as anonymization means that place specifications are missing.

3.2.3 CASE 05

This project was a major refurbishment of five PCB-contaminated high-rise buildings south of Copenhagen. JJW focused on creating healthy homes as their competition strategy and won the project. However, the process changed rapidly to a focus to economy, when the full extent of the costs related to the PCB remediation became clear.

PROJECT INFORMATION

- The main focus for the refurbishment was a social development strategy called 'Green-City'.
  - Aim to lift the social problems by refurbishing the entire area. The five buildings in this case study represented the first part of this development process.
- Refurbishment of five PCB-affected residential buildings
  - Decide the most suitable remediation strategies
  - Determine the economic cost of the remediation process

DESIGN TEAM

The design team differed from that of other JJW projects by having specialists in PCB as an integrated part of the team, together with architects and engineers.

Figure 51 - Case 05 design team setup.

From JJW:

- Architect 1: Project leader, sustainability expert, LEED consultant, knowledge about waste disposal, design for disassembly
- Architect 2: Sustainability expert, DGNB auditor
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

- In the initial design phase, focus upon healthy homes
  - To safeguard residents after refurbishment despite PCB being present in the past.
- LCC calculations
  - Determine the economic cost of the project in which remediation that removes PCB is the uncertain factor.

TECHNICAL INPUTS

- LCC calculations for different remediation strategies
- LCA for different remediation strategies

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops were mapped and illustrated in Figure 52. Here the dark blue arrow illustrates the design phase of the project at the time of the case study at JJW. The dark blue box contains the design decision loops and the orange dot indicates where interaction with the PhD researcher and the technical inputs took place.

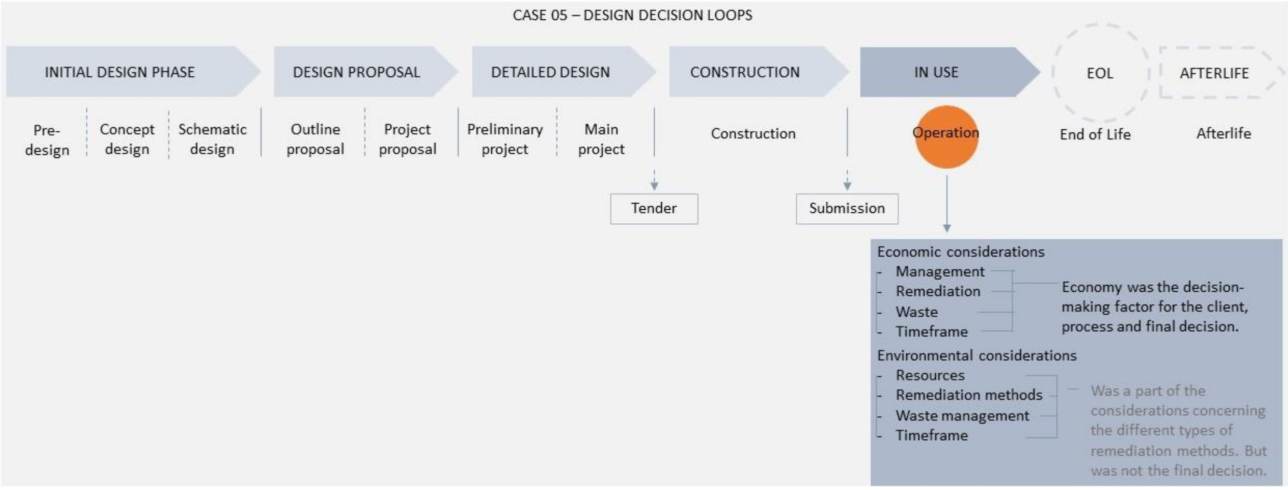


Figure 52 - Case 05 design decision loops, the dark blue arrow illustrates the design phase of the project at the time of the case study at JJW, the dark blue box contains the design decision loops and the orange dot indicate where interaction with the PhD researcher and the technical inputs took place.

MAPPING IED

No IED parameters available in this project.

MAPPING DGNB

DGNB CRITERIA	CRITERIA DESCRIPTION	CASE 05 Directly affected	Indirectly affected
	Global and local environment		
ENV 1.1	Life Cycle Impact Assessment (LCA) - Environmental impacts	X	
	Environment Impact		
ENV 1.2	Local Environment Impact - High-risk materials and substances for environment and health	X	
	Resources and waste		
ENV 2.1	Life Cycle Impact Assessment - Primary Energy (LCA)	X	
	Total life cycle costs		
ECO 1.1	Life Cycle Cost (LCC)	X	
	Health, comfort and user satisfaction		
SOC 1.2	Indoor Air Quality	X	

KNOWLEDGE BASED DESIGN

- Suggest two remediation techniques based on known results
    - Remove PCB to the minimum level stipulated in the requirements
- LCC calculations support the suggested remediation

KNOWLEDGE DEVELOPMENT

- A large environmental impact of one small building material
- The economic consequences of removing the PCB

- How it impacts social acceptance and use

REFLECTIONS

This project shows how great an impact one hazardous material like PCB, present in such a small building part as a join, can have on adjacent building materials and thereby have enormous consequences'.

- Social – unhealthy indoor climate affected by PCB in the air.
    - Residents are subject to an increased risk of life-threatening diseases such as cancer.
    - Residents who have lived there for decades would have to move as part of the refurbishment strategy.
    - Despite the remediation, some PCB would be left in the buildings, although it would be within the permitted limits, and this might cause some people to want to avoid moving back.
- Economical – the available remediation techniques mean that the refurbishment is expensive.
    - The workers would be required to use safety gear
    - The PCB-contaminated material that is removed would have to be treated as hazardous waste
    - Since the costs of the refurbishment of PCB-affected buildings are very high, who will finance it and how.
- Environmental – there are very low limits for the permitted content of PCB in the air in buildings.
    - The Danish threshold is 300 ng PCB/m3 in the indoor air, which is much lower than in Sweden, our neighbouring country (Ohms et al., 2018). This calls in question the value of the threshold.
    - Two student projects, both supervised by the PhD researcher, did thorough LCA studies based on this case project. One of the projects resulted in a journal paper, which determined the environmental impacts of the refurbishment (Ohms et al., 2018). The second study project demonstrated that demolishing the buildings would have a lower environmental impact, based on the LCA (Wraa-Hansen, 2018).

The complexity of building components has increased and more new materials are being introduced. It is worth considering what the new building materials used today might lead to in the future, particularly if hazardous materials are present in any building component.

3.2.4 CASE 11

This project was a smaller for the refurbishment of three existing buildings. The main focus was to raise the quality of the building and change the plan layout to fit the needs of the client.

PROJECT INFORMATION

- Refurbishment of two buildings - adapted to new use
  - Offices
  - Lecture rooms
  - Meeting rooms
  - Safety for employees and users
- New windows
  - Poor daylight in existing buildings
  - Many are blemished and would have to be changed anyway
- Polluted street outside, requiring different ventilation

DESIGN TEAM

The design team consisted of the architects from JJW, engineers and a developer. The architects had ongoing contact with the client and so could specify their needs and expectations.

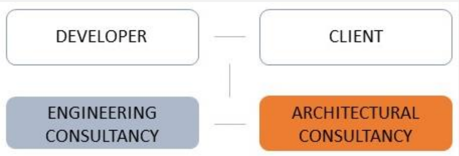


Figure 53 - Case 11 design team setup.

From JJW:

- Architect 1: Project leader, interior designer
- Architect 2: Sustainability expert, DGNB auditor
- Landscape architect: Education in accessibility
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

- Visual comfort – daylight conditions
- Safety for the users – employees and visitors
- Energy performance
- Good indoor thermal comfort

TECHNICAL INPUTS

- Daylight simulations
  - Using Velux Daylight Visualizer
- Energy performance, conducted by the engineers
  - Using Be15

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops were mapped and they are illustrated in Figure 54. Here the dark blue arrow illustrates the design phase of the project at the time of the case study at JJW. The dark blue box contains the design decision loops and the orange dot indicates where interaction with the PhD researcher and the technical inputs took place.

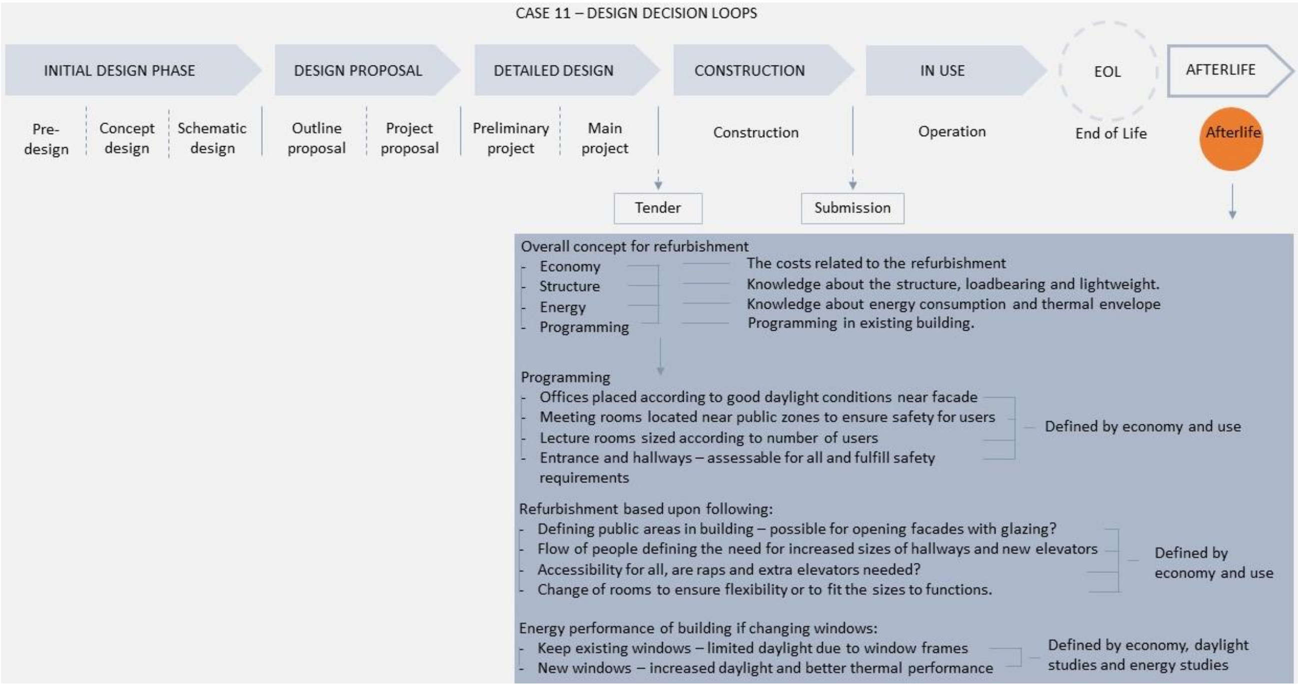


Figure 54 - Case 11 design decision loops, the dark blue arrow illustrates the design phase of the project at the time of the case study at JJW, the dark blue box contains the design decision loops and the orange dot indicates where interaction with the PhD researcher and the technical input took place.

MAPPING IED

XXX	**High focus**
XX	Middle focus
X	General focus

IED-PROCESS	IED-CRITERIA	CASE 11
Reduce	Context	X
	Orientation/placement	
	Geometry	
	Daylight	XXX
	Facade design	
	Zone/ programming	XX
	Structural concept	
	Energy concept	XXX
	Use of roof area	
Optimize	Windows	XX
	Lighting	X
	Ventilation	XXX
	Cooling/heating system	
	Automation/ controlling	
Produce	Renewable energy	
	Passive cooling	

MAPPING DGNB

DGNB CRITERIA	CRITERIA DESCRIPTION	CASE 11 Directly affected	Indirectly affected
	Global and local environment		
ENV 1.1	Life Cycle Impact Assessment (LCA) - Environmental impacts		X
	Environment Impact		
ENV 1.2	Local Environment Impact – High-risk materials and substances for environment and health		X
ENV 1.3	Responsible Procurement - certified timber and natural stone		X
	Resources and waste		
ENV 2.1	Life Cycle Impact Assessment - Primary Energy (LCA)	X	
	Total life cycle costs		
ECO 1.1	Life Cycle Cost (LCC)		X
	Economic guaranteed future		
ECO 2.1	Flexibility and adaptability		X
ECO 2.2	Robustness		X
	Health, comfort and user satisfaction		
SOC 1.1	Thermal Comfort	X	
SOC 1.2	Indoor Air Quality	X	
SOC 1.3	Acoustic Comfort	X	
SOC 1.4	Visual Comfort	X	
SOC 1.6	Quality of outdoor spaces	X	
SOC 1.7	Safety and Security		X
	Functionality		
SOC 2.1	Design for All / Accessibility	X	
SOC 2.2	Public Access	X	
SOC 2.3	Cyclist Facilities		X
	Aesthetics		
SOC 3.1	Design and Urban Quality		X
SOC 3.3	Plan layout and disposal		X
	Technical completion		
TEC 1.2	Sound Insulation		X
	Planning process		
PRO 1.2	Integrated Design		X

KNOWLEDGE BASED DESIGN

- Change windows in order to
  - Improve daylight conditions
  - Improve U-value
  - Limit noise from street

REFLECTIONS

- The builidngs in this case were not in very good condition or aesthetically pleasing. However, it is important to realise that existing buildings still have a quality appreciated by many people.
  - This project is relatively simple in regards of refurbishment.
  - The buildings are ready for an afterlife and a new function.
  - Important to realise that not all client either have the money or interest in demolishing and building new instead of refurbishing.

3.2.5 CASE 12

This project is divided into three parts. The first part consists of the process regarding the evaluation of existing buildings, and the decision of whether to refurbish them or demolish them in favour of a new building. The two following parts is based upon the decision of building new.

PROJECT INFORMATION

Part 1:

- Evaluate existing buildings and decide whether to refurbish or demolish and build new.
    - Existing buildings are affected by mould and have been left empty for some years.

Part 2 and 3:

- New building for child day-care and a school.

DESIGN TEAM

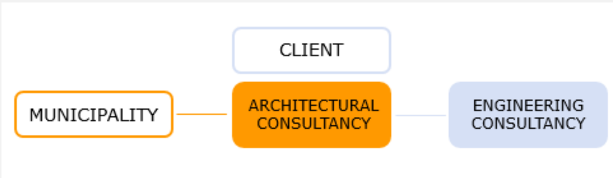


Figure 55 - Case 12 design team setup.

From JJW:

- Architect 1: Project leader, had taken sustainability courses.
- Landscape architect: Education in accessibility
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

Part 1:

- LCC to decide on either refurbishment of existing buildings or demolition and replacement.
    - The LCC was supported by the MBA v. 2016.
    - New building was suggested and decided

Part 2:

- Geometry, location on site and orientation
- Energy concept
    - Natural ventilation
    - Rejected by the engineers

Part 3:

- Main building structure, CLT was suggested
    - Other material selected

TECHNICAL INPUTS

Part 1:

- LCC calculations
    - Using LCCByg v. 1.6.0
- Sustainability considerations
    - Using Copenhagen Municipality MBA v. 2016 tool (Københavns Kommune, 2016)

Part 2:

- Sustainability screening
    - Using One Page Strategy at the beginning of the phase
- Daylight simulations
    - Using Velux Daylight Visualizer

Part 3:

- Material studies of CLT (Cross-Laminated Timber) vs. other materials
  - By literature study
  - Using LCAByg for simple analysis
- Daylight simulations
  - Using Velux Daylight Visualizer

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops were mapped, and they are illustrated in Figure 56. Here the dark blue arrow illustrates the design phase of the project at the time of the case study at JJW. The dark blue box contains the design decision loops and the orange dot indicates where interaction with the PhD researcher and the technical input took place.

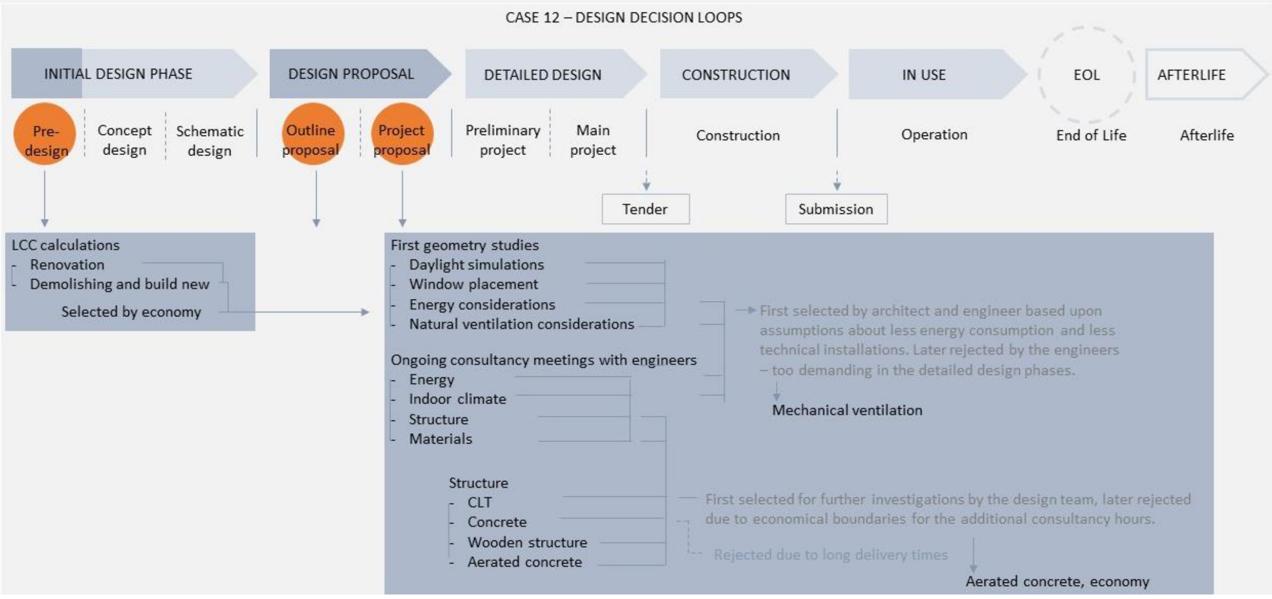


Figure 56 - Case 12 design decision loops, the dark blue arrows illustrate the design phases of the project at the time for case study at JJW, the dark blue boxes contain the design decision loops and the orange dots indicate where interaction with the PhD researcher and the technical inputs took place.

MAPPING IED

XXX	**High focus**
XX	Middle focus
X	General focus

IED-PROCESS	IED-CRITERIA	CASE 12 PART 1	CASE 12 PART 2	CASE 12 PART 3
Reduce	Context	XXX	XXX	XXX
	Orientation/placement	XXX	XXX	XXX
	Geometry		X	X
	Daylight		XXX	XXX
	Facade design		XX	XX
	Zone/ programming	XX	XXX	XXX
	Structural concept	XX	XXX	XXX
	Energy concept	X	XXX	XXX
	Use of roof area		XXX	XXX
Optimize	Windows			
	Lighting			
	Ventilation		XXX	XXX
	Cooling/heating system			
	Automation/ controlling			
Produce	Renewable energy			
	Passive cooling		XX	XX

MAPPING DGNB

DGNB CRITERIA	CRITERIA DESCRIPTION	CASE 12 Directly affected	Indirectly affected
	Global and local environment		
ENV 1.1	Life Cycle Impact Assessment (LCA) - Environmental impacts		X
	Environment Impact		
ENV 1.2	Local Environment Impact - High-risk materials and substances for environment and health	X	
	Resources and waste		
ENV 2.1	Life Cycle Impact Assessment - Primary Energy (LCA)		X
	Total life cycle costs		
ECO 1.1	Life Cycle Cost (LCC)	X	
	Economic guaranteed future		
ECO 2.1	Flexibility and adaptability	X	
ECO 2.2	Robustness	X	
	Health, comfort and user satisfaction		
SOC 1.1	Thermal Comfort	X	
SOC 1.2	Indoor Air Quality	X	
SOC 1.3	Acoustic Comfort	X	
SOC 1.4	Visual Comfort	X	
SOC 1.6	Quality of outdoor spaces	X	
	Functionality		
SOC 2.1	Design for All / Accessibility	X	
SOC 2.2	Public Access		X
	Aesthetics		
SOC 3.1	Design and Urban Quality		X
SOC 3.3	Plan layout and disposal		X
	Technical completion		
TEC 1.1	Fire Safety	X	
TEC 1.2	Sound Insulation		X
TEC 1.5	Cleaning and Maintenance	X	
	Planning process		
PRO 1.2	Integrated Design	X	
PRO 1.3	Design Concept	X	

KNOWLEDGE BASED DESIGN

- LCC defines the project task from the initial phase
  - Supported by MBA sustainability tool
  - Geometry is supported by daylight studies

REFLECTIONS

- This project emphasises the importance of LCC in the initial design phases.
  - It also shows how it can influence the entire project and design process.
  - LCCByg is a simple tool to support design suggestions and sustainability considerations.
- Implementing new materials is a process initiated by the architectural office
  - The investigations of CLT can be used in other projects in the future, now that the economic impacts of the process are known.

3.2.6 CASE 15

This project was a smaller refurbishment project of some row houses with some restrictions due to the value of their cultural heritage.

PROJECT INFORMATION

- Small scale refurbishment of residential row houses

DESIGN TEAM

The design team was a classic combination of architects and engineers collaborating with the municipality and the client.

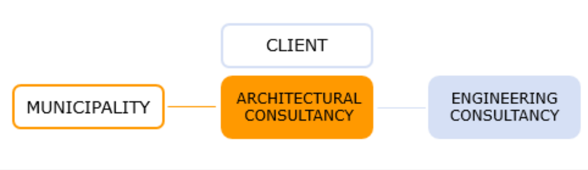


Figure 57 - Case 15 design team setup.

From JJW:

- Architect 1: Project leader, sustainability expert, LEED consultant, knowledge about waste disposal, design for disassembly
- Architect 2: Experience with refurbishment projects
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

- Deciding a type of window based on environmental, economic and technical considerations.

TECHNICAL INPUTS

- LCA for the three window types, using LCAByg
- LCC for the three window types, using LCCByg

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops were mapped and they are illustrated in Figure 58.

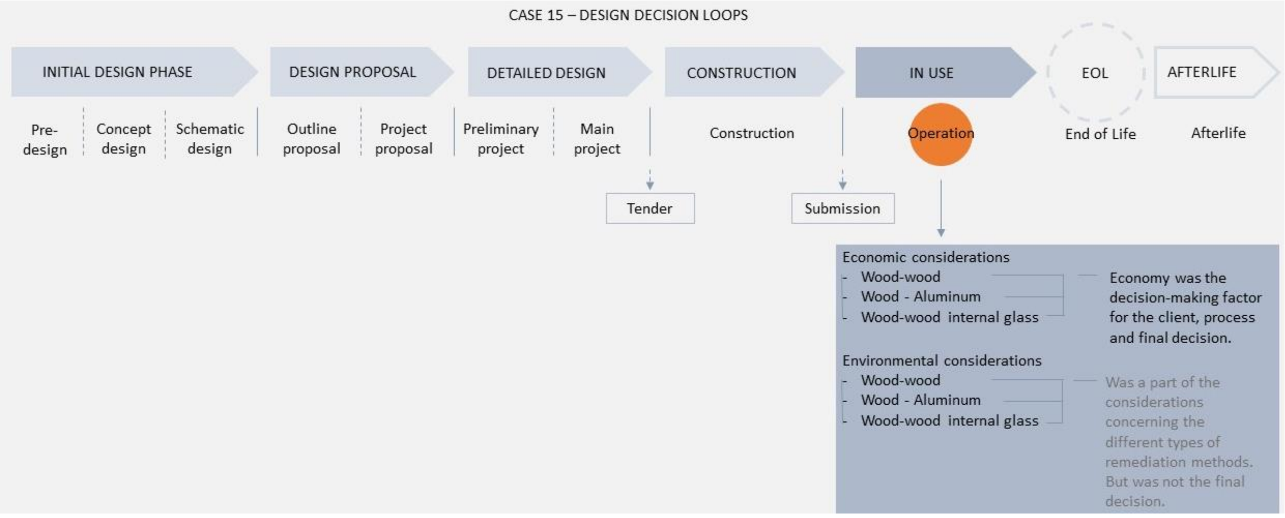


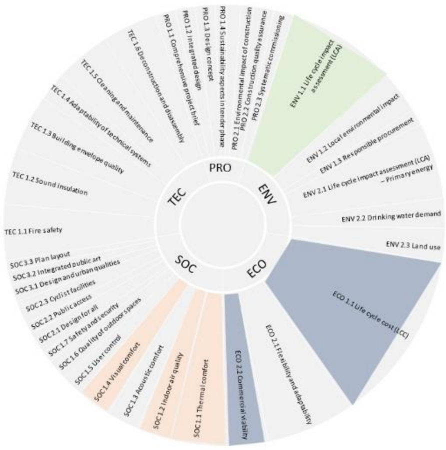
Figure 58 - Case 15 design decision loops, the dark blue arrow illustrates the design phase of the project at the time of the case study at JJW, the dark blue box contains the design decision loops and the orange dot indicates where interaction with the PhD researcher and the technical input took place.

MAPPING IED

XXX	**High focus**
XX	Middle focus
X	General focus

IED-PROCESS	IED-CRITERIA	CASE 15
Reduce	Context	
	Orientation/placement	
	Geometry	
	Daylight	X
	Facade design	X
	Zone/ programming	
	Structural concept	
	Energy concept	XX
	Use of roof area	
Optimize	Windows	XXX
	Lighting	
	Ventilation	
	Cooling/heating system	
	Automation/ controlling	
Produce	Renewable energy	
	Passive heating/cooling	

MAPPING DGNB



DGNB CRITERIA	CRITERIA DESCRIPTION	CASE 15 Directly affected	Indirectly affected
	Global and local environment		
ENV 1.1	Life Cycle Impact Assessment (LCA) - Environmental impacts		X
	Total life cycle costs		
ECO 1.1	Life Cycle Cost (LCC)	X	
	Economic guaranteed future		
ECO 2.2	Robustness	X	
	Health, comfort and user satisfaction		
SOC 1.1	Thermal Comfort		X
SOC 1.2	Indoor Air Quality		X
SOC 1.4	Visual Comfort		X

KNOWLEDGE BASED DESIGN

- LCC and LCA both support the architects' selection of window type.

REFLECTIONS

- LCC and LCA studies can very well complement each other in a process of decision-making.
    - This scale of study is easy to assess due to the limitations imposed on the three components.
    - LCAByg and LCCByg ensure a simple process and all involved in the process were able to discuss inputs and outputs.

3.2.7 CASE 17

This project was a partial refurbishment of two university buildings. The main functional units in the buildings were laboratories and offices.

PROJECT INFORMATION

- Partial refurbishment of two university buildings housing laboratories and offices of different sizes.

DESIGN TEAM

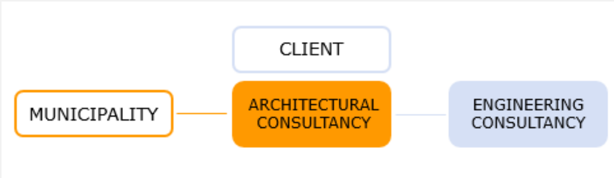


Figure 59 - Case 17 design team setup.

From JJW:

- Architect 1: Project leader, experience in refurbishment
- Architect 2: Experience with refurbishment projects
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

- The economically best solutions, in terms of LCC, when including the life cycle of the rooms and facilities.
- LCC was requested by the client when the design process had already reached the Outline proposal, which limited any possible impact.

TECHNICAL INPUTS

- LCC for different refurbishment scenarios, using LCCByg

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops were mapped, and they are illustrated in Figure 60. Here the dark blue arrow indicates the design phase of the project at the time of the case study at JJW. The dark blue box contains the design decision loops and the orange dot indicates where interaction with the PhD researcher and the technical inputs took place.

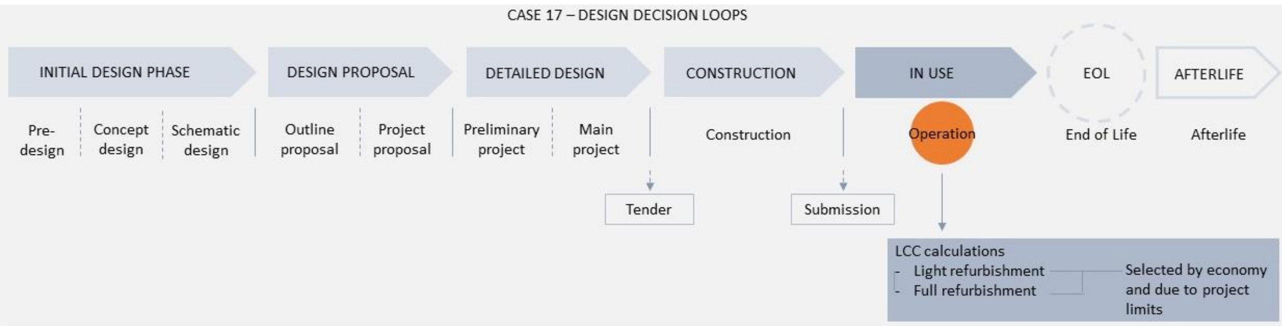


Figure 60 - Case 17 design decision loops, the dark blue arrow illustrates the design phase of the project at the time of the case study at JJW, the dark blue box contains the design decision loops and the orange dot indicates where interaction with the PhD researcher and the technical inputs took place.

MAPPING IED

XXX	**High focus**
XX	Middle focus
X	General focus

IED-PROCESS	IED-CRITERIA	CASE 17
Reduce	Context	
	Orientation/placement	
	Geometry	
	Daylight	
	Facade design	
	Zone/ programming	XX
	Structural concept	XXX
	Energy concept	XXX
	Use of roof area	XXX
Optimize	Windows	
	Lighting	
	Ventilation	XX
	Cooling/heating system	XX
	Automation/ controlling	
Produce	Renewable energy	
	Passive heating/cooling	

MAPPING DGNB

DGNB CRITERIA	CRITERIA DESCRIPTION	CASE 17 Directly affected	Indirectly affected
	Total life cycle costs		
ECO 1.1	Life Cycle Cost (LCC)	X	
	Economic guaranteed future		
ECO 2.1	Flexibility and adaptability	X	
	Aesthetics		
SOC 3.3	Plan layout		X
	Technical completion		
TEC 1.5	Cleaning and maintenance		X

KNOWLEDGEBASED DESIGN

- LCC calculations to evaluate the degree of refurbishment

REFLECTIONS

- Here, the LCC calculation would have been more useful in the earlier design phases.
    - With this timing, there was no possibility to alter the design.
    - Performing an LCC analysis at an earlier design phase might have resulted in a more long-lasting solution.

3.2.8 JJW design phases and sustainability topics

The elaboration of the case studies focused on the horizontal part of the matrix in Figure 46. In this sub-section the results in the matrix will be elaborated vertically across case studies.

As mentioned previously, the mapping of the cases included an overview of the design phases of which JJW was a part and those phases of the project that could be influenced by my technical inputs. In Figure 61, this is marked by a blue square. This part has the basis for mapping the projects in the practical context of the Danish Description of Service.

The mapping also described the sustainability focus that was decided for the specific case study, which is relevant to obtaining overview of the reference point for each case. This is illustrated by the green square in Figure 61. Finally, the red square in Figure 61 marks the level of sustainability reached in all the case studies, which can be used as indicator for applicability in practice and the inclusion of sustainability criteria.

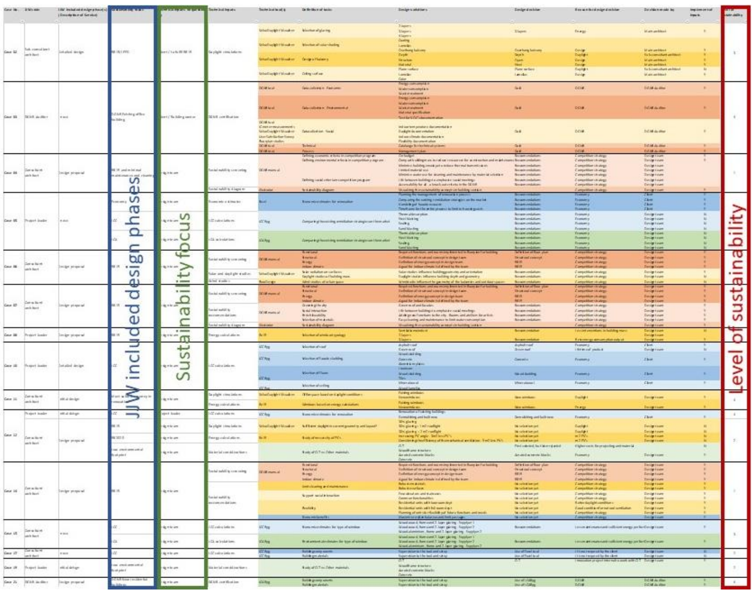


Figure 61 - Highlights of topics in the matrix of the mapping, based on case studies at JJW.

Focusing on the blue and green squares in Figure 61: the results are illustrated in relation to the Danish Description of Service and make it possible to see the relation between the 'Design phase' and the 'Sustainability focus'.

Figure 62 shows the Description of Service and each case number and the 'Sustainability focus' is listed underneath each design phase. A distinction has been made between 'Economy' and 'LCC', where 'Economy' designates an overall economic awareness and forecast using simple tools as Excel, whereas in 'LCC' a specific LCC calculation was performed, mostly using the Danish LCCByg calculation tool, as previously mentioned in '1.3.3 Environmental footprint'. In the definitions of 'Low environmental footprint', 'Maintenance and Cleaning' and 'LCA' were distinguished in terms of their detail level and the tools required: 'LCA' designated only the use of the LCAByg calculation tool, which was previously mentioned in 1.3.3 Environmental footprint, while the two other definitions were more selective in their methods and tool. 'BR15' was the current building regulation during the case studies and 'Building class 2020' was an elective and stricter building class that could be attained.

Figure 62 - Case studies and sustainability focus mapped according to the Danish Description of Service.

From Figure 62 it may be seen how the range of the design phases in the case studies conducted in the PhD research. Case 12 was followed through a longer period of time and so it is illustrated in three different design phases. There is a tendency that the cases in the 'Initial design' phase had their focus on the building regulations and not on specific sustainability criteria, and one case focused upon LCC. Most of these cases were new buildings, which explains the focus on BR15. For the cases in the 'Design proposal' and 'Detailed design' phases the focus varied. For the case studies in the later design phases 'In use' and 'Afterlife' LCC, LCA and economy in general were the main focus, and one case focused on DGNB. Most of these buildings were about to be refurbished, which explain the focus on economy and the environmental impact.

3.2.9 Level of sustainability reached

The results for 'Level of sustainability reached' from the red square in Figure 61 are derived from the scale seen in the matrix in Figure 63. The rating system was developed by the PhD researcher as a part of the mapping of case studies at JJW. When mapping all case studies, a rating scale was developed to score how the inputs from the technical investigations were received. The findings were rated on a 4-point scale:

1– Mentioned: Sustainability was mentioned by the design team but was not taken further in the process. This can occur as part of screening the project brief, when making a check-list of sustainability approaches.

2 – Investigated: Some sustainability topics were investigated by the PhD researcher and communicated to the design team but not taken further. "Investigated" covers the whole range from literature study or online search, to calculations or simulations for the specific topic.

The two last two scale values designate how sustainability input was taken a step further and the degree of its implementation.

3 – Partly implemented: The investigations conducted by the PhD researcher (or sustainability expert) were partly implemented into the design and taken further in the design process.

4 – Fully implemented: The investigations conducted by the PhD researcher (or sustainability expert) were fully implemented into the design by the design team.

Using this ranking, the cases and the 'Technical inputs (by the PhD researcher)' are listed in Figure 63:

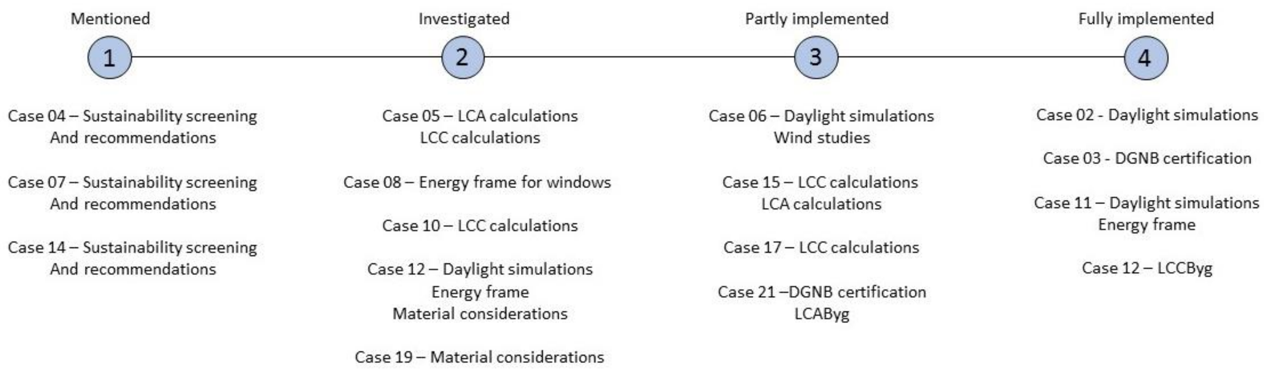


Figure 63 - Rating and sustainability level based upon the matrix, rating from: Mentioned, Investigated, Partly implemented, to Fully implement.

In Figure 63 some tendencies can be identified concerning the ‘Sustainability ranking’ and the types of ‘Technical inputs (inputs by the PhD researcher)’. In the case studies where sustainability is ‘Mentioned’, the inputs were all had the character of a sustainability screening and represented an overview of sustainability related to the specific case study. In two of the three cases (Case 04 and 07) the architectural competition was not won so the project was abandoned before there was any possibility of further development, and in Case 14, the focus was limited before submission to the competition. LCA tended to be ranked mainly as ‘Investigated’ and as ‘Partly implemented’, whereas LCC calculations and daylight simulations were scored from ‘Investigated’, to ‘Partly implemented’ and ‘Fully implemented’.

3.2.10 Sub-discussion

The case studies at JJW included a large variety of projects as discussed in this sub-section. The projects vary in terms of team composition, participation in design phases, sustainability focus, implementation of technical knowledge, etc. Some cases only used sustainability as a checklist and some cases used it throughout the design process.

The case studies exhibit a varied approach to sustainability in the design process in terms of how it was implemented and when.

For Cases 04, 07, 08, and 10 sustainability was used as a validator before submission of the competition. Here there was only limited interaction with sustainability experts and a limited degree of implementation of sustainability into the design.

For Cases 02, 03, 05, 06, 11, 12, and 14 a one-page-strategy was formulated in the initial design phases, to ensure a focus on the project framework and visions. Despite this, only Cases 11, 12, and 14 used the second version of the one-page-strategy in which sustainability was an implemented topic. Sustainability was only included in the tool and process for these three cases. Here the inclusion and use of the DGNB wheel ensured a focus on all sustainability parameters from the very beginning.

Finally, Cases 02, 03, 05, 06, 11, 12, 14, 15, 17, 19 and 21 all had specific sustainability criteria in focus all through the design phases. Digital engineering tools were used to provide the design process with simulations or calculations, to ensure that the design would be more knowledge-based.

The degree of implementation of sustainability is also illustrated in Figure 63. The figure shows a very varied degree of implementation at JJW, with cases that just mentioned sustainability and cases where it was fully implemented.

3.3 IED and DGNB in practice

Integrated Energy Design (IED) and DGNB were central elements in this PhD research from the very beginning and mixed methods were used to investigate the state-of-the-art of implementation in practice and its use in the design process. The first results presented are therefore based upon the initial mapping of IED and DGNB, followed by the mapping of existing projects derived the year before the PhD started and finally the mapping of the active case studies in practice.

3.3.1 Relation between IED and DGNB certification system

A mapping was conducted of the IED parameters and the DGNB (Office 2014) criteria to identify the degree to which direct and indirect indicators were fulfilled in the DGNB system when using the IED method. Here the focus was divided into 'Primary Energy' and 'Environmental Impacts' as seen in Table 19 (Landgren & Jensen, 2017), APPENDIX B.

Table 19 - Mapping of DGNB criteria related to the IED method (Landgren & Jensen, 2017).

IED-Process	IED-Parameters	Primary energy		Environmental impacts	
		Direct DGNB criteria	Indicators fulfilled	Indirect DGNB criteria	Indicators fulfilled
Reduce	Context	SOC1.4	1+2	ECO1.1	
	Orientation/placement	ENV2.1	B6	ECO2.1	1
	Geometry			ENV1.1	A1+A2+A3+B4+B6
	Daylight			ENV1.2	
	Façade design			ENV1.3	
	Zone-programming			PRO1.3	
	Structural concept			SOC3.3	1.1+2.3+2.4
	Energy concept				
	Use of roof area				
Optimize	Windows	SOC1.1	1-8	ECO1.1	
	Lighting			ENV1.1	B4+B6+C3+C4+D
		SOC1.2	2		
	Ventilation	ENV2.1	B6	ECO2.2	
	Cooling-/heating/system			TEC1.6	
	Automation/controlling			PRO2.3	
Produce	Renewable energy	ENV2.1	B6	ECO1.1	
	Passive heating			ENV1.1	B6+C3+D

As a follow-up to the previous mapping, a diagram was prepared showing all DGNB related IED parameters with the degree shown using the weighted points given by the system for each indicator, see Figure 64 (Landgren & Jensen, 2017), APPENDIX B. The indicators are coloured in dashed colours to identify the indirectly affected indicators and full coloured to identify the directly affected indicators for each criterion.

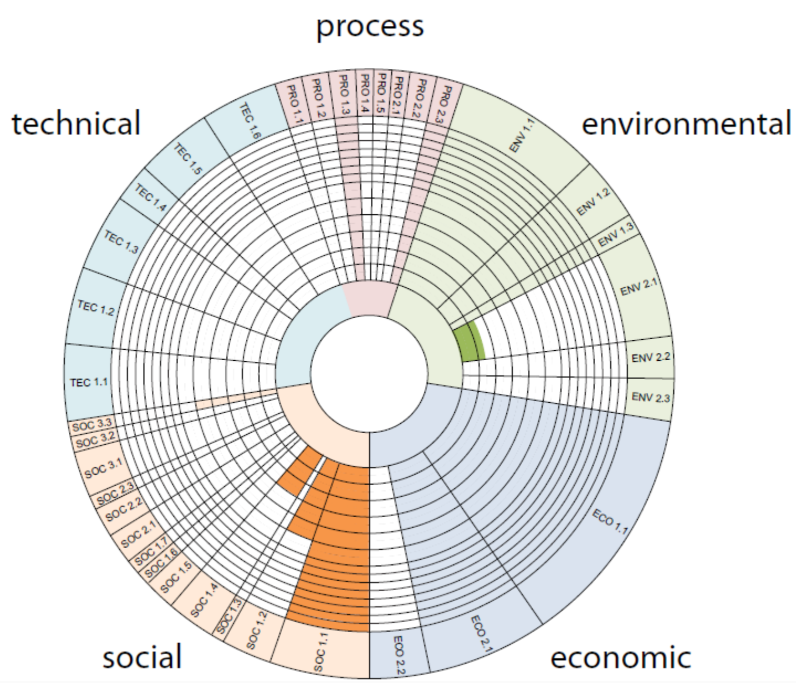


Figure 64 - DGNB wheel showing mapping of IED in relation to DGNB. Dashed colours = indirectly affected, full colours = directly affected (Landgren & Jensen, 2017)¸ APPENDIX B.

The results clearly indicate a limited direct fulfilment of DGNB when using the IED-method, however the indirect fulfilment is quite large and indicates considerable potential (Landgren & Jensen, 2017), APPENDIX B.

3.3.2 Level of IED and DGNB at JJW

The results from the mapping of existing projects at JJW from one year's production of projects before the start of the PhD study are given in this sub-section (Landgren & Jensen, 2017). Table 20 shows the results from the mapping of IED in all 10 case project folders that were available for study, however it does not include an explanation of to what extent the IED parameters were used. This eliminates the possibility of investigating the level of integrated process and the focus must therefore be on the energy design parameters.

Table 20 - Mapping IED in 10 case projects at JJW (Landgren & Jensen, 2017), APPENDIX B.

IED-Process	IED-parameters	C01	C02	C03	C04	C05	C06	C07	C08	C09	C10
Reduce	Context	X	X	X	X		X	X	X	X	X
	Orientation/ placement	X	X	X	X		X	X	X	X	X
	Geometry	X	X	X	X		X	X	X	X	X
	Daylight	X	X	X			X	X	X	X	X
	Façade design	X	X	X	X		X	X	X	X	X
	Zone-programming	X	X	X	X		X	X	X	X	X
	Structural concept	X			X	X	X	X	X		
	Energy concept	X	X	X	X	X	X	X	X	X	X
	Use of roof area	X	X	X	X			X		X	X
Optimize	Windows	X	X	X	X			X		X	X
	Lighting	X	X		X			X		X	X
	Ventilation	X	X	X			X		X	X	X
	Cooling/heating system		X	X		X	X	X	X	X	X
	Automation/ controlling		X						X		
Produce	Renewable energy	X	X	X				X	X	X	X
	Passive heating										

From Table 20 the projects seem to implement several IED parameters (Landgren & Jensen, 2017), APPENDIX B.
Secondly the percentage of the mentioned DGNB criteria in the 10 case study projects are illustrated in Figure 65. The diagram shows one case per circle from the middle. The coloured areas are therefore the numbers of DGNB criteria mentioned and not the degree. The differentiation of the sizes of each criteria is based on the percentage rating in the DGNB system as previous described in sub-section '1.3.6 DGNB'.

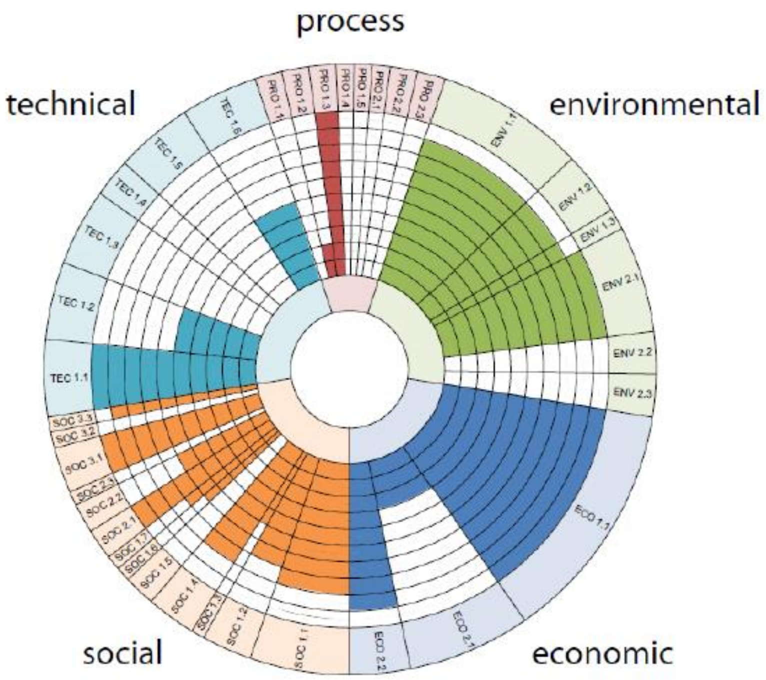


Figure 65 - A merged diagram of the mapping of DGNB in all cases (Landgren & Jensen, 2017), APPENDIX B.

The mapping of existing cases at JJW indicates that IED parameters and DGNB criteria were extensively used in their final submitted project folders. Taking this as the state-of-the-art for the implementation of IED and DGNB in practice at JJW, it was used as the basis for the further mapping of active participation in case studies in practice.

3.3.3 Active participation in Case studies at JJW

This sub-section is based on the mapping of case studies at JJW in section '3.2 Overall mapping of case studies at JJW'. Focusing on the use of the IED-method parameters, the DGNB criteria in two case studies are taken as representative in this sub-section.

CASE 02

This case study as seen in sub-section '3.2.1 CASE 02' was highly influenced by the IED-method. It focused on energy performance as defined in the Danish BR15 and on the improvement of daylight conditions to optimise the number of workplaces. Even though most of the geometry and plan layout of the building was specified before JJW was involved, some parameters were still unspecified, namely glazing type, solar shading, ceiling surface, and structure of the balcony. These parameters all have impacts on the daylight, view of the sea and thermal comfort in the adjacent office rooms. These parameters guided the iterations of daylight studies conducted in the course of the design process and were used by the main architect who made the final decisions.

This part fulfils the IED-method also in the integrated work process, having experts in daylight studies working closely together with a sustainability expert so that the correct approaches were used in the studies and in the analysis of the results, which were then communicated through visuals to the main architect and client.

In the initial phase of consultancy, a DGNB screening was conducted to compare the expected certification level with additional LEED certification. The results were presented to the main architect and client, who decided to use the LEED certification, which had to be conducted by the main engineering consultancy. This meant that only a limited number of DGNB criteria were considered in the rest of the process of this case study, and they mainly concerned daylight.

Despite the overall limited level of sustainability in the frame of IED and DGNB, this project demonstrated the influence and effects of daylight simulation tools as design input at JJW. More knowledge was gained about daylight conditions in the different scenarios. This experience might cause future projects to focus upon daylight from an earlier design phase, where the design is less fixed.

The final decisions based on the design loops from Figure 48 for the daylight studies are illustrated in Figure 66:

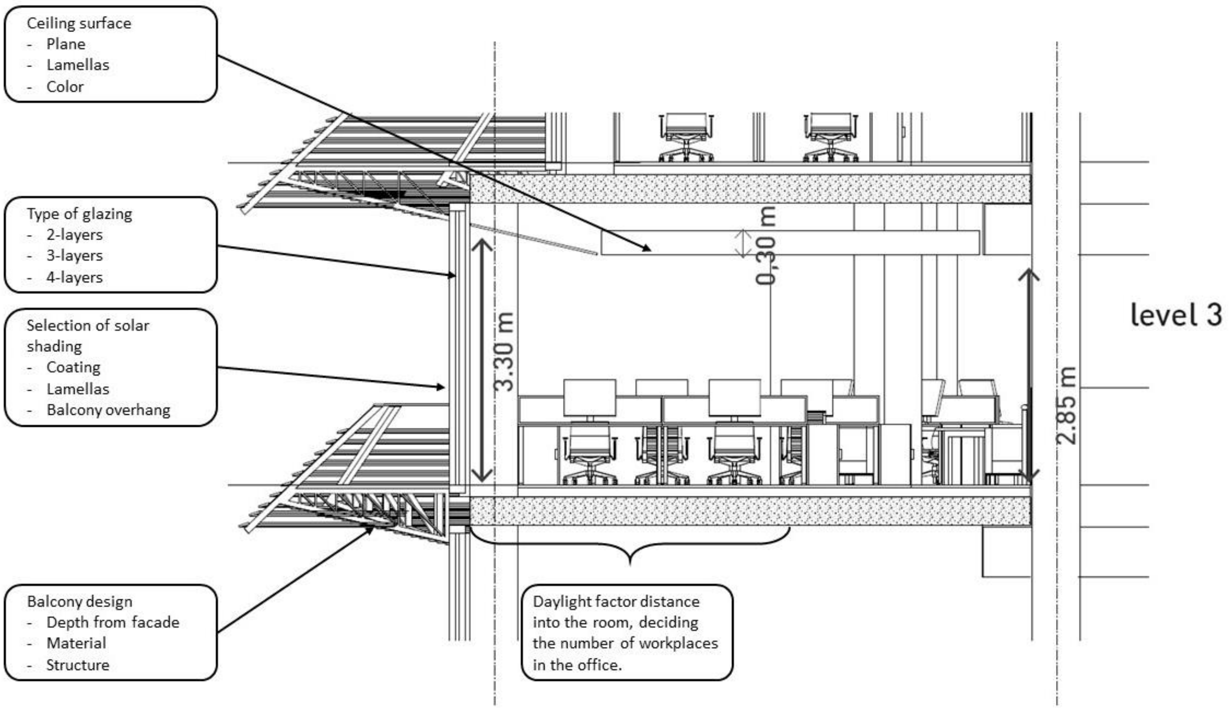


Figure 66 - Sustainability section for Case 02.

CASE 12

This case study, described in sub-section '3.2.5 CASE 12' was influenced by the holistic approach in the DGNB certification system at different stages throughout the design process. The case study was conducted in three parts along the design process: 'Part 1 – Initial design phase', 'Part 2 – Outline Proposal', and 'Part 3: Project proposal' in the 'Detailed design phase'.

'Part 1 – Initial design phase': LCC had a great impact at the start of the entire project, since the calculations showed least costs when demolishing the existing buildings and building a new building instead. These LCC calculations were then supported by the sustainability tool MBA from the Municipality of Copenhagen, where social and environmental aspects were also included. The decision by the client followed the recommendation from the design team, based on the results from these tools, to demolish the existing buildings and to build a new building instead.

'Part 2 – Outline Proposal', and 'Part 3: Project proposal' in the 'Detailed design phase': The IED-method was represented by a close collaboration between architect and engineers to ensure the geometry supported energy performance, daylight conditions and thermal indoor climate, by first attempting to use passive strategies, although optimisation eventually resulted in mechanical ventilation and improved U-values for the thermal envelope.

Figure 67 illustrates the sustainability considerations for Case 12, via a plan drawing for the 'Initial design' phases in Part 2. Here all the main topics presented in this sub-section were considered. Part 3 had the same topics but was more detailed in the selection of building components. The simple version was therefore selected to best illustrate how drawings can include technical knowledge.

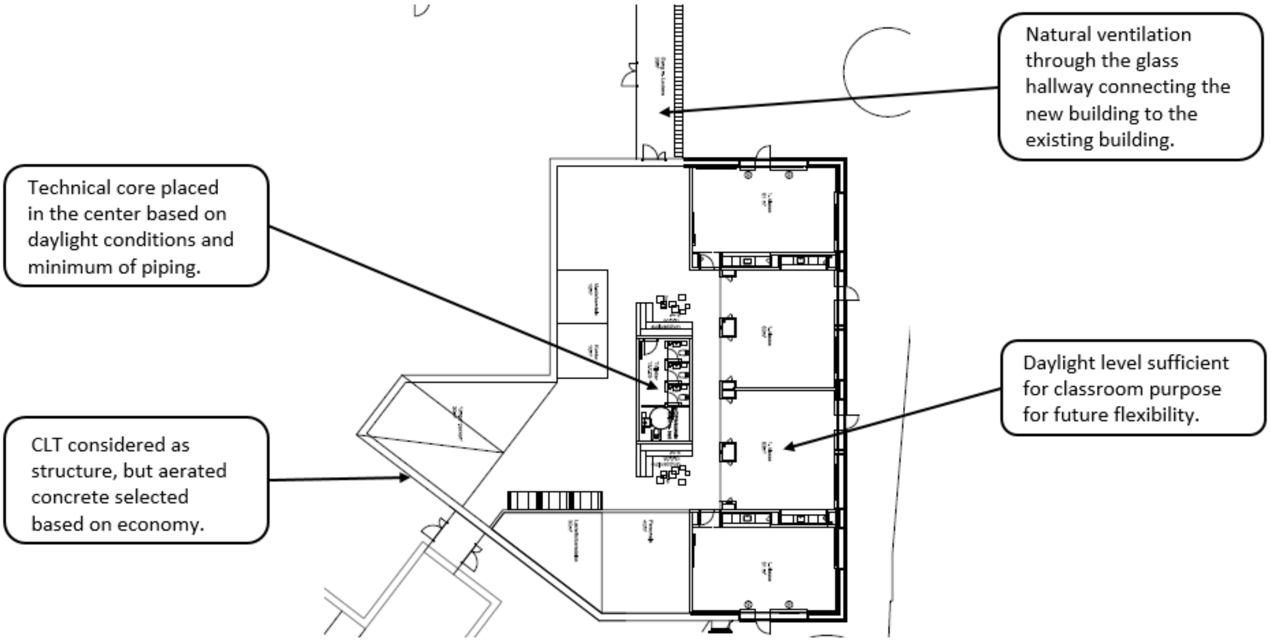


Figure 67 - Case study 12, sustainability illustration from plan drawing in Part 2.

3.3.4 Sub-discussion

This sub- section provides a summary of the focus on IED and DGNB.

The mapping showed the relation between IED and DGNB, where the IED parameters were fulfilled by following the DGNB criteria. However only a few DGNB criteria were fulfilled by using the IED-method, which suggested a new method for achieving sustainability, the goal of this PhD research.

The mapping of existing case projects at JJW shows extensive use of IED parameters even though the method was not used explicitly. This was probably due to the general development that had taken place in the building industry, which had started to place considerable focus on the same parameters that are included in the method: energy performance, daylight, thermal comfort, etc. The mapping of DGNB in the available case studies indicated a focus on various criteria, showing that they had a broader focus upon sustainability, than the parameters from the IED. This can be linked to the general focus upon DGNB in the office and to the holistic thinking promoted by DGNB. Case 02 and 12 illustrated how the IED-method can be used in practice and how it can be expanded by adding other sustainability topics to increase performance and support architecture at the same time.

3.4 LCA and LCC in practice

Energy consumption in buildings in operation has been the driving factor for building design projects – also due to increased regulations. Lately the focus has changed to consider the environmental footprint for the entire building life cycle, and total energy use has been reduced considerably by moving the focus for optimisation towards environmental impact and the embodied energy of the building mass.
LCA and LCC are rather new methods in the building industry and are used to define and calculate the environmental footprint and the overall economy of building projects. In the Danish building industry there is no industry-wide agreement to include LCC and LCA in the design process and the present mapping and research was intended to support such an agreement. LCA and LCC in design processes in practice as therefore a main research topic through this PhD study. The state-of-the-art for implementing LCA and LCC was investigated and used as a reference when investigating how is it implemented in design processes in practices, what tools are used, and what drives the use of the two design methods to implement LCA and LCC. This sub-section elaborates the results obtained from the mixed research methods, consisting of case studies, questionnaires and interviews as described in the 2.METHODS section.

3.4.1 LCA and LCC as design tools

The mixed methods of research included a mapping of the LCA and LCC as design driving tools in the framework of the Danish Description of Service, from which the diagram shown in Figure 68 was developed (Landgren, 2017), as seen in APPENDIX C. The diagram is a result of the interviews and case study research showing how an optimised design process might look, when including LCC and LCA as design tools. Active participation in case studies at JJW showed to what degree data are available in forms that can be used for LCC and LCA, which are also included in the diagram.

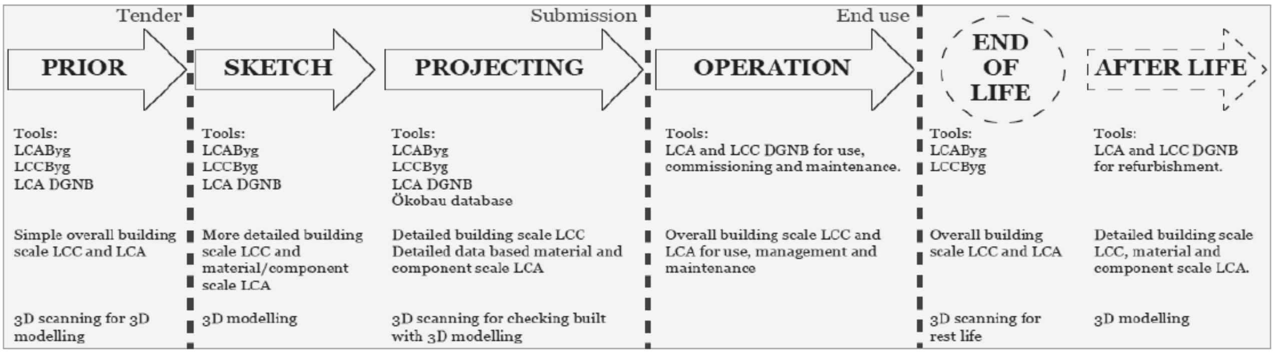


Figure 68 - The optimised design process including LCC and LCA, based upon mapping and interview study, in relation to the Danish Description of Services (Landgren, 2017), APPENDIX C.

As previously described in '2.2.2 Mapping of Integrated Energy Design and DGNB', the IED method focuses upon moving design decisions to the earlier design phases to ensure informed design on energy efficiency and indoor thermal comfort. The goal is to ensure good holistic design decisions and avoid last minute technical add-ons to the design. However, when implementing LCC and especially LCA, this is not by definition the same approach since the data level in the drawings or 3D modelling in the initial design phases is rather limited and since LCA can be rather time consuming and thereby not fit into the flow of the design process. This concern also emerged in the interviews with sustainability experts in the Danish building industry, and is illustrated by the following citation:

"It requires that the models are corrected and that the quantity extraction is thoroughly modified to ensure that it is ok for sharing. This is very time consuming and therefore also, a very costly affair to do in the initial design phases compared to the following design phases, where the LCA can seem relatively easy."

[Translated from interview A, 18th November 2016, APPENDIX Y]

As Figure 68 also illustrates, only simple calculations are possible in the early phase, so limited data are available. However, it is important to know the importance these technical inputs might have at the start of the project, here referring to Case 12 from prior sub-section '3.3.3 Active participation in Case studies at JJW', where the LCC had a great influence upon the decision to demolish the existing buildings in favour of a new building.

From the interview study a mapping of the use of various sustainability topic tools was conducted, as seen in Figure 69 (Landgren, 2017). The results show a limited use of LCC and especially LCA by the interviewee in the first round of interviews, which also corresponds to the questionnaire research as described in sub-section '3.1 Work Profiles at Architectural Offices'.

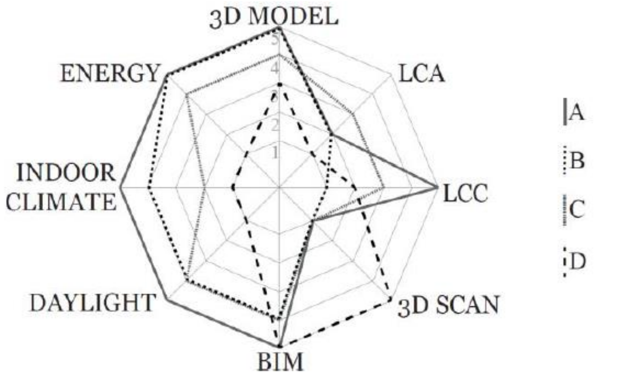


Figure 69 - Mapping of sustainability topics in spider web diagram, based upon interviews. A, B, C and D are the interviewee. Where 1 is limited use and 5 is highly used (Landgren, 2017) APPENDIX C.

LCA and LCC are highly connected, since the procurement of the materials has economic implications. The same relation holds for replacement of materials. Both the robustness of the materials and maintenance affect the life time of the materials and both have some economic consequences. The relation between LCA and LCC is strong, but when implementing it in a real life setting the economic implications are complex, so it is allocated into design phases or divided between design and construction, with one pile of money for construction and another pile of money for operation. The missing link between the two economic spheres can have crucial effects on the LCA and the LCC, which in practice often leads to short lasting solutions that benefit the economy of the construction. This issue restricts the possibility of applying sustainable design to the full life cycle.

A limited use of LCA is also indicated, since the main driver for LCA in practice is the DGNB certification system or if the client has specific requirements for this topic, as stated here:
"*LCA is mainly conducted when it is required by the client – often this is due to a DGNB certification.*"

[Translated from interview B, 22nd November 2016, APPENDIX Y]

DGNB also causes the design team to directly focus on the relation between the different criteria, and thereby not solely focus upon LCA or energy performance, as an interviewee states:

"The new part is that more and more clients request DGNB screenings, which require that these topics are taken into consideration, and it is not enough only to consider LCA, also LCC, daylight, and energy simulations. All these things have to be done for it all to make sense."

[Translated from interview A, 18th November 2016, APPENDIX Y]

The interviewees revealed that there was a tendency to work with LCA at various levels; building level for DGNB certifications and at material level for internal use to support knowledge-based design decisions, as described in following citation:
"I work with LCA in two ways: One way, is for our [architectural office] own knowledge, where it is much more useful and we look at m^2 emissions within the same product category to be able to compare what is the best product. This is done to be able to make knowledge informed design decisions concerning choice of materials… The second way I work with LCA is through DGNB … where I work with LCA of the full scale building."

[Translated from interview C, 18th November 2016, APPENDIX Y

DGNB is as described by the interviewee as one driver for LCA in design processes, however there are also some critiques of working with LCA related to the DGNB, so only limited definitions on how to do it are available, and large variations in the level of detail of the LCA occur. Interviewee C sees this as an important and crucial problem for the use of LCA in practice, when conducting LCA's:
"I think DGNB is described with limited information for the projecting people, especially if they are not familiar with LCA or DGNB."

[Translated from interview C, 18th November 2016, APPENDIX Y]

Also, as she describes, this lack of definition for LCA which results in varied outputs and less correct data can result in better outputs. More details lead to more environmental emissions and thereby worse results:
" Ironically, as more time spend [upon the LCA] as worse the numbers gets … I'm very interested in it [LCA] and I want to do it correctly, but it is not defined what is correct and what is not."

[Translated from interview C, 18th November 2016, APPENDIX Y]

Martha's comments are supported by interview A, who states, that:*" We are in principle happy about the DGNB system, because into a certain degree this makes it comparable. Because there are a set of rules and a system boundary defined… there will always be differences, due to different datasets … use of different EDPs which is more or less precise… because here it's a benefit to calculate less precise since it results in better results… Also, life times of materials can vary a lot depending on the reference, where the official SBi list for life times has relative long life times than I think is correct. And this problem I don't think will be solved soon with the guide."*

[Translated from interview A, 18th November 2016, APPENDIX Y]

According to interviewee C, the most optimal way of working with LCA is in material scale to make informed design decisions: The most optimal use of LCA *"is as m2 LCA analysis, so when having a façade and searching a good story, you can argue for the use of façade cladding X and not Y, because X has a good CO^2 profile, which is a parameter the client has begun to understand".*

[Translated from interview C, 18th November 2016, APPENDIX Y]

There are various tools available on the market for conducting LCA analysis at different levels of detail, however to some extend the simpler LCA tools are sufficient for use in design phases (Ohms et al., 2018). The complexity of LCA and the tools makes it difficult to implement in practice, thus interviewee B states that with the right simple tools for LCA, all would be able to work with it without having a DGNB education or specialist knowledge:

”It does not necessary require a DGNB education. It depends on having some [LCA] tools which are finalized to some extent, so only amounts have to be added, ensuring right material properties and database are linked and then it [LCA] should be easy to handle.”

[Translated from interview B, 22nd November 2016, APPENDIX Y]

As Jørn describes, the implementation in practice requires operational tools, which might not need any further education or knowledge, however interviewee A focuses more on the quality of the LCA and is worried that the limited knowledge of the architects and engineers in practice results in an incorrect analysis of the LCA results and thereby wrong design decisions from an environmental point of view.: *“I think it might be necessary to educate more people in LCA to ensure deep enough knowledge about it”*

[Translated from interview A, 18th November 2016, APPENDIX Y].

At the moment the LCA’s are mostly conducted by the specialists and the general knowledge about LCA in the architectural offices is relatively low, as interviewee A states: ”*Here, at this architectural office, I am the only person conducting LCA’s but I cannot force everybody else to draw correctly [for this]. Just because there might be a chance that we need to be able to conduct a LCA in three months… Our idea was that our tool should not risk harming the already existing work flows”.*

[Translated from interview A, 18th November 2016, APPENDIX Y]

As mentioned, there are ways of accommodating this objection by the use of simple tools and by looking at a limited range of criteria. LCAByg is used among practitioners because it is the LCA tool in the Danish building industry and is adapted for use by DGNB Denmark and the Municipality of Copenhagen, as interviewee D explains in the interview:

”We started in 2011-2012 to work with LCC, and since then we developed the LCC tool. Well previously it was the Danish state that conducted the LCC but from 2011-2012 it also included the municipalities. … We worked parallel with the development of DGNB, but hence there was no tool for LCC we made our own. Now that there is the LCCByg tool, we will use and support this as well. … The natural next step to take from LCC, since everybody in the building industry is discussing sustainability, was how we approach sustainability. This … led to the sustainability tool with the first version in 2014… Now we are updating it again and aiming at getting closer to the DGNB, though more as a process tool and not as a checklist. … and then we will do the analysis in LCCByg and LCAByg and then use the results in our own process tool”

[Translated from interview D, 25th November 2016, APPENDIX Y].

Another interviewee thinks there is a missing benchmark for LCA in the regulations, as such for energy and indoor climate, which also limits the use of LCA.

”It has to get to a political level … we need a requirement for materials and LCA, which is on its way through the new Elective Sustainability Class.”

[Translated from interview C, 18th November 2016, APPENDIX Y]

Another limitation in practice for the use of LCA is the limited data on products and materials for inclusion in the LCA. Though the increased use of LCA due to DGNB forces the producers to include this type of data more and more as interviewee D states: ”W*hen we request what data are needed for conducting a LCA, it places a requirement on the industry to supply these data. The more requests they receive, the more they have* *to update their data. At the moment only, the bigger players in industry can provide these data and EPD's. However, it would be nice to have more data for less used and more alternative materials."*

[Translated from interview D, 25th November 2016, APPENDIX Y]

A circular economy involving recycling, upcycling and reuse and Design for disassembly has also been a hot topic recently due to the increased focus on the environmental footprint of buildings (Guldager Jensen & Sommer, 2016; Vandkunsten, 2016). There has been an increased focus on reusing and recycling building materials, but regulations limit the possibilities due to missing quality tests and certificates. Sometimes this knowledge is crucial due to hazardous materials embedded in the building components, which limits the possibilities for reuse but also makes the refurbishment processes more difficult. This was found to be so in a case study conducted at JJW and resulted in a journal paper (Ohms et al., 2018), which is further elaborated in sub-section '3.4.3 Active participation in Case studies at JJW'. Design for disassembly is a way to accommodate sustainability in the later design phases by the selection of materials and components.

3.4.2 Level for use of LCA and LCC at JJW

A questionnaire on LCA and LCC was distributed at JJW. The questionnaire was distributed twice with an interval of one year from spring 2017 (Q_JJW1) to spring 2018 (Q_JJW2) to identify any changes of knowledge and use of LCA and LCC. Q_JJW1 was distributed before the Green-page-strategy replaced the one-page-strategy and around the time when the PhD researcher was making short presentations at JJW on LCC and LCA. A year later the second questionnaire Q_JJW2 was distributed and the green-page-strategy had been implemented, and this might have influenced the comparison between the questionnaires.

The response rate varied between the two questionnaires, where Q_JJW1 had a response rate at 37% and Q_JJW2 had a response rate at 22%, as seen in Figure 70.
The PhD research used the existing tools at JJW as base. One of the internal tools investigated was the Pixie meeting, as described in Table 2, which was included in the questionnaire. The following diagram in Figure 70 shows the feedback from the questionnaires, rating from 1 = never participated, to 5 = in every project. From Q_JJW1 the majority of the respondents had never participated in a Pixie meeting or just once. However, looking at Q_JJW2, the majority of the respondents had participated at least once or in half of their projects.

Another internal tool as described in '1.2.1 JJW Architects and DTU' was the one-page-strategy. In 2016 this tool was supported by a newly developed tool, the green-page-strategy to increase the focus on sustainability. The first questionnaire was distributed in the period for developing the green-page-strategy hence, this is the term used in the questionnaire. The green-page-strategy was later implemented in one-page-strategy, however the terms in the questionnaire stayed the same to maintain consistency and the focus upon sustainability. Figure 70 shows how many of the respondents who heard about the green-page-strategy tool for both Q_JJW1&2. For Q_JJW1 the awareness was similar, however most respondents had not heard about the tool, while in Q_JJW2, twice as many of the respondents had heard about green-page-strategy.

Figure 70 shows the results from both questionnaires, which shows that only a few persons had much knowledge about LCA and LCC or had used it and the rest did not know about it or had little knowledge about it. It may be seen that LCC was more widely known than LCA. In the second questionnaire the same tendency is seen apparent. However, for a few specialists and even for the remainder with a limited knowledge about LCA and LCC, the overall level of knowledge about both did increase slightly.

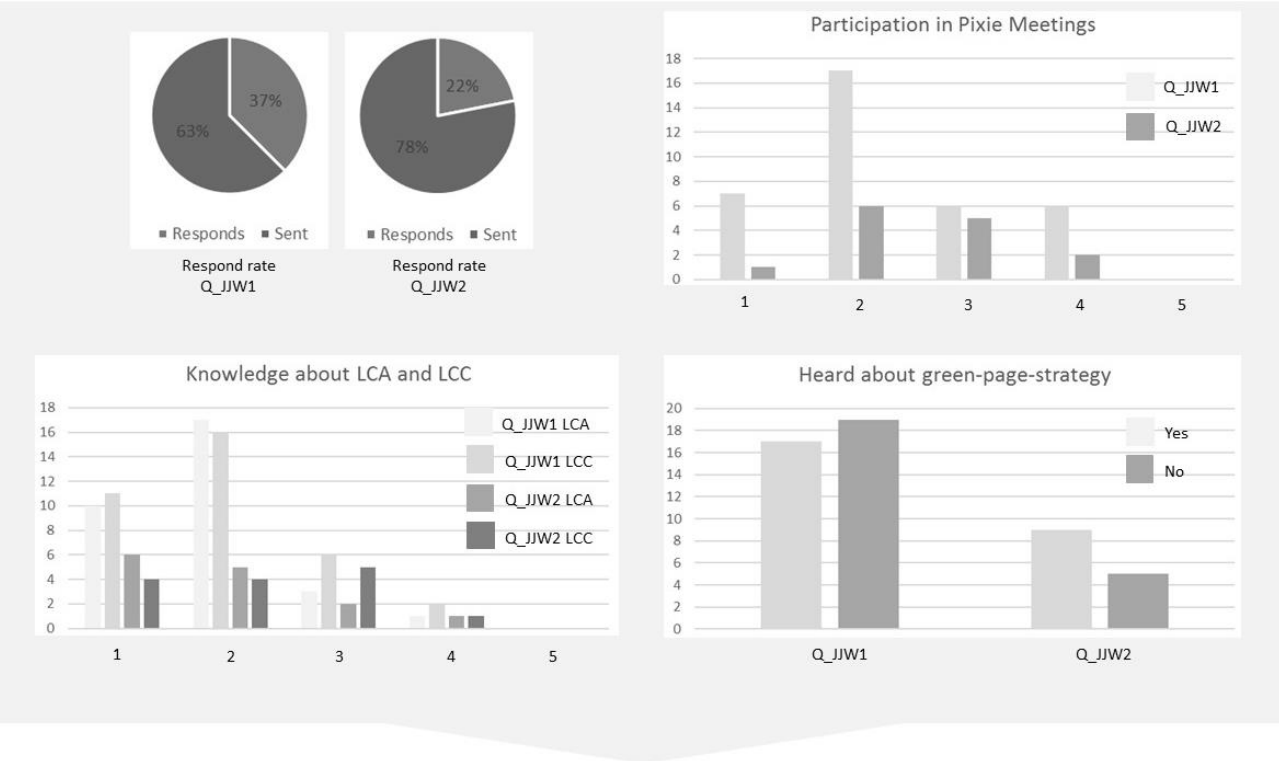


Figure 70 - Results from Q_JJW1+2, showing respond rate, participation in Pixie-meetings, knowledge about LCA and LCC, and how many heard about the green-page-strategy.

To investigate the use of LCA and LCC at the office, the following four diagrams in Figure 71 sum up in which building design phases LCA and LCC was used and to what degree, where 1 = Limited and 5 = Always used.

In both questionnaires and topics only, a few were using the technical inputs for LCC and LCA in practice, and the majority of the respondents did not use it in practice. For LCC there was a change between Q_JJW1 and Q_JJW2, and more respondents seemed to work with LCC between the 'Concept Design' phase and the 'Preliminary Project' phase.

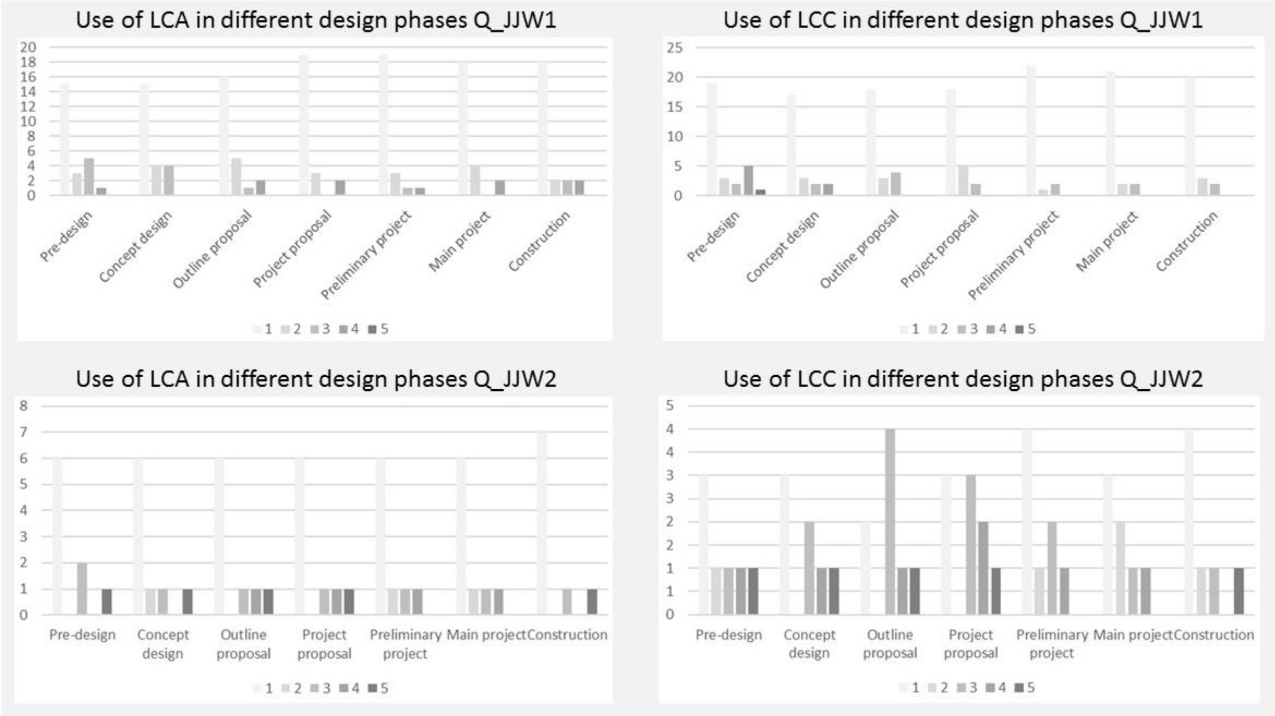


Figure 71 - Results from Q_JJW1+2, showing the use of LCA and LCC in different design phases.

3.4.3 Active participation in Case studies at JJW

This sub-section reports mapping of case studies at JJW in section '3.2 Overall mapping of case studies at JJW'. Focussing upon the use of LCA and LCC in practice and whether it influences design decisions, two case studies are used as examples in this sub-section.

CASE 05

This case from '3.2.3 CASE 05', was rather unique in itself and for JJW as it was a major refurbishment project of a building polluted by PCB. There was a limited focus on DGNB in this project. In the 'Initial design' phases of the architectural competition, the focus was on providing healthy homes to ensure that people would rent the apartments after the PCB remediation and refurbishment, as there was a risk that the history of hazardous chemicals in the buildings would scare people away and result in empty buildings.

In the later design phases, when JJW won the project, the first task was to focus upon the different remediation techniques and how to handle the PCB within the given time frame and then to determine the resulting costs. The design team soon realised that there would be increased costs due to the PCB remediation, which would lead to discussion with the client concerning the degree of the refurbishment or whether demolition should be considered. From the perspective of JJW as consultants they had an interest in investigating the environmental footprint of the different remediation strategies for handling PCB, and the selection of method for handling the PCB challenge became central. However, this study was not a part of the decision parameter for the client since the only concern was economy. This project resulted in a journal paper (5) as seen in APPENDIX E. The environmental aspect however was also important due to the way PCB was handled in the refurbishment, which was also the largest economic cost factor. From the perspective of JJW as consultants they had an interest in investigating the environmental footprint by means of LCA studies conducted by the two students and the PhD researcher.

Figure 72 illustrates the building and the plan drawing from the project manual, including signatures for the PCB distribution. These data were used in the process of conducting LCA and LCC for the project, to determine the PCB distribution in the buildings and provide an overview of the refurbishment.

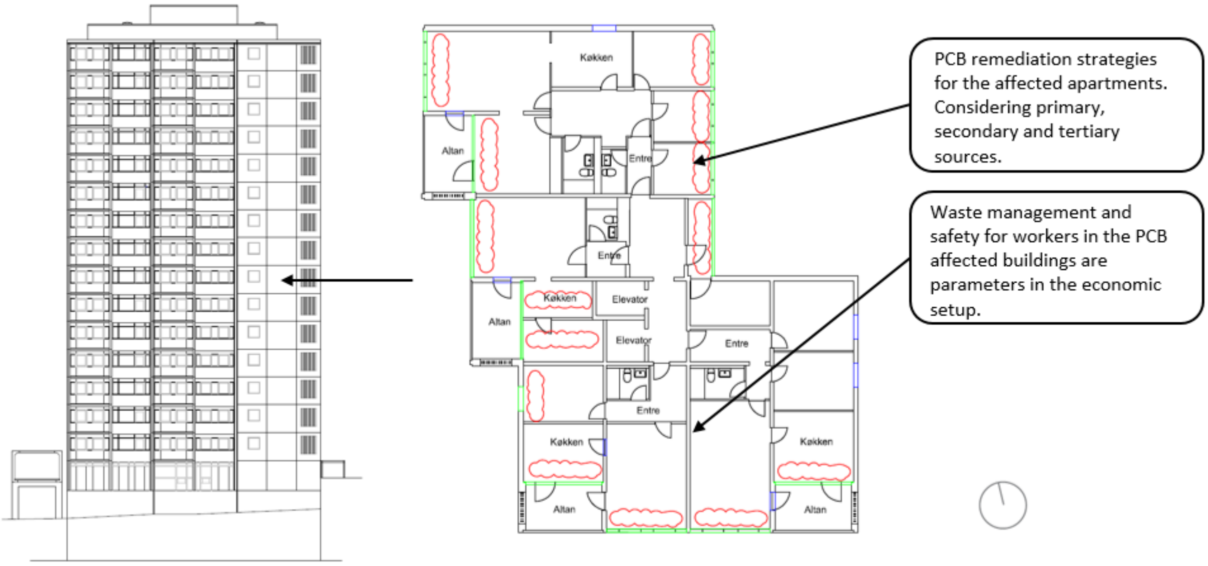


Figure 72 - Case study 05 facade and floor plan.

CASE 15

The case study described in sub-section '3.2.6 CASE 15', was a more standard case for JJW and for architectural practice in general. It was a refurbishment of residential buildings, with some restrictions due to the building heritage as defined by the municipality.

The specific tasks and variations of the case are shown in the project photo of the building seen in Figure 73, where LCC and LCA were conducted to support the selection of windows. Three types of windows were investigated to determine their LCC and simultaneously using LCA.

The recommendation for the client was to choose the Wood-wood windows, based on the inputs from the LCC and LCA, as the assessments showed that the two wooden windows were nearly the same except for the increased need for maintenance for the 'Wood-wood-internal-glazing' type, so the 'Wood-wood' type was favoured. In this case no decision had yet been made, although the LCA and LCC calculations had been implemented by the design team in their dialog with the client. The LCA and LCC were thereby important tools for decision making in this project.

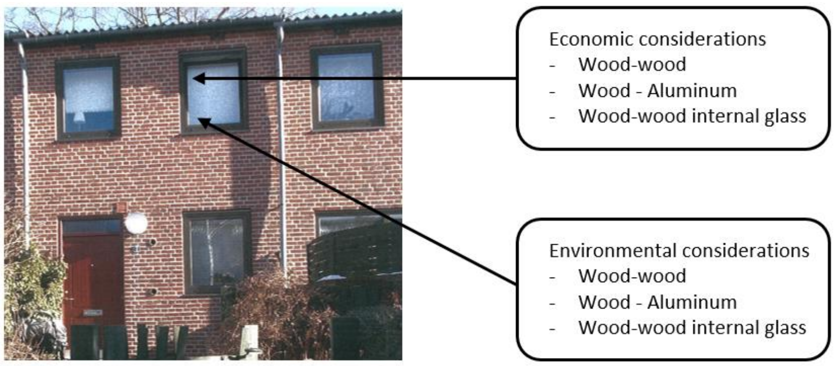


Figure 73 - Case study 15 project specifications.

3.4.4 Sub-discussion

LCA and LCC as design parameters are new to the Danish building industry, as described in this sub-section. The experts from the building industry who were interviewed considered LCA and LCC to be important tools in the development of sustainable design, where life cycle thinking is essential if the environmental challenges are to be handled in an economically defensible way. The results of the questionnaires at JJW support the interviews in stating that LCA and LCC are far from implemented in practice, because most employees had only heard about the terms and had not used them. At JJW the tendency was for most people to have only a basic or limited knowledge about such topics and that only a few were expert in them. Based on interviews the mapping shows that both LCA and LCC could be assessed already in the initial design phases, by various means.

Like the IED-method, LCC can move many decisions usually taken in later design phases to the fore by addressing them in the initial design phases. The calculations might even change the entire direction of the project, as was seen in Cases 12 and 05. For LCA the process is not exactly the same, because this assessment requires a great deal of data and is a time-consuming process, which might exclude its use in some initial design phases. LCA is therefore mostly used to support LCC studies in the initial design phases, by some very simple overall assessments, as was seen in Case 05. In the later design phases, more data are available so LCA can provide detailed results as the basis of design decisions, as was seen in Case 15.

The time it takes to conduct a LCA, the limited data available, and the quality of the available data are all concerns that were identified by the interviewees. Despite these concerns, there was a positive attitude towards the topics and a hop, that it can move the building industry in the direction of more sustainable buildings. LCA and LCC were therefore in focus when developing the new ISD-method in this PhD research.

3.5 Interdisciplinarity and integrated design

The complex topic of 'sustainability' in the built environment places various requirements upon the design team, because it requires both an overview of the entire topic and some specialised knowledge within each sustainability category to ensure successful sustainable building design. In this PhD research, the design process used by the design teams who worked with sustainability was investigated through the mixed methods of mapping projects, case studies, questionnaires and interviews. This section discusses the results of the research on the topic of the design process, collaboration in interdisciplinary design teams, and last but not least, integrated design.

Through the active research performed in the case studies, technical knowledge was provided by the PhD researcher about the design process and their responses and their subsequent actions were recorded. Furthermore, research on the importance of communication using visuals of technical knowledge and quantification of architectural quality in the engineering and architectural profession was performed.

A total of three papers support the research related to these topics and are presented as a part of this section.

3.5.1 Interdisciplinary design team and integrated design in the case studies at JJW

In general, the design teams in the case studies at JJW comprised both architects and engineers, as seen in Figure 74, which also shows that the client had direct contact with the architects and sometimes also with the engineers, at least in some cases. The architects and engineers in the same team still worked in their separate offices. The engineers contributed by external consultancy. When an intern with architectural engineering background or the PhD researcher participated in the design process, the communication was directly with the architects, but the architects and engineers communicated directly with each other and thus worked as an actual team. In the later design phases, it was mainly the external consulting engineers who were in contact with the contractors, although in a few cases the architects had this contact. In later phases contact with the craftsmen and sub-contractors was always through the external consulting engineers.

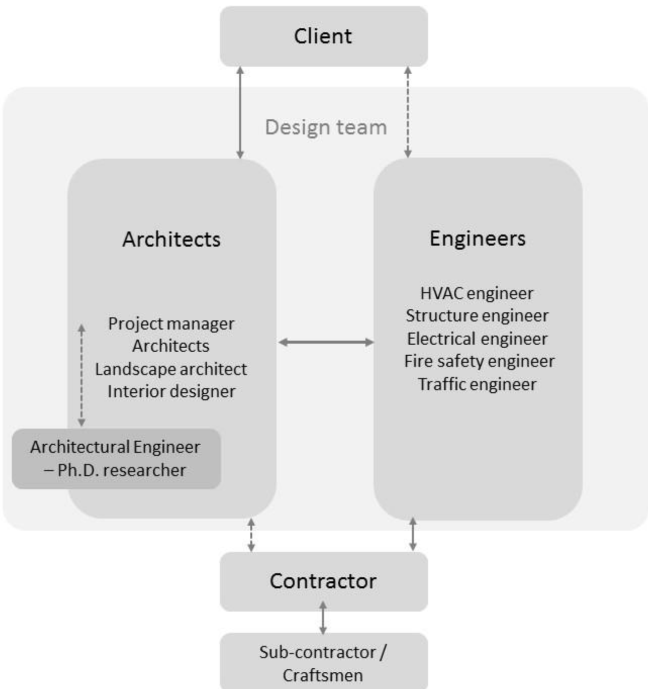


Figure 74 - Design team setup. The dashed arrows show a limited relation and the full lined arrows show the direct collaboration.

The design team at JJW normally consisted of one to three architects including a landscape architect or an interior designer, depending on the project. The group of external engineers related to the design projects always included a HVAC engineer, structural engineer, electrical system engineer, and sometimes a fire safety engineer, and sometimes a traffic engineer or other specialised engineers. In the case studies at JJW the communication took place mostly through meetings between the architects and either all external engineers at once or in separate meetings, depending upon the topic under discussion. In short, this was a classic engineering consultancy, in which the work was conducted separately and aligned at meetings. This type of design work was interdisciplinary, since all the above professions and specialists collaborated in the framework of the same project. The question is if these processes can be termed integrated design. To elaborate on this, some observations of Case 02, 12, 05, and 15 are discussed below.

CASE 02 – The design team from JJW consisted of two architects, one intern with a background in architectural engineering from DTU and the PhD researcher. The collaboration between these three persons in the team was close, in that they sat together in the office, which therefore resulted in direct dialogue, but also in the sense that the tasks and analyses were performed together. The architects saw the potentials and qualities in the view of the sea from the workspaces in the building, which then became a design parameter when the architectural engineers performed the daylight simulations to investigate alternative designs. Through iterative processes the optimal combination was presented to the main architect and client, who provided their feedback and ideas for design changes. This led to another iteration and to the next presentation, until the final design was chosen. The process is considered to have been successful for the internal integrated process at JJW and also in terms of the communication with the main architect and the client.

CASE 12 – The design team consisted of one architect from JJW in the design phases studied by the PhD researcher and three engineers: HVAC, structure and electrical engineer. The design team worked in separate offices, so no spontaneous or direct contact could occur. However due to the tight economy imposed by the client, a public school, the architect emphasised inputs from the engineers from the early design phases and throughout the process. This resulted in regularly meetings and iterative design concepts with inputs from the engineers at several steps. The architect emphasised a low-tech building with passive strategies for ventilation and light, which challenged the HVAC engineers for solutions concerning natural ventilation and good daylight conditions through large window openings.

"Well you can say that natural ventilation is not completely new but still it is to some degree, because we architects have dreamed about it for many years. I have been part of meetings where the engineer just laughed and said; 'forget about it'. Here he (the engineer) was open for the idea for some time, until he got home and thought about it."

[Translated from interview H concerning Case 12, 26th January 2018, APPENDIX Y]

As the quote from the interview with the project leader indicated, the engineer eventually found that only mechanical ventilation could provide an acceptable solution, despite the effort and positive meetings. However, the decision was based on knowledge and the solution was chosen from among several suggestions. The design team wanted best possible daylight conditions in the building and to avoid overheating at the same time. The architect therefore considered smaller glazing areas in the south aspect and larger glazed areas towards the north. To support the discussion concerning window placement and size, the PhD researcher performed some daylight studies in Velux Daylight Visualizer, as seen in Figure 75.

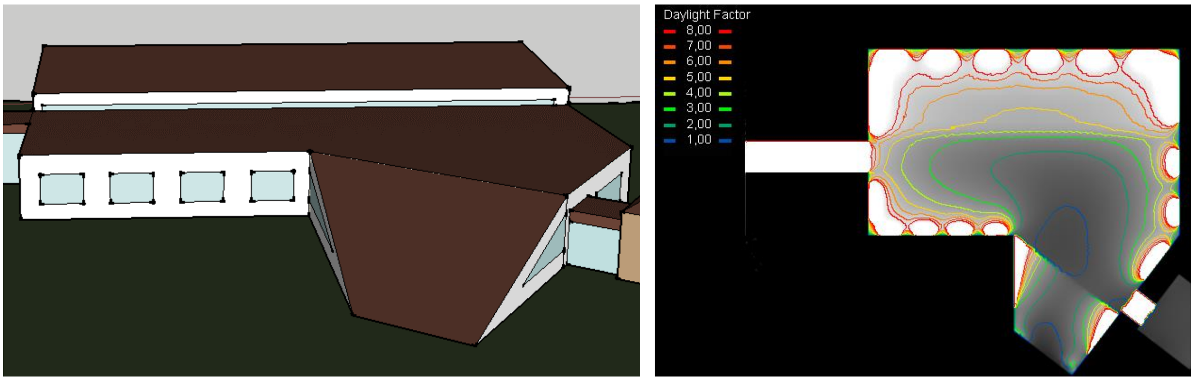


Figure 75 - Case 12, Visuals from an initial daylight simulation.

The structural engineer was challenged by the architect's vision for CLT elements as a sustainable and aesthetic alternative to concrete, and the entire design team made a big effort to investigate CLT and include it. However, in the end the cheaper material - aerated concrete blocks - was chosen instead of CLT for economic reasons and a lack of time before the deadline. The inputs were used to challenge the client and engineers as the project leader states:

"The inputs (from the PhD researcher) were not used to the degree I would have liked it to be, because it was decided for other reasons not to go with these parameters. So you can say we used it (the inputs) as arguments for the client, internally in the organisation and for the engineers."

[Translated from interview H concerning Case 12, 26th January 2018, APPENDIX Y]

CASE 05 – This case only reached the initial design phase, and had a mixed design team consisting of three architects from JJW, engineers specialising in HVAC, structure and electricity, and two PCB and waste specialists. The collaboration worked well, but was not very integrated, as the team did not work in the same place and had only a few meetings. Mainly the architects performed the economic calculations and requested values and data from both the engineers and specialists to use in further calculations. In the project, two architectural engineering students from DTU based their thesis on the remediation strategies for the buildings from a LCA perspective, as seen in Table 21, and this attracted great interest among the design team.

Table 21 - Remediation strategies for the PCB affected buildings, the environmental footprint based on LCA.

Remediation techniques			
Thermal desorption	**Steel blasting**	**Sealing**	**Sand blasting**
Lowest environmental footprint	High environmental footprint due to waste	Middle environmental footprint	Highest environmental footprint due to waste

"This is a strange task, where we get an assignment to construct something and we end up recommending that it should be demolished – so the task changed in the process. But I think the inputs (technical inputs) could have contributed more, if they were ready for it, to justify the decision at a more scientific level. If we had made a LCA for the entire demolition process and compared it to the refurbishment process, they would have been comparable"

[Translated from interview I concerning Case 05,, 12th January 2018, APPENDIX Y]

Despite presentations by the students to the design team and the interest they expressed it was not the LCA, which guided the client's decision in the end. The final decision was based on cost.

CASE 15 – The design team consisted of two architects from JJW, the PhD researcher and engineers specialising in HVAC and structural aspects. The two architects had clear strategies concerning the refurbishment of the windows and the engineers supported the architectural strategies with calculations of energy performance, which made for an easy collaboration process. However, the team did not work directly together in the same office on a daily basis. The PhD researcher was asked by the architects to assist their selection of window by conducting LCC calculations and simplified LCAs.

"We ask for this because we need to quantify our decision. So when we continuously keep explaining to the client what we think and know empirically, we will also be able to explain it to the client based upon a serious study." … "The inputs are value-added where they qualify a decision and they are useful because we can use them (the technical inputs) to justify a decision or create more value."

[Translated from interview I concerning Case 15, 12th January 2018, APPENDIX Y]

The reports were discussed in the design team and brought to the client for further discussion. No final conclusion had yet been made, but this rather classical collaboration did have some integrated aspects in the process.

3.5.2 Methods as a medium for collaboration and communication

The case studies at JJW revealed a tendency for the architects tend to quantify their design decisions to support the architectural concepts, when communicating with engineers and clients. As previously described, the integrated process was not defined and described to the point where it could be fully implemented and used in practice, though some parts of it provided common methods for communication and collaboration. Both quantification of architectural quality and design decisions and visuals to communicate technical analysis and results to design teams were methods that were used in all the above processes, paper (4) elaborated on this aspect, as seen in APPENDIX D.

Quantification of architectural quality and design decisions

As seen in the case studies (Case 02 and Case 12 in the previous sub-section) daylight simulations were used as tools to quantify the daylight in the room, but this was not sufficient to describe the architectural feeling or importance of the light in the room. LCC and LCA are now used as tools to quantify design decisions from the early design phases. From the beginning of the research to its completion 3 years later, the researcher has experienced an increase in their use. LCC came to be used for investigating the economic benefit of whether to refurbish a building or demolish and built new (Case 12) or for choosing which type of remediation strategy was the best when refurbishing PCB affected buildings (Case 05). LCA was used to decide the type of materials and components (Case 15) or to argue for the selection of a more sustainable material than the usual concrete for the main structure of a building (Case 12). Historically, LCA has been in the engineering field, but with the increased focus upon sustainability and certification systems, more has to be documented and quantified. A reason for the increase in interest in LCA could be that the architects aim to perform these analyses themselves in order to continue to have their own deciding impact on the design decisions.

Visuals to communicate technical analysis and results to the design team

Just like the architects, the engineers also aim to communicate more efficiently with the architects. This is of importance to ensure implementation of the technical knowledge from the early design phases, as the IED method emphasises. As mentioned earlier, the purpose derives from the observation that buildings cannot be

made to perform at a sustainable level just by adding technical components (Landgren, Skovmand Jakobsen, Wohlenberg, & B. Jensen, 2018). The right design decisions have to be made early in the design process. Engineers use visuals, not because they want to implement as many technical engineering digital tools and simulations as possible into the design process, but to ensure the required quality in the design process in question. The analysis of the results and communication of these results to the design team is important when ensuring that the design process is provided with adequate technical knowledge.
The topics of indoor thermal comfort related to temperature, daylight, acoustics, and ventilation are all topics that can be visualised to communicate the results and emphasize the importance from the early design phases (Case 02 and Case 12). Energy performance is also a topic for early communication through visuals in design processes. However, despite the good intentions of visualising technical knowledge it is not always received in a positively by the team or result in its being implemented in the design.

As a result of a thorough literature study of IDP guides, it is proposed that technical knowledge can perform in three different ways in a design process: as validator, as informer or as driver, as seen in paper (6) APPENDIX F.:
Validator: Validation is the more traditional function, where a design process has been conducted and the engineers have to validate the design in terms of indoor climate, energy performance, structure and other parameters, for instance to obtain a building permit. The technical information is therefore brought into the process at the end of the design phase, as documentation.
Informer: The technical analysis and simulations are conducted along with the designing of the building to investigate different possibilities and identify best practices while designing and thereby to ensure knowledge-based design.
Driver: The performance of the building is the main topic and all design decisions are made on this basis.

The three terms can be illustrated by the scale seen in Figure 76, where selected IDP guides are mapped to identify their perception of how to implement technical knowledge in practice.

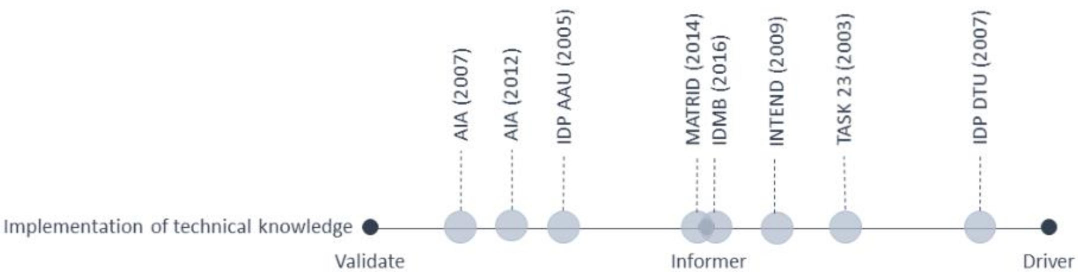


Figure 76 - Scale for implementation of technical knowledge in design processes, ranging from validator to informer to driver APPENDIX F.

As seen in Figure 76, there is great variation between the IDPs and how they suggest implementation of technical knowledge in practice, however they tend to take the Informer approach. When comparing this result with the IED method, where the importance of early influence is emphasized, both the Informer and Driver approach are used to ensure sustainable design. The driver approach can be seen by architects as difficult to combine with the creative design process, which the case studies in paper (6) also indicate, APPENDIX F.

3.5.3 The international perspective: Small scale interdisciplinary work in the context of BISS

The BISS summer school 2017 focused on interdisciplinary design processes. The setting was perfect for testing the implementation of technical digital tools in the design process used by the international master student groups from five nationalities, although it was easier said than done. The mentor team consisted of two PhD students, the authoring of this PhD thesis and a PhD researcher with a background in Historical Architecture. The topic was predefined by both mentors as: "The sustainable link – the haze of the past in the future" aiming at using the knowledge and background of both mentors to support the interdisciplinary work of the student groups. Sustainability was approached by short presentations and sequences of atelier critiques and supervision by the PhD researcher, then it was the task of the students to reflect and implement this knowledge in their design processes. Despite the intention to have interdisciplinary groups, not all managed to have such a constellation in their group, which was also reflected in their design process and their success in implementing technical knowledge in their design. One group had daylight simulations and physical 3D models for light studies in their design process, which guided their design decisions and ensured knowledge - based design. Another group focused on the social sustainability aspect related to social interaction to support urban development. Finally, the third group was too uniform in their disciplinary constellation and they use do their existing architectural design method and remained in their comfort zone, finding it difficult to include knowledge from other disciplines. This observation was supported by questionnaires, student logbooks, and a final focus group discussion, APPENDIX Y.

The projects conducted by these three groups during the summer school also showed that integrated design will not occur just by having an interdisciplinary group in the same room with one given task for ten days. The integrated process must be guided and the importance of inputs from all participants followed by joint discussions and reflection must be emphasized. The one common tool was visuals, which ensured communication and collaboration across disciplines, APPENDIX Y.

3.5.4 From a London perspective

From the interviews with five experts working with sustainability in the building industry in London it was found that there were many similarities to the development that has taken place in Denmark. LCC and LCA are new parameters for inclusion in the building design process in the UK as well. Although there is an increased interest in limiting the environmental footprint and in implementing this from the early design phases, there are as yet no generally accepted methods for how to do it, so some companies develop their own tools. The tools make it easier to handle the complexity of LCA in the design phases, for instance through plugins to 3D modelling tools. Parametric design is not an integrated part of the building industry, but it is rapidly becoming common for architects with a background in environmental design to support their design concepts and ensure knowledge-based design from the earliest design phases [Synthesis from interview J from AtmosLab, 28th November 2017, APPENDIX Y]. Other offices try to achieve integrated design and implementation of LCA by using BIM modelling tools, which are already implemented in their workflow [Synthesis from interview K, 22nd November 2017, APPENDIX Y]. This tendency for an increased focus on LCA as a design parameter by increased use of BIM modelling tools, is similar to what is taking place in Denmark [Synthesis from interview A, 18th November 2017, APPENDIX Y].

Energy performance and thermal comfort have a high priority in the design processes in London, and some architectural offices still have a tradition of working with passive houses, where energy performance and passive strategies are the driver of the design [Synthesis from interview K, 22nd November 2017, APPENDIX Y]. According to the interviewees, the most commonly used sustainability certification system in London is the British system; BREEAM and occasionally LEED, and not all were familiar with the DGNB system [Synthesis from interview J, from AtmosLab, 28th November 2017, APPENDIX Y]

3.5.5 Sub-discussion

It is difficult to describe and asses exactly the integrated process that was used in the case studies, because there is no universally accepted definition of an integrated design process (IDP), as was found in the literature study in the journal paper (6), APPENDIX F. Here it is stated that the different versions of IDPs describe how the design team must include different professions in order for the process and ‘output’ to be integrated. How exactly the integrated process should occur when the different professions are working together is not well defined – it is like a black-box, knowing the input and output but not what is occurring in the box (Landgren et al., 2018), attached in APPENDIX D. In the four case studies above, it was seen how varied the scope of interdisciplinary collaboration and integrated design processes were in practice at JJW. In the above a simple ranking was performed according to the physical accessibility in the interdisciplinary team. This included an observation of whether they worked in the same office and observations of whether the specialists’ inputs were taken into account and the level at which the inputs influenced the design decision.

The scale developed to define the way technical knowledge was used in practice appears in Figure 76. Here it is divided between validator, informer, and driver. Only Case 03 used the DGNB as a driver, and this was because it was a DGNB pilot project. In the other case studies there was considerable variation.

3.6 Integrated Sustainable Design

This section presents the outcome of the case studies, interviews and questionnaires that are described in the previous sub-sections. The findings have been condensed into a method for Integrated Sustainable Design (ISD), which is one of the main results of the current PhD research. The ISD-method can be illustrated by an 'umbrella' covering design processes with their major focus on sustainability in practice in Denmark, a guideline for existing tools and methods and how they can be implemented in a building design process. The method is an attempt to combine methods from the engineering field in an architectural context to contribute to the design process, as the point of view was that of the PhD researcher with a background in Architectural Engineering, implementing engineering tools and knowledge in the building design processes at an architectural office, JJW.
The approach to design processes, methods and teams therefore differs from a classical architectural approach, which might be an advantage in the discussion and comments from practitioners set out below. ISD was intended to provide a general format as a process tool that functions as a successor to the Integrated Energy Design (IED) method and as an optimized interface to the DGNB certification system. ISD therefore takes an operative approach to the complex topic of performing processes whose purpose is to ensure documentable sustainability in an architectural office. The ISD-method is defined by Figure 77, which provides an overview of the design method that focuses on implementing sustainability. The diagram is oriented horizontally, and each layer is a step further towards a detailed description of the method. The steps are defined as follows, and explained in the following sub-sections:

Step 1: Life cycle approach for the ISD, based on the Description of Service
Step 2: Unfolding the sustainability topics and tools in the building design phases
Step 3: From generic ISD-method to office specific method at JJW
Step 4: Setting up the team for Integrated Sustainable Design

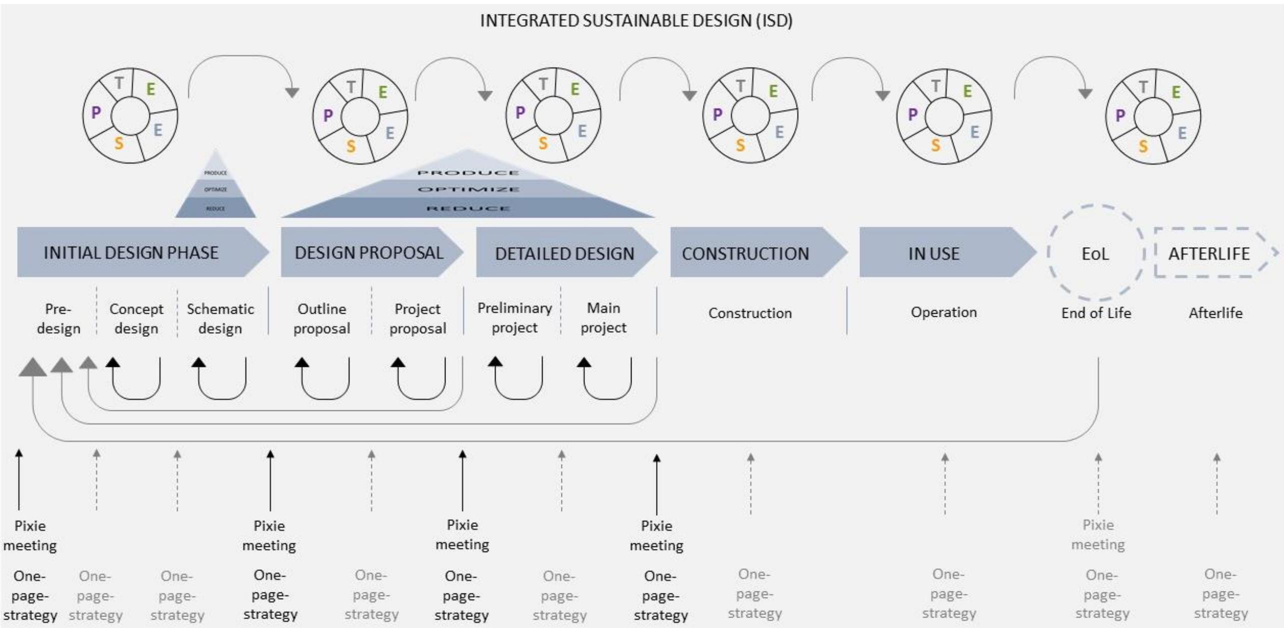


Figure 77 - The Integrated Sustainable Design (ISD) method developed in this PhD research is based on the Danish Description of Service and in the framework of IED and DGNB.

3.6.1 Step 1: Life cycle approach for the ISD, based on the Description of Service

The development of ISD was based on the Danish Description of Service (DANSKE ARK and FRI, 2012) since it is a driving factor for the design process in the Danish Building Industry, as previously described in '2.2.1 The Danish Description of Service'. The Description of Service overall divides the design process into the: Initial Design Phase, Design Proposal, Detailed Design, Construction Phase and the In-Use Phase. The method and thereby the diagram for ISD in Figure 77 was founded on the Danish Description of Service, although an addition was made, which is shown by the dashed lines in Figure 77 and Figure 78. The importance of this additional part is the focus upon the building life cycle which is important when discussing sustainability. When conducting a LCA or calculating the LCC there must always be an expected lifetime for the building or building components, however after the use phase for which the building was designed is the point at which a decision on the End of Life or Afterlife of the building must be made. If it is decided that the building is to be refurbished, the entire diagram is repeated from the starting point – thereby life cycle approach.

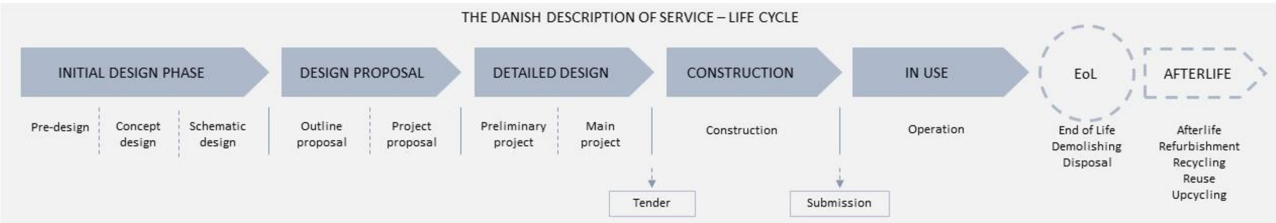


Figure 78 - The Danish Description of Service (DANSKE ARK and FRI, 2012) modified into a life cycle.

This simple and overall umbrella structure has the purpose of communicating the content and process of implementing sustainability in practice by using the ISD method. Using familiar process as the framework is and the advantage when to communicating the new design method to architects that are used to the form of the Description of Service in Denmark. The design phases are presented step by step in the remainder of this sub-section to lead the reader through the main topics when dealing with sustainability in the building design process, to ensure that the goal of sustainability can influence the design all through the process. This also emphasises the use of ISD as part of the design process rather than as a checklist of sustainability criteria.
These case study research indicated that often the design process and the sustainability process are parallel processes instead of one common design process, as is illustrated in Figure 79. This type of process occurred in Cases 04, 06, and 07. The parallel processes were often dictated by the limited time available and the financial constraints on the Description of Service, which was the basis of all the projects.

Figure 79 - Parallel design process and sustainability process, which case studies show often occurs in practice.

The ISD deals with the problems encountered in the Description of Service and implements the sustainability process in one common design process, as is further described in the following section.

3.6.2 Step 2: Unfolding the sustainability topics and tools in the building design phases

The process of transforming IED into ISD is illustrated in Figure 80, which shows how the Kyoto Pyramid has to change in shape to be able to include the additional topics LCA and LCC. Including even more sustainability aspects will require an even wider diagram.

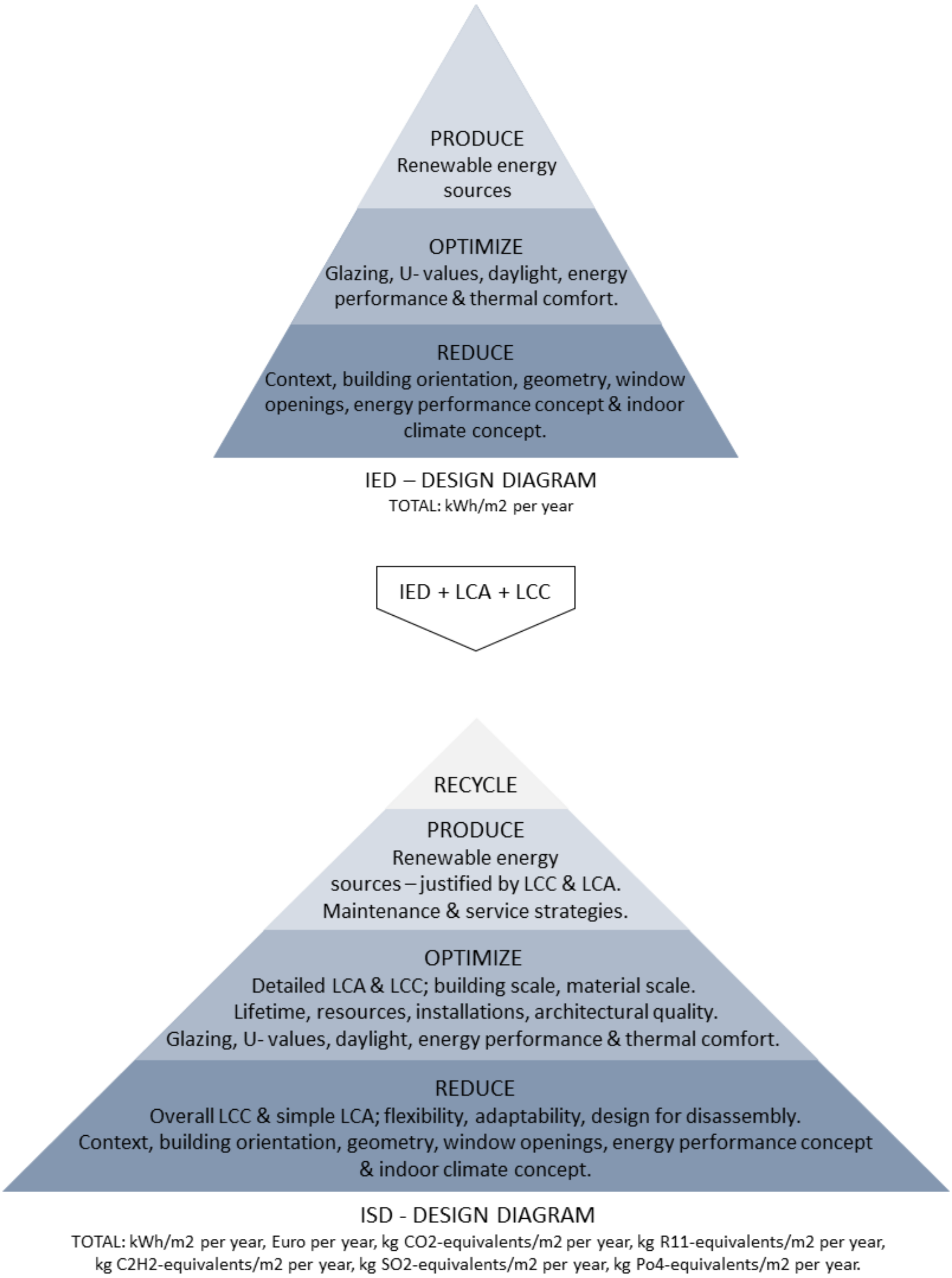


Figure 80 - Moving from IED towards ISD, by adding LCC and LCA. This results in the change from one final measured unit to several final measured units.

The definition of the IED can to some extent be used for the other topics on their own, including passive strategies. Reduce and optimize can also be used for the purpose of LCC and LCA, thus limited use of materials

and knowledge-based design decisions will cause material usage to be limited and optimised for the design, which will improve the economy. The simplicity of the diagram limits its use in practice, and different ways of using it will most likely occur. Each topic will then result in different approaches and use. The results are therefore being further described and condensed in more focused topics, splitting Environmental, Economic, and Social sustainability in relation to the design process time line. This means that the trade-offs that are made in IED and DGNB are included and discussed. It will be seen that some aspects are similar in relation to the ISD and other aspects are not the same.
The IED-method based upon the existing Kyoto Pyramid does not include LCC or LCA. LCC, like IED, focuses on the early design phases, as important decisions concerning LCC must be made early to ensure maximal influence with minimal economic consequences. This was an output from the case studies and is supported by the following interview with the project leader, in a project in which LCC was a main driver (Case 17:

"The investigation of whether to do a full refurbishment or a partly refurbishment – was already decided, but it would have been a good idea to do a LCC calculation to know what would be the best solution"

[Translated from interview G, 23 January 2018, APPENDIX Y]

As a result, the Kyoto Pyramid as an illustration of IED including LCC can stay the same overall. However, when including LCA in the design process, the research showed that only overall and conceptual LCA can be conducted at the very beginning of the design process. Despite the low level of detail this simple analysis can have a huge impact upon the environmental footprint of the building, even on such an important parameter as the main structure of the building, which is defined in the very early design phases. The detail level of the building design is crucial when conducting precise LCA so information available only in the later design phases is needed to define the total impact of the building and impacts components which are only defined or redefined in later design phases. This changes the focus of the IED process from mainly early design phase design to include later design phases as well, as seen in Figure 77. Due to the late LCA, the LCC calculations also have to follow to derive the economic consequences of the environmental considerations. By adding these additional sustainability topics, ISD becomes different from the IED method, changing from a static method focusing on the early design phases to a life cycle perspective, which is more dynamic and complex.

The mapping of IED elements in projects and the many case study processes of adding LCC and LCA to the 'classical' IED topics (indoor climate and energy balance) were central for the case studies at JJW. The results gained have been supplemented by overall mapping from questionnaires completed in various architectural offices practicing in the Nordic area. From this Figure 77 was elaborated into sustainability process timelines for each of the three sustainability topics: Economic, Environmental and Social. In DGNB two extra topics are included: Technical and Process criteria, which are also briefly included here as well. Figure 81 to Figure 83 show all five criteria mentioned here and are intended to provide insight into which criteria lead to which topics, processes, calculations and a need for expert knowledge.

Figure 81 shows the Economic criteria and related digital engineering tools in the framework of the sustainable design process, as seen in section '3.1 Work Profiles at Architectural Offices', '3.2 Overall mapping of case studies at JJW' and '3.4 LCA and LCC in practice'. Life Cycle Costing (LCC) has a great impact in the DGNB system, as explained in '1.3.6 DGNB', so the focus is mainly here, when examining the Economic criteria. The questionnaire study and the interviews with sustainability experts in the Danish building industry made it clear that LCC and economic considerations are the driving factors for implementing sustainability in building design projects in practice.

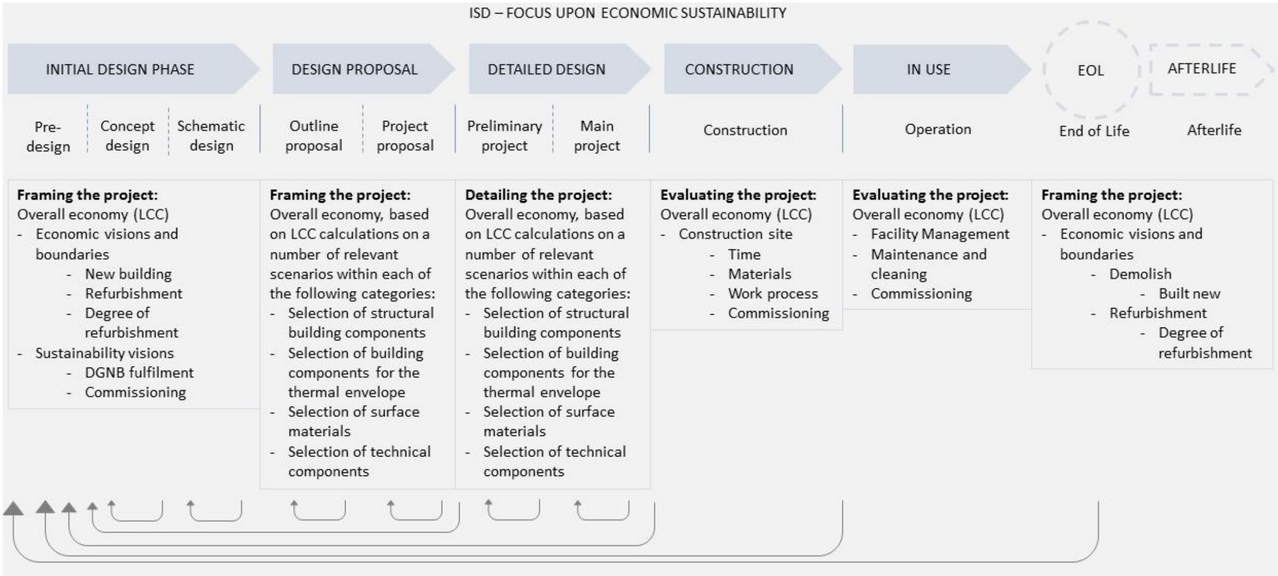


Figure 81 - ISD with focus upon economic sustainability.

Figure 82, shows the Environmental criteria and related digital engineering tools in the framework of ISD, as seen in section '3.1 Work Profiles at Architectural Offices', '3.2 Overall mapping of case studies at JJW' and '3.4 LCA and LCC in practice'. Life Cycle Assessment (LCA) has a great impact in the DGNB system, as explained in '1.3.6 DGNB', so the focus is mainly here when examining the Environmental criteria. However, this topic has not the same driving force as LCC in the design process in general, which is further supported by the questionnaire study and by the interviews with sustainability experts. Despites the limited impact as a design driver, the importance of LCA for sustainability is very high as the design process is then considered in more detail.

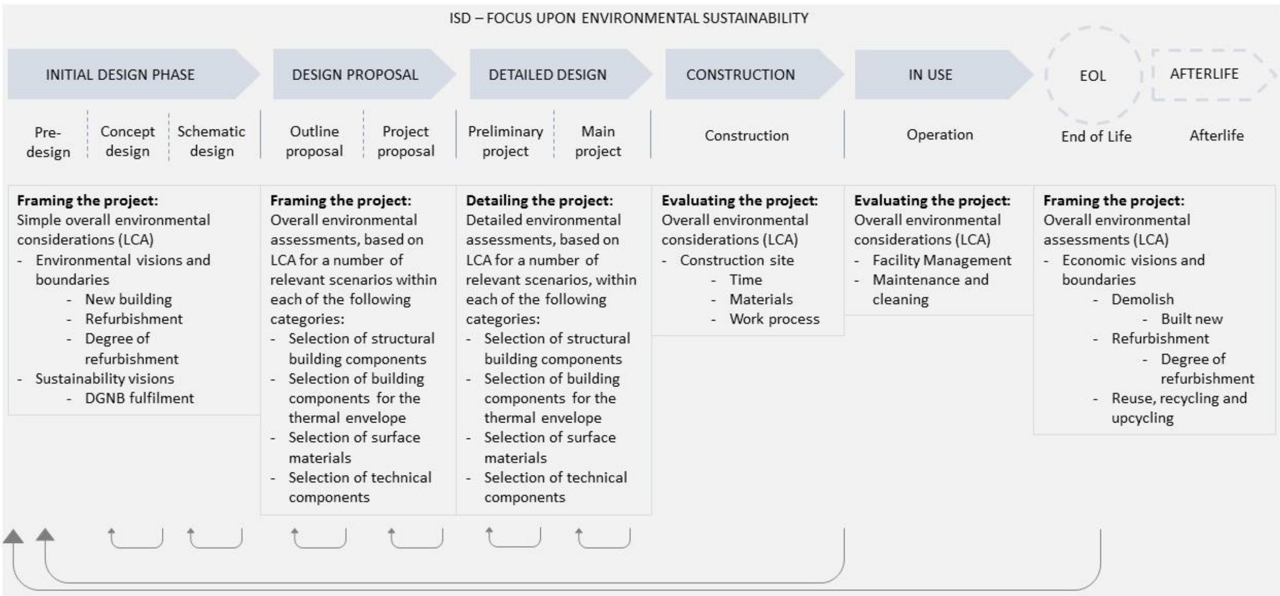


Figure 82 - ISD with focus upon environmental sustainability.

Figure 83, shows the Social criteria and related digital engineering tools in the framework of ISD as seen in section '3.1 Work Profiles at Architectural Offices', '3.2 Overall mapping of case studies at JJW' and '3.3 IED and DGNB in practice'. Here the focus upon the IED method in the present research led to a selection among the criteria focusing on indoor climate and energy consumption, which is further described in '1.3.6 DGNB'. The criteria 'SOC1.1 Thermal comfort', 'SOC1.2 Indoor air quality', 'SOC1.3 Acoustic comfort' and 'SOC1.4 Visual comfort' from DGNB all reach the shared field of topics treated by both architects and engineers.

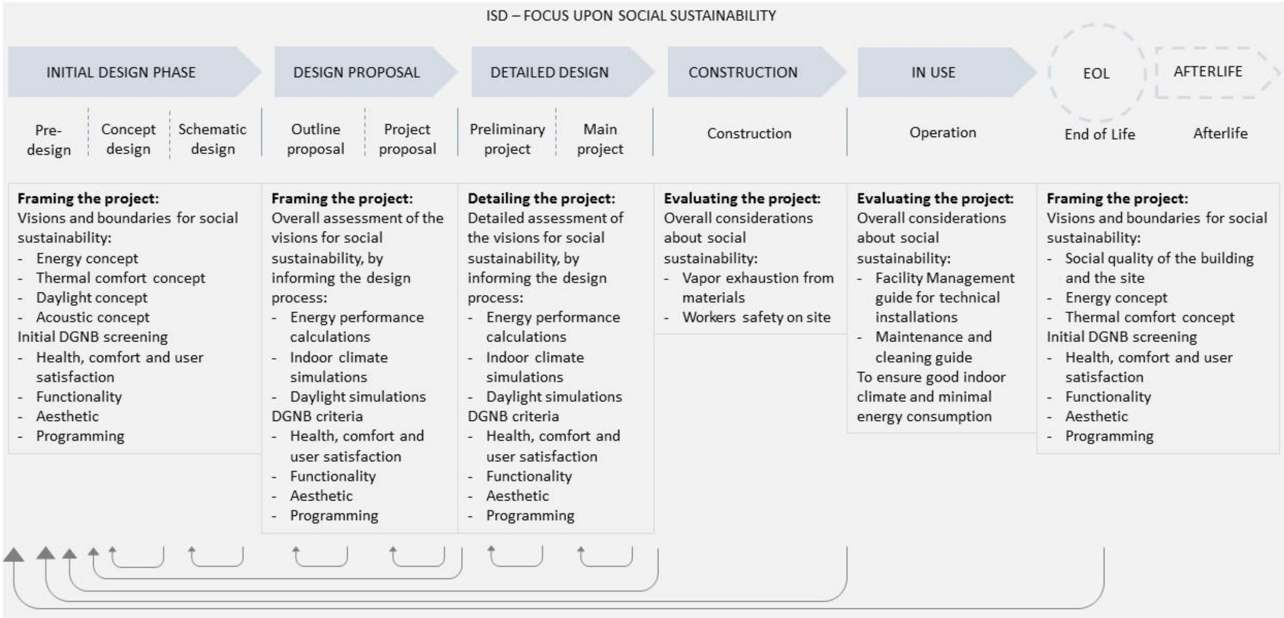


Figure 83 - ISD with focus upon social sustainability.

Figure 81-Figure 83 are all a part of the ISD method and they emphasize the close connection between sustainability criteria and how they are linked together. This underlines the importance of process, timing, and knowledge, which are all moved upfront, to be able to take knowledge-based design decisions at the points where when it is still possible to include them in the design. The ISD also underlines the importance considering the lifecycle of a building, with all the possibilities, limitations, and challenges that this entails.

3.6.4 Step 3: From generic ISD method to office specific method at JJW

ISD was taken from the generic level described above into the context of a specific architectural office at JJW, since they were the test bed and case supplier for the entire PhD study.
The development of the green-page-strategy and its inclusion in their existing one-page-strategy tool had the effect of emphasizing sustainability in their workflow and generated more awareness of the topic by forming a part of this mandatory tool.

The one-page-strategy was used by the project leader as a process tool from the very first design phase to introduce the visions of the project and any as additional visions contributed by JJW. When filled out by the project leader it still fit the one-page as the name implies and it was elaborated in a so-called Pixie-meeting at which the entire design team set the common goals and allocated specific responsibilities. This one-page followed the project and for each change in design phase or each change in project manager this one-page was reconsidered and discussed, as seen in Figure 84. The one-page-strategy thus supports an iterative design process, as it is used for each project start and for each phase transition in the design process, to discuss and evaluate the visions and tasks of which the project consisted.

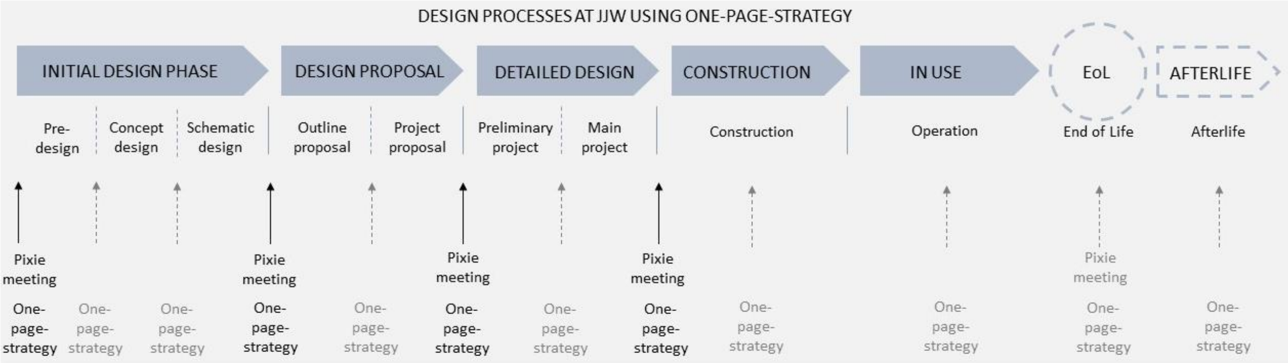


Figure 84 - The design process and the phases where the tool is included and the pixie-meetings. The blue text is indicated if there is a change in design team or phase, which thereby require the use of the tool and the black is the main design phases and thereby where the tool and meeting is needed.

The discussions ensured that reconsiderations and redesign were undertaken when needed and advanced the design project into the next design phase against a knowledge-based background.
Originally, no specific mention of sustainability was made in this tool, but now the topic is included more explicitly, which emphasizes the focus upon sustainability in each project where the tool is used, as seen in Table 2, from section '1.2.1 JJW Architects and DTU'.

Despite the above benefits of the internal one-page-strategy tool, JJW only used the tool to some extent as seen from the questionnaire in section '3.4.2 Level for use of LCA and LCC at JJW'. By increasing the focus on using the tool in practice, iterative processes will be increased generally and a general focus on sustainability will be maintained.

3.6.5 Step 4: Establishing the team for Integrated Sustainable Design

The ISD method consists of several suggestions for implementing sustainability in practice – a guide to cope with the overview as a generalist and at the same time know when to become involved with the different specialists to ensure that the desired the level of sustainability is attainable. However, although the intention was to provide a full overview of the ISD method, it is a complex matter. All design projects are different, and sustainability is such a complex topic that it will never be completely addressed. Setting up the team for an optimal integrated sustainable design process is therefore also a complex matter.

In the previous sub-section '3.6.2 Step 2: Unfolding the sustainability topics and tools in the building design phases', the black-box of integrated design was investigated and described, but it is still open to further development and discussion. Nevertheless, these results lead to some guidelines for setting up the team to perform integrated sustainable design, which is described further below. The mixed methods of research that were used showed the importance of the architect as a generalist who maintains the widest possible overview of the design process, but some understanding and education within sustainability is necessary in an ISD process. Knowledge about the process that must be used to include specialized knowledge when one's own knowledge is no longer adequate in specific sustainability topics, requires familiarity with and respect for other professions and their knowledge. For this engineers or other architects with specific knowledge on specific sustainability topics must be involved.

To achieve a sustainable building without compromising the architecture there is a need for iterative design loops, to ensure an informed design process and implement the suggestions of other team members or at least take them into considerations and discuss them. An integrated design process occurs when the team works closely together in these design iterations, implementing knowledge from one another to achieve a common goal – sustainable design and good architecture. The specialists might be from the same architectural office or they may be external specialists, depending on the employee setup in the specific architectural office – recently there has been a tendency for engineering consultancies to buy and run architectural offices, and for some architectural offices to create specific engineering or sustainability departments so as to have a wider range of competences in-house. But this change might not necessarily result in a more integrated design process or ensure interdisciplinary design teams.

As previously mentioned, a tool that ensures better communication and collaboration through visuals is required, and the various possibilities within BIM can help the process and support communication to make it possible to reach the sustainable visions within a limited time frame and at a given level.

3.6.6 Sub-discussion

This section describes the developed ISD-method, as illustrated as seen in Figure 77. The method consists of four steps which have all been elaborated in the above sub-sections.

The first important step in the method is its base in the Description of Service. With this, easier implementation in practice becomes possible and a common design process for design and sustainability is facilitated.

The second step is that it is based on the IED-method, where the research has shown the need for further sustainability parameters to handle the complexity in one method. The three sustainability criteria: environmental, economic and social each have their individual design process, as a guide to the three topics.

Thirdly, the method was developed to fit into the work flow at JJW, by implementing their internal tool, the "one-page-strategy". This tool ensures a focus on iterations in a design project, by discussing the previous phase at each transition to the next phase.

The final step for the ISD is the composition of the team, not because it is the least important – in fact it might be one of the most important aspects of the method, because by establishing a design team in which many different competences are represented, more knowledge has already been implemented, including the knowledge of when to reach out and ask specialists for specific inputs.

This section thus introduces the ISD-method as a guide. It includes knowledge about topics, team and process, which can be the basis for discussion and elaboration in each specific case.

4. DISCUSSION AND CONCLUSION

This research was conducted at the interface between architecture and engineering. In the case studies, engineering tools and knowledge were implemented in architectural design processes, and the results were observed and analysed. The researcher was used to working at this interface between architecture and engineering, with an MSc in Architectural Engineering from the Technical University of Denmark that included specialisation in indoor climate and energy design. In the course of the PhD study, the researcher undertook further specialisation in LCA and LCC and a consultancy education on the application of DGNB for new office buildings.

JJW had not employed engineers in-house prior to the start of this PhD research and was in this regard representative of most such offices in Denmark. The researcher took part in the work of various design teams to investigate their work processes and test the implementation of different technical information as part of the development of a new design method - ISD. The three years of PhD research succeeded in testing the hypothesis underlined in the following paragraph and the results are discussed in this section, within each of the main topics in the 3.RESULTS section.

One hypothesis of the PhD research was that if all design phases work with the technical knowledge relevant to specific sustainability criteria, this will raise the level of sustainability in building projects (and the built environment). In general, the idea is that more awareness and knowledge of sustainability will occur in design teams if they use engineering digital tools in the design process, even in an architectural office. This knowledge would then inform their design decisions, resulting in a higher level of sustainability. This hypothesis was examined in case studies of various design phases, '3.2 Overall mapping of case studies at JJW' and compared to the 'baseline' of previous projects in paper (2) in APPENDIX B. The hypothesis could be confirmed in the sense that the case studies showed that it was possible to implement LCC and LCA in the design process at an architectural office. LCC and LCA affected design decisions instead of merely being used as documentation in sustainability certification. The case studies at JJW (Case 02, 12, and 21) confirmed the hypothesis by using LCA and LCC as design tools in the design process. Interviews at JJW in APPENDIX Y and the results of questionnaire Q_JJW1+2 document a steep increase in knowledge about LCC at the architectural office. In the year between these two questionnaires the researcher had managed to increase the focus on LCC and LCA, by means of presentations about LCC and LCA at JJW for all employees and specific case studies, where the researcher performed assessments that served as inputs to the design teams. This active research mapped each design process in the case studies at JJW and observed and analysed them. The conclusion was based on observations and analysis of what influenced each design decision in real ongoing design projects at JJW. The case studies were thus able to prove the hypothesis.

The hypothesis was derived from the tradition of integrated design that assumes that a closer collaboration across different disciplines will advance sustainable building design. The present research additionally inquired how such collaboration could be made operational by proposing the new ISD-method. It was actively examined in the case studies conducted by the PhD researcher, who tested parts of the ISD-method by providing input in the form of LCA-, LCC- and IED-related technical assessments. An important part of the research was to study both the 'how to add' and the 'effect of adding' LCC and LCA to the existing IED-method and to investigate them in relation to the DGNB system. As mentioned above this was performed at an architectural office through case studies, by active research in each design team, where these concepts were implemented, and their effects were observed and analysed.

The results confirm the hypothesis that LCA and LCC can be applied as design parameters in the early design phases. They also confirm the hypothesis that by expanding the IED-method to include LCA and LCC, a higher level of sustainability can be attained.

From these results, the ISD-method was derived. It embodies the conclusions of the research and is suggested as a practical method that can be applied in Danish architectural practice.

WORK PROFILES AT ARCHITECTURAL OFFICES

From the results in Section '3.1 Work Profiles at Architectural Offices', seven different work profiles were identified. The profiles show that each architectural office is unique in layout, focus and implementation of technical knowledge, although some general traits can be observed. They show a tendency for the respondents to most often have a background as an architect, followed by construction architects and project managers. In only two of seven offices were respondents' engineers, while in three of seven at least one respondent was a landscape architect. This indicates that the employees in the seven offices were from many different professional backgrounds and also that the engineering professions are not generally represented in architectural offices in Denmark.

Most respondents reported that their own level of holistic/multidisciplinary thinking was higher than it was in their architectural offices' general design approach. This could simply indicate that the (self-selected) respondents to the questionnaires were the ones most in favour of integrated design, and the ones with most knowledge of sustainability.

The questionnaires reported that there was a high degree of knowledge about and use of daylight and energy performance tools in the design process at these architectural offices.

The questionnaires reported a lower level of knowledge in the use of LCC and LCA in the design processes. These results are described in '3.4 LCA and LCC in practice', where it is seen from the questionnaires Q_JJW1+2 that knowledge about and use of LCA and LCC at JJW was rather limited. The same applies to the Danish building industry, as reported by the interviewees, APPENDIX Y.

Although all five topics (microclimate comfort, daylight, energy performance, LCC, and LCA) were addressed in the questionnaires, there was a tendency for 'quality in design' to be mainly based on daylight tools. The next most used topic was microclimate comfort and while energy performance, LCC and LCA had less impact on design decisions. An important result is that the questionnaires show that the design process is usually based on 'rule of thumb' or 'intuition'. This means that there is a great need to include technical knowledge in design decisions. However, for many respondents 'technical inputs from others' was a common way of working. It can be argued that this was because the respondents were mainly architects, who do not conduct technical inputs themselves, as shown by the questionnaire, but receive technical inputs by collaborating with external consulting engineers.

CASE STUDIES AT JJW

The results of the case studies showed that focus on sustainability topics varied between projects. The projects were more or less equally focused on: DGNB (overall), social sustainability criteria (SOC), environmental criteria (ENV) or economic criteria (ECO). Within these topics, some specific criteria had an increased focus. Within SOC there was a focus upon daylight and thermal indoor comfort, within ENV the focus was mainly related to LCA and for ECO the focus was mainly related to LCC.

The approach taken to the topics varied, as did the degree of implementation. Specific sustainability simulations or calculations within the mentioned above criteria were used to inform the design process, to ensure that the design would be knowledge-based and would result in more sustainable architecture.

The mapping of the DGNB criteria showed that there was an increased focus on the specific criteria when a sustainability expert or the PhD researcher implemented technical knowledge. The mapping of DGNB in the case studies revealed a tendency that even projects that were not aiming at DGNB certification did include many DGNB categories. In the projects aiming at DGNB certification, most of the criteria were met, as seen in Case 03. However, the research was not able to document a higher DGNB score before and after the technical inputs, simply because the case studies were not completed within the time frame of the thesis and they had not yet been DGNB certified.

Sustainability was addressed all through the design process in Cases 02, 03, and 05, where the sustainability expert or the PhD researcher was a part of the design team from the beginning to end of the project and did not just function as a task-specific consultant. In Cases 06, 12, 15, and 21, the sustainability expert or the PhD researcher functioned only as a task-specific consultant. The sustainability expert was thereby only consulted at the very end of the process, to check and document the level of sustainability that had been attained. This observation confirms the hypothesis that by informing all design phases with technical knowledge the level of sustainability in building projects will be raised.

The level of sustainability varied greatly, ranging from 'Mentioned' to 'Fully implemented'. There was a tendency for the case studies that included daylight simulations, (Cases 02, 06, and 11) to reach a sustainability level of 'Partly implemented' or 'Fully implemented' and this was also so for LCC calculations (Cases 12, 15, and 17). This supports the results from the questionnaire that stated that daylight has a great influence on design decisions. That LCC had a similarly large impact was more of a surprise, since LCC was not a familiar term at the office before the researcher arrived, as seen in the interviews at JJW in APPENDIX Y as well as in questionnaire Q_JJW1+2. It was probably due to the high focus on economy in the building industry, for which LCC could easily be implemented in practice. The overall sustainability screenings (Cases 07, and 14) tended to be conducted just once by the sustainability expert or PhD researcher, at the start of the design process. In the later design phases, the focus was changed by the design team and did not address sustainability.

The implementation of LCA tools and methods varied rather more (Cases 05 and 15). Full building scale LCA assessments were attempted but not fully implemented in Case 05. Component scale LCA assessments is attempted and (to some degree) implemented, as seen in Case 15. This might indicate an interest and intention to use LCA but that the actual implementations of the tools were still found to be difficult in practice. This was what was indicated in the questionnaires and interviews.

The interviews with experts in the Danish building industry showed that in projects in which the client had a clear sustainability focus or made an explicit request for DGNB certification, the sustainability level was significantly increased and thus worked as a driver, APPENDIX Y. The same was true in projects in which JJW expressed an explicit intention to achieve sustainability, as in Cases 03 12, 15, 17, and 21. The case studies that used the JJW internal tool known as the 'one-page-strategy' were able to take the project to a higher level of sustainability, by addressing the topic from the initial design phases. This indicates that it is just as important to formulate an explicit intention to achieve sustainability from the beginning, as to integrate technical knowledge in the design process. However, it might also be that the stated goal of achieving sustainability motivated the effort to integrate technical information in the design process, despite its being time consuming and a challenge for everyone in the team.

<u>IED AND DGNB IN PRACTICE</u>

The mapping of IED and DGNB was able confirm another hypothesis, namely that the parameters of IED are an integral part of DGNB. However, as the mapping of IED and DGBN showed in paper (2) APPENDIX B, the IED method addresses only a limited number of DGNB criteria, as it has a narrower framework addressing energy performance and some thermal comfort parameters. A classic architectural design process starts with a very open approach, with a wide range of possibilities, which are later narrowed down to a preferred design. This 'tradition' might be challenged when introducing the IED, where analysis and technical inputs are available to quantify design concepts from the very earliest design phase. In more rigid IED setups, as paper (6) APPENDIX F showed, the design process starts with a definition of a 'solution space' possibly informed by technical inputs. The inclusion of technical knowledge and a technically defined design method thereby changes the classical architectural approach to some extent, as these limitations are not present in the creative design process. The question is, does such a change in the design process limit creative thinking and thereby reduce the architectural quality? Or whether such a change is beneficial for the design process because it

ensures a holistic approach, and sustainable architecture? This is crucial, since buildings are for people and maintaining architectural quality may mean keeping buildings instead of demolishing them, which in itself may increase sustainability and has a great impact on LCC and LCA.
Several case studies at JJW (Cases 02, 12, and 21) support the hypothesis that a design process informed by technical knowledge ensures a higher level of sustainability without compromising architectural quality.

DGNB has been the predominant certification system in Denmark since 2011. It has become a framework for sustainability on which municipalities and clients base their understanding and descriptions of sustainability. Evidence of DGNB being the defining framework for sustainability was provided by the interviews conducted among experts in the industry and in the case studies at JJW, APPENDIX Y. In that sense the prominent definition of sustainability inherent in DGNB made it a driver for sustainable buildings, to ensure a common scale of evaluation. JJW used DGNB as the framework in their internal tool, the 'One-page-strategy', to achieve a holistic approach to their projects throughout the design process. The PhD researcher was involved in the process at JJW, whereby attempts were made to make DGNB operational as a tool in design processes bu its inclusion in their one-page-strategy tool. The idea was to assist the architects at JJW to define their sustainability focus and to use a common scale for measuring sustainability. In this regard it can be argued that the DGNB system assisted architects at JJW to create more sustainable projects. However, the interviews and case studies revealed that the DGNB system cannot stand alone, because it is an evaluation system. DGNB can therefore work only partially as a process tool by implementing the 'process' category in the setup.
In current research the emphasis was on trying to use DGNB throughout each design process. However, it was observed that DGNB is difficult to operationalise as a method. Another way of spanning the entire scope and including other tools in practice was needed. For this the ISD method is a candidate. By implementing the One-page-strategy into the ISD method, it became focused on JJW and their work culture. The One-page-strategy emphasises the design iterations by continually using the tool at each phase transition. The sustainability ranking or evaluation was achieved by mapping case-relevant criteria in the 'DGNB wheel'.

LCA AND LCC IN PRACTICE

In recent decades the building industry focused mainly on energy performance, due to the increasingly strict building regulations applied to this topic, as explained in the '1.3 Background'. In the present PhD research, this has been designated the 'first wave' of sustainability in the building industry in Denmark. The second wave focuses upon sustainability in a wider perspective, where environmental, economic and social criteria are included. Here LCA and LCC play an important role. The focus on LCC and LCA derives from the DGNB criteria ENV1.1 and ECO1.1, which are very important topics if a high overall score is to be achieved in the DGNB certification system. It was also with inspiration from DGNB that the Copenhagen Municipality included LCA and LCC in their MBA as well, as was seen in the interviews.
At JJW there is a tendency for there to be rather few specialists with much knowledge about LCC and LCA and that the general level of knowledge about these topics was relatively low, as seen from the Q_JJW1+2 questionnaires. This tendency was supported by the interviews and questionnaires from other architectural offices, which documented the low knowledge level of LCC and LCA in Danish Architectural offices in general.
However, from the mapping of the DGNB criteria in the existing project briefs in Section '3.3 IED and DGNB in practice' it was seen that the existing projects at JJW did have some focus on LCA and LCC. However, the degree of fulfilment of ENV1.1 and ECO1.1 was not available. In the subsequent active participation in design projects at JJW the intention of including LCA and LCC into the design process and projects emphasised, as seen in Cases 05, 10, 12, 15, 17, 19, and 21.

In the DGNB setup, LCC and LCA were used late in the design process for evaluation purposes. However, they could often have been used in the early design changes, with limited costs, based on decisions informed by knowledge from LCA and LCC, as seen in Case 17. The fact that both LCA and LCC were originally used for post-design evaluation of finished projects has shaped the understanding of LCA and LCC in the industry. LCC has great potential when used in the early design phases e.g. to ensure that design decisions will be taken on an economic basis, with more insight, as seen in Case 12. For refurbishment projects, this can influence the evaluation of the lifetime and robustness of existing materials, e.g. to estimate the appropriate level of refurbishment, as seen in Cases 15 and 17. LCA can also inform the early design phases, by defining the most sustainable option for the main structure of a building, as seen in Cases 12 and 21. Or to support the registration process of existing buildings, to compare existing embodied emissions to those of a demolishment scenario, as seen in Cases 05 and 15.

Despite the potential for using LCA in the early design phases, there are also limitations due to limited data for the calculations and the fact that the calculations can be rather time consuming. These two limitations were the main concerns of the interviewee in '3.4 LCA and LCC in practice', APPENDIX Y.

The implementation of LCA and LCC tools are in development in the building industry, which is emphasised in Section '3.4.1 LCA and LCC as design tools'. Some simple tools are available to the Danish building industry without cost, such as LCAByg and LCCByg and other tools that are more complex to use in the building design process, as discussed in Paper (5) APPENDIX E. The complexity of implementing the tools in practice has caused some companies to develop their own tools, as emerged in the interviews with experts in building industry. Some offices develop interfaces with BIM and LCA and LCC to implement these parameters directly in the design process, as stated in the interviews in Section '3.4.1 LCA and LCC as design tools', APPENDIX Y.

There are no regulations requiring the use of LCA in the Danish building industry. This limits its use in practice because it is simply considered to be an extra cost. However, the questionnaire study and interviews with experts on sustainability in the Danish building industry documented that LCC and economic considerations are the driving factor for implementing LCA in building design projects in practice. LCC is of more interest to architects because it can provide a justification for more expensive one-time-costs if they can be shown to be cheaper in the long run due to less maintenance and a more long-lasting solution. This may be optimal for clients too, as it ensures lower costs in the long run.

INTEGRATED SUSTAINABLE DESIGN

The *raison d'être* for the ISD method is the increasing demand for quantifying sustainability and the lack of methods for achieving this in a building design process. It is essential to implement knowledge of actual sustainability levels into the design processes, as shown the results that were discussed above. The ISD method can meet this demand for quantification of sustainability and can ensure a common, integrated process for both sustainability and design development that is capable of replacing the current approach of following two parallel processes. In a number of architectural offices – including JJW – sustainability experts typically manage the process of documenting sustainability as a separate track.

In order to facilitate a process that integrates sustainability with design development, the respected and already operational and implemented IED-method was chosen as the basis for design development in the initial design phase. This was then supplemented by adding the perspective of sustainability, by including LCA and LCC elements, which increases the complexity by the introducing factors that are expressed in different units. There is no longer a common unit of *kWh/m2 per year* that quantifies the output but also *Euro/m2 per year* and the environmental emissions shown in Figure 80. Comparisons therefore become more difficult, which differentiates ISD from IED. The difference between IED and ISD is also manifested in the approach to different design phases, where IED is somewhat static, focusing mainly on the initial design phase, although it can be implemented in other phases as well, as seen in the case studies at JJW. ISD deals with the entire life cycle of the building and including even the ‘End of Life’ and ‘Afterlife’ phases. These two building life cycle phases have great environmental impacts, because of the environmental impacts embedded in the building mass. An example of the importance of considering the ‘End of Life’ and ‘Afterlife’ of buildings when making a design decision was shown in Case 05. Here one small building material containing the hazardous chemical PCB impacted the entire building mass and thereby resulted in large environmental, economic, and social costs, as described in ‘3.2.3 CASE 05’.

The ISD-method is based on the Danish Description of Service, which is the foundation for design processes and economy in practice and is therefore familiar to all practitioners: It can be argued that the Danish Description of Service is conservative and does not fit very well with new design processes and other recent changes in the building industry. In the present PhD research this problem was emphasised in Paper (6), APPENDIX F. However, is undeniable that basing ISD on the Danish Description of Service will facilitate its implementation in practice, since it is so well known, as emphasised in Section ‘3.6.1 Step 1: Life cycle approach for the ISD, based on the Description of Service’. The Description of Service is usually associated with restrictions in process and economy, whereas the ISD-method emphasises the iterative design process.

The ISD method is generic but can be adapted to use in specific work profiles at different offices, as was done at JJW by including the JJW-specific tool known as the ‘One-page-strategy’. ISD can influence the entire design process culture of an office by generating a strong awareness of sustainability through the ongoing quantification and visualisation of sustainability levels that it requires. However, ISD in itself is not a design process culture, it is instead a guide that can accommodate different individual design processes, as all design projects and design teams are unique, as are the work profiles at each architectural office, which was documented in the present research, so the solution must be ‘tailored’ to fit each office.

The high costs of DGNB certification can be the reason that many projects are not certified. To raise the general level of sustainability, a “light” version of the DGNB can make it easier to reach some degree of sustainability, without performing the full DGNB certification. The ISD-method is a way to achieve this in practice, without additional costs. The idea is that if sustainability has already been implemented as part of the design process, then it will not be more costly to design sustainable buildings compared to ‘regular’ building design.
A greater focus on sustainability and the life cycle of a building has had an impact on the Danish building industry, which led to a rapid development of tools and methods in the same timeframe as this PhD research. The ISD-method is therefore only one of many possible approaches to handling sustainability in the design process. However, the method is available for all to use, challenge and develop in practice. Architects may criticise the method as being unduly influenced by the PhD researcher’s own background in architectural engineering and thus intended to introduce as many engineering tools and methods as possible to the architectural design processes. However, if the building industry works together, sustainability will be more attainable than if individual companies and professions go their own way.

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6. FIGURES

7. TABLES

8. APPENDIX

APPENDIX A

PAPER (1)

In: Proceedings of the Integrated Design Conference ID@50, 2016, University of Bath (ISBN-13: 978-0-86197-192-3. ISBN-10: 0-86197-192-2)

Conference paper presented at the Integrated Design Conference ID@50

MAPPING ONE YEAR'S DESIGN PROCESSES AT AN ARCHITECTURE FIRM SPECIALIZED IN SUSTAINABLE ARCHITECTURE – HOW DO SUSTAINABILITY CERTIFICATION SYSTEMS AFFECT DESIGN PROCESSES?

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ABSTRACT: The current study mapped how a Danish architecture firm integrated sustainability in their projects over a year. All the projects concerned were aimed at being sustainable within the framework of the DGNB certification system. The focus of DGNB is equally divided between environmental, economic and social aspects. During the mapping process, a picture was drawn of the state of the art for integrating DGNB in design processes and of the challenges involved. Case studies formed the basis of the study and helped substantiate the complexity of integrating DGNB's criteria as design parameters in practice.
The framework for the study is the increased focus in recent decades on minimizing the energy consumption used for operating buildings, because the building industry accounts for 40% of the total energy consumption in the EU. This focus has led to more optimized design processes within the framework of the Integrated Energy Design (IED) method, in which many decisions related to indoor climate and energy consumption are made in the early stages of the design process and have therefore become an important design factor for both architects and engineers. The tendency is now to widen the perspective to design decisions in all phases of the entire lifecycle of a building. Life Cycle Assessment (LCA) moves to the fore in the design process to make it possible to meet the overall purpose of reducing CO_2 emissions and the general environmental impact of the entire building industry.

Keywords – IED, DGNB, Design method, Sustainability, Case study

1. INTRODUCTION

Sustainability was introduced and defined for the first time as equally vital for economic, environmental and social development in the Brundtland Report in 1987 (Brundtland 1987). This understanding of sustainability has since been developed as a natural part of design methods as well; one outcome was the Integrated Energy Design (IED) method (Intelligent Energy Europe 2009). The main purpose of the IED method is to limit the primary energy consumption in the operation phase of the building as a way of achieving the aim of sustainable buildings. An important tool for the IED method is the Kyoto Pyramid, which was developed in Norway as a passive energy design strategy (Intelligent Energy Europe 2006). The Kyoto Pyramid has since been developed and simplified, underlining the three steps in the design process: Reduce, Optimize and Produce. This simplified version of the Kyoto Pyramid, shown in the simple graphic in *Figure 1* (Kongebro 2012), is the version used in this study. The IED method explicitly focuses on the bottom level of the pyramid – the early design phases – arguing that 'reduce' is achieved by careful geometry: window façade design and orientation. IED focuses solely on indoor climate and energy balance. Another approach for achieving the idea of sustainable buildings has been the development of several certification systems in recent years. The German certification system DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) was adapted in 2010 to Danish requirements and standards. The aim of the certification system was to increase the focus upon sustainable buildings and create a quantifiable reference standard. The Danish DGNB certification system is administrated by the Green Building Council (DK GBC). There are various certification categories, defined by the building typology. For this study, we used the version for office buildings. The DGNB certification system has five categories, of which the Economic, Environmental, Social and Technical criteria have equal weight (22.5%) while the Process criteria weigh 10% of the total, as shown in *Figure 2* (DK-GBC 2014). The DGNB manifests a much broader perspective with many more parameters than are included in the IED method, in which the focus is solely on indoor climate and energy consumption during the operation of the building.

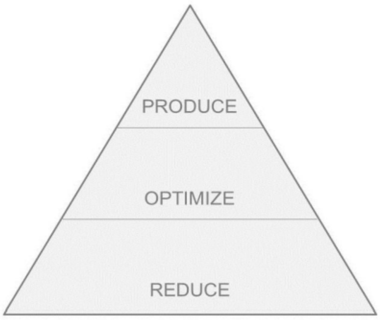

Figure 1 – Kyoto Pyramid
(Kongebro 2012)

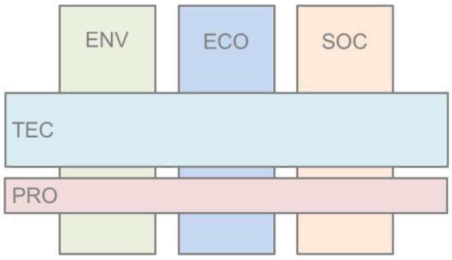

Figure 2 – DGNB's criteria
(DK-GBC 2014)

The increased interest in sustainable buildings has affected the processes of design across the whole range of the building industry, and in particular how architects work. Although the focus upon sustainability has increased, its broad definition has made the process of reaching the goals difficult, and it is therefore still a tense topic (Intelligent Energy Europe 2009). The research question is how to develop early-phase design methods that include more and more parameters without losing the benefits of IED.

2. METHOD

The research this paper describes was conducted in two parts. First, we made an overall study of the Integrated Energy Design (IED) method in the framework of the Danish version of the DGNB certification system to get an overview of the sustainability criteria which are directly and indirectly related to the design method. Second, we carried out a mapping of projects over a year at an architectural firm in Denmark. This study was based upon the known IED method, but the DGNB certification system was also used as a framework for analysing sustainability in state-of-the-art design processes. In this way, we intended the study to give an indication of whether the IED method promotes sustainability as shown in *Figure 2* from the DGNB certification system. Furthermore, we used case studies to investigate whether the DGNB system is practical in a design team. The method of this study was to use a mapping process which has been developed as tables based upon the Integrated Energy Design (IED) method. The tables ensure an operational process tool which can be further expanded if needed and integrated into a variety of projects. The mapping was also carried out in the framework of the DGNB system, with the aim of quantifying sustainability in the architectural design processes. The mapping process in this study was divided into three different studies, which are described in the following sections.

2.1 Mapping IED in the framework of DGNB

The IED method was the object of the first study, in which it was mapped in the framework of the DGNB criteria. This study distinguished between the DGNB criteria that are directly related to IED and are automatically fulfilled during the process of using the IED design method, and the indirect DGNB criteria, which will only be fulfilled to the extent the design team actively changes the early-phase design process specifically to address these DGNB criteria. The IED parameters evaluated is shown in *Table 1*.

Table 1 – List of IED parameters (*Kongebro* 2012)

IED-Process	IED-Parameters
Reduce	Context
	Orientation/placement
	Geometry
	Daylight
	Façade design
	Zone-programming
	Structural concept
	Energy concept
	Use of roof area
Optimize	Windows
	Lighting
	Ventilation
	Cooling/heating system
	Automation/controlling
Produce	Renewable energy
	Passive heating

The first step in the design process is to reduce the IED-parameters to increase the quality of the building from the very beginning. Next the buildings are further detailed and optimized with regard to indoor climate and energy consumption and, finally, additional renewable energy production may be needed to achieve the energy framework (Intelligent Energy Europe 2009). The DGNB criteria for office buildings are shown in Table 2, which gives an overview of the framework for the study (DK-GBC 2014).

Table 2 – The criteria of the DGNB certification system (DK-GBC 2014).

	Global and local environment	SOC 2.2	Public Access
ENV 1.1	Life Cycle Impact Assessment (LCA) - Environmental impacts	SOC 2.3	Cyclist Facilities
	Environment Impact		**Aesthetics**
ENV 1.2	Local Environment Impact – High-risk materials for environment and health	SOC 3.1	Design and Urban Quality
ENV 1.3	Responsible Procurement – certified timber and natural stone	SOC 3.2	Integrated Public Art
	Resources and waste	SOC 3.3	Plan layout and disposal
ENV 2.1	Life Cycle Impact Assessment – Primary Energy (LCA)		**Technical completion**
ENV 2.2	Drinking Water Demand and Waste Water Volume	TEC 1.1	Fire Safety
ENV 2.3	Land Use	TEC 1.2	Sound Insulation
	Total life cycle costs	TEC 1.3	Building Envelope Quality
ECO 1.1	Life Cycle Cost (LCC)	TEC 1.4	Adaptability of Technical Systems
	Economically guaranteed future	TEC 1.5	Cleaning and Maintenance
ECO 2.1	Flexibility and adaptability	TEC 1.6	Deconstruction and Disassembly
ECO 2.2	Robustness		**Planning process**
	Health, comfort and user satisfaction	PRO 1.1	Comprehensive Project Brief
SOC 1.1	Thermal Comfort	PRO 1.2	Integrated Design
SOC 1.2	Indoor Air Quality	PRO 1.3	Design Concept
SOC 1.3	Acoustic Comfort	PRO 1.4	Sustainability Aspects in Tender Phase
SOC 1.4	Visual Comfort	PRO 1.5	Documentation of Facility Management
SOC 1.5	User Control		**Building process**
SOC 1.6	Quality of outdoor spaces	PRO 2.1	Environmental Impact of Construction
SOC 1.7	Safety and Security	PRO 2.2	Construction Quality Assurance
	Functionality	PRO 2.3	Commissioning
SOC 2.1	Design for All / Accessibility		

Because the main focus of the IED method is upon optimal indoor climate and energy balance in the building, we carried out a further mapping in the operation phase. Here, the focus was expanded to the entire life cycle of the building, but still focusing upon the primary energy balance. Finally, to round off the first study, the entire life cycle and its environmental impacts were included to examine the fulfilment of the DGNB criteria.

2.2 Mapping IED in case projects

The entire mapping process was carried out at a Danish architectural firm that specialises in sustainable buildings. The case projects varied in typology, ranging from schools and residential projects, to town halls and homes for the care of the elderly, but they all had the common aim of creating sustainable buildings in terms of the DGNB system, *Table 3*.

Table 3 – List of case projects and typology

C01 - Homes for the elderly	C06 - Hospital
C02 - Town hall	C07 - Residential buildings
C03 - Residential buildings	C08 - School
C04 - Homes for the elderly	C09 - School
C05 - Office building	C10 - Homes for the elderly

All case projects selected were carried out during 2015 and the number of cases is defined by their common focus upon sustainability. The amount of projects complying with this frame amounted to 10 during 2015. The design teams for all 10 cases were structured alike, with an internal sustainability manager advising and guiding the projects during the process. The sustainability manager also contributed with the sustainability-related description and diagrams in the final submitted folders for the competitions. In this respect, the dictums of IED were honoured (Gaardsted *et al.* 2007). The mapping of IED parameters was carried out by scanning the available material from all cases, which consisted of the final submitted folders. The mapping identifies whether the method was used in all cases and whether all parameters were taken into account. The mapping was conducted to indicate the state of the art with regard to using the IED method in design processes.

2.3 Mapping DGNB criteria in case projects

To take the study a step further, the 10 cases were then analysed with regard to the DGNB certification system. The mapping distinguished between DGNB criteria that were directly and indirectly fulfilled to examine to what degree the sustainability parameters were taken into account. We investigated whether the full life cycle of the building was taken into account and whether all five main criteria of the DGNB system were included in the projects. Finally, we investigated whether the building typology had a big influence upon the integration of DGNB criteria in the design process.

3. RESULTS

The results of the study are divided into three sub-sections (like the method) to fully underline the outcome of each study. The mapping was the main tool for the study and constitutes the main result, as is clearly illustrated in the tables and figures of this section.

3.1 Mapping IED in the framework of DGNB

The mapping was conducted in the form of a table as a synthesis of data and furthermore, the tables are transferred into graphics to underline and illustrate the findings. In the first two columns of *Table 4*, the IED parameters are listed in relation to the three design steps; Reduce, Optimize and Produce. The third column contains the directly related DGNB criteria for primary energy consumption, distinguishing between DGNB's main criteria and its indicators. The last column contains the indirectly related DGNB criteria and indicators, and also includes the environmental impact categories.

Table 4 – Mapping IED in the framework of DGNB

IED-Process	**IED-Parameters**	**Primary energy**		**Environmental impacts**	
		Direct		Indirect	
		DGNB criteria	Indicators fulfilled	DGNB criteria	Indicators fulfilled
Reduce	Context	SOC1.4	1+2	ECO1.1	
	Orientation/placement	ENV2.1	B6	ECO2.1	1
	Geometry			ENV1.1	A1+A2+A3+ B4+B6
	Daylight			ENV1.2	
	Façade design			ENV1.3	
	Zone-programming			PRO1.3	
	Structural concept			SOC3.3	1.1+2.3+2.4
	Energy concept				
	Use of roof area				
Optimize	Windows	SOC1.1	1-8	ECO1.1	
	Lighting			ENV1.1	B4+B6+C3+
		SOC1.2	2		C4+D
	Ventilation	ENV2.1	B6	ECO2.2	
	Cooling-/heating/system			TEC1.6	
	Automation/controlling			PRO2.3	
Produce	Renewable energy	ENV2.1	B6	ECO1.1	
	Passive heating			ENV1.1	B6+C3+D

Table 4 and *Figure 3* give an overview of the mapping. The diagram is designed as a simplified version of the DGNB evaluation graph, in which each criterion is indicated for the related percentage of the total certification (DGNB - German Sustainable Building Council 2013). In this way, a difference in the various steps of the IED method directly and indirectly related to DGNB criteria can easily be measured, so that the mapping is quantified in the framework of DGNB. The bright-coloured cells indicate the direct DGNB criteria and the pale-coloured

cells indicate the indirect DGNB criteria fulfilled.

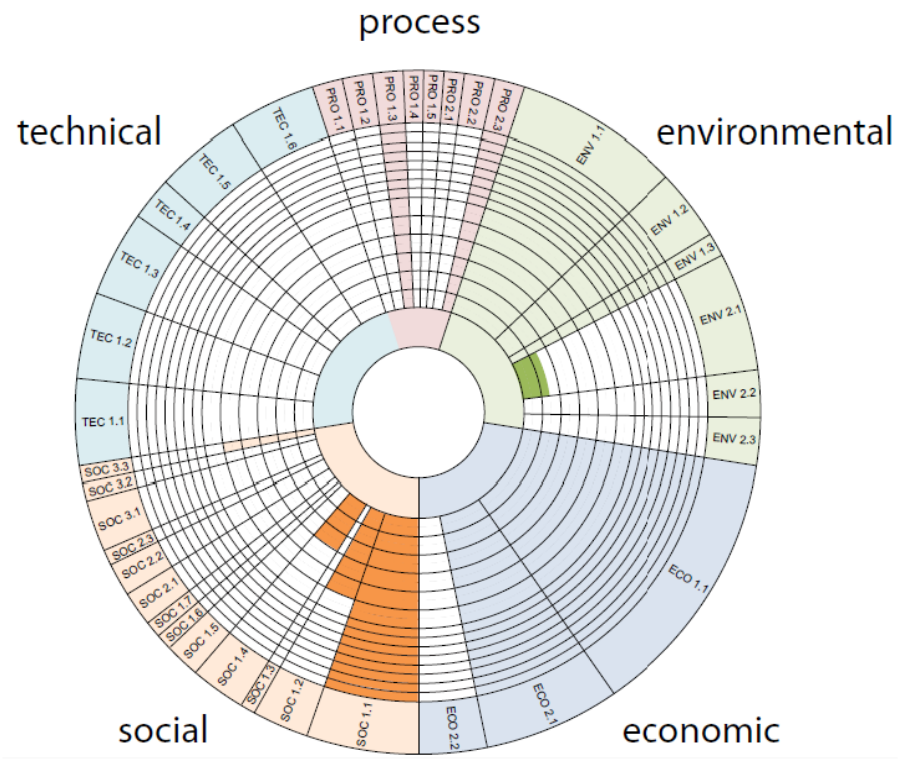

Figure 3 – DGNB evaluation graph of IED in the framework of DGNB

The diagram in *Figure 3* shows how few DGNB criteria will be affected when the only focus is on the primary energy of the operation phase, as opposed to when the focus is extended to the entire life cycle and environmental impacts as well, and Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) become the main parameters. Since such a small number of the DGNB criteria are affected, it seems clear that the use of the IED method alone is not enough to ensure a sustainable design. It can be argued, however, that it is an important step towards a sustainable design method because it has a direct focus and guides design decisions during the process toward that focus.

3.2 Mapping IED in case projects

The IED method is not intended to be followed directly step-by-step, but meant as a guideline, which gives a natural flow to the decision-making from the very early design phase. At the architectural firm, IED is not the usual approach, but was used as the basis for this study, so it is interesting to see the compliance with this design method.

The results from the mapping process are intended to quantify sustainability in the design method of IED, which is directly indicated by the strict definitions and grid for the process. *Table 5* shows the mapping of the 10 case projects in relation to the IED method and parameters. The cases are labelled C01-C10, as previously in *Table 3.* All the grey cells marked with “X” have the related IED-parameters integrated within the design of the given case project.

Table 5 – Mapping IED in 10 case projects

IED-Process	IED-parameters	C01	C02	C03	C04	C05	C06	C07	C08	C09	C10
Reduce	Context	X	X	X	X		X	X	X	X	X
	Orientation/ placement	X	X	X	X		X	X	X	X	X
	Geometry	X	X	X	X		X	X	X	X	X
	Daylight	X	X	X			X	X	X	X	X
	Façade design	X	X	X	X		X	X	X	X	X
	Zone-programming	X	X	X	X		X	X	X	X	X
	Structural concept	X			X	X	X	X	X		
	Energy concept	X	X	X	X	X	X	X	X	X	X
	Use of roof area	X	X	X	X			X		X	X
Optimize	Windows	X	X	X	X			X		X	X
	Lighting	X	X		X			X		X	X
	Ventilation	X	X	X			X		X	X	X
	Cooling/heating system		X	X		X	X	X	X	X	X
	Automation/ controlling		X						X		
Produce	Renewable energy	X	X	X				X	X	X	X
	Passive heating										

The case study indicates the degree to which the IED design method was used in the design processes at the architectural firm. Analysis of the results shows that 6 out of 10 cases include 75% or more, 3 out of 10 cases include 56% or more of the design parameters and 1 out of 10 cases includes only 19% of the design parameters from the IED method. The study shows that though IED is not explicitly used by the architectural firm, the IED approach to design is nevertheless implicit in the design process of most projects. Only in one case (C05) does a completely different approach seem to have been used for the design process, as only few IED-parameters are in focus.

3.3 Mapping DGNB criteria in case projects

As a follow-up on the previous study, a mapping of topics outside the IED method was conducted to examine the overall focus upon sustainability in the project cases. Most of the project cases had some focus areas in the final folder, which were scanned to identify additional parameters to the parameters from the IED method.

Table 6 gives an overview of the parameters mentioned in the 10 case projects as focus areas additional to those of the IED method. This study is a link towards identifying the related DGNB criteria in all the project cases. The table illustrates the mapping of the additional parameters; the cells are marked with grey and an “X”.

Table 6 – Mapping sustainability criteria in 10 case projects

Additional parameters	C01	C02	C03	C04	C05	C06	C07	C08	C09	C10
Acoustics/Noise	X	X		X			X		X	
Flow	X	X	X	X					X	
Accessibility	X	X	X	X		X			X	X
Identity	X	X	X	X		X	X		X	X
Materials	X	X	X	X	X	X	X		X	X
Flexibility		X				X			X	
User interaction			X			X				
View			X						X	X
Site (LAR, biodiversity)	X		X	X			X	X	X	
Green facades							X			
Renovation		X		X				X		
Energy monitoring		X	X							
Rain water collection		X	X				X			

Finally, the 10 case projects were set in the framework of DGNB to put a value on the sustainability parameters, as shown by the percentage fulfilment of the DGNB criteria in *Figure 4*.

When the cases are related to the DGNB system, we find that they not only accommodate specific DGNB criteria directly in relation to the IED method but also a broader range indirectly as well, which indicates the complexity of the topic. But if we ignore the IED method and look directly at the cases in relation to the DGNB criteria, quite a high percentage of the cases include a number of the criteria, as shown in *Figure 4*.

As mentioned previously, this study does not take into account the degree of fulfilment for each criterion, and this means it is not possible to evaluate the sustainability of each case based upon this study, but it does give a general idea of the mind-set of the design teams involved and their attitude to sustainability. Neither does the study give an indication of the criteria and decisions, which are strongly dependent upon each other. In fact, decisions can have completely opposite (negative or positive) influences upon the various criteria. Here we might mention the issues related to daylight, indoor climate and energy consumption as well as the economic costs related to the quality of the building materials and the related flexibility of the building, which are all very important aspects considered in several of the case studies.

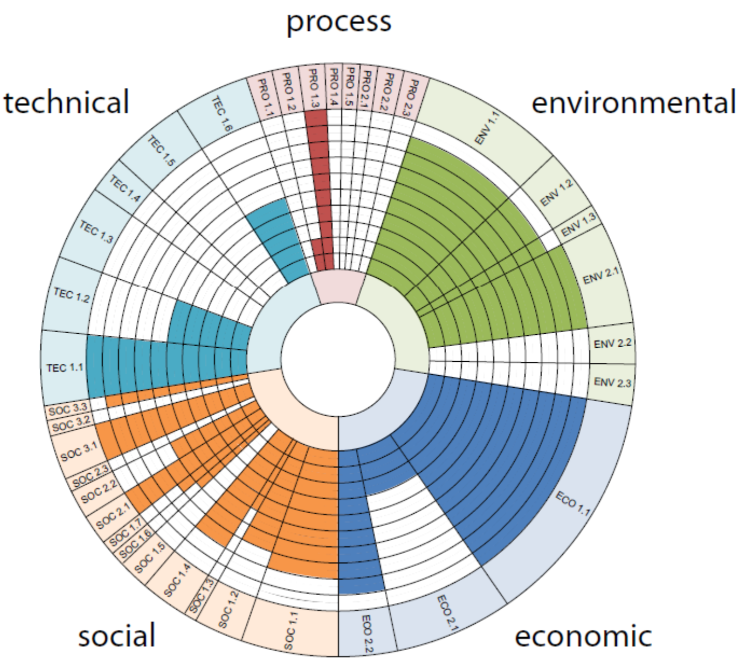

Figure 4 – The percentage of the fulfilled DGNB criteria in the 10 cases

The 10 cases studied have different building typologies, as described in *Table 2*. We wanted to see if there is a correlation between the building typologies and the degree of integration of the DGNB criteria in the design process. Here we took into account only the DGNB criteria for office buildings so as to make the study of the various projects comparable and as building typology is not the focus of this study. The graph in *Figure 5* shows the building typology related to the DGNB criteria, where the criteria are grouped into the five categories.

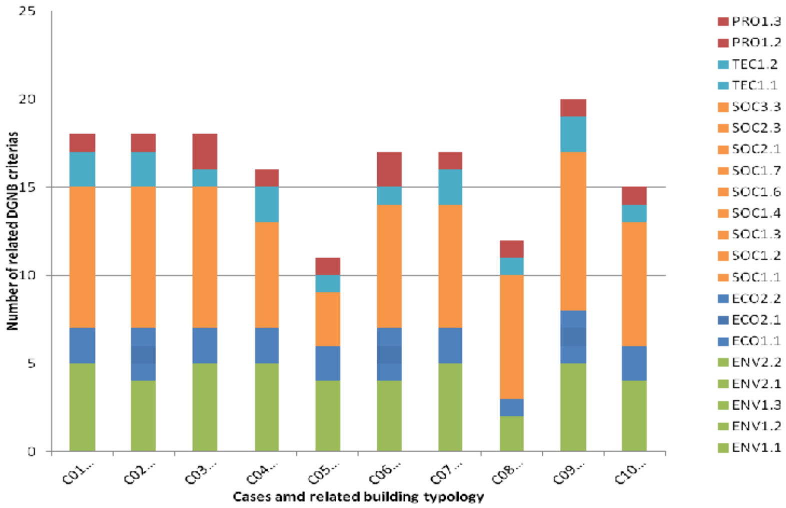

Figure 5 – Building typology related to the DGNB criteria, each criterion counted individually and grouped into the five categories.

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The graph in *Figure 5* shows that the standard practice of the DGNB is employed irrespective of the type and nature of the building typology. This indicates that the design process at the architectural firm focuses equally on the sustainability aspects defined by the DGNB criteria, despite the different building typologies. The degree of compliance to the DGNB system seems rather to be defined by the individual cases than by the building typologies, which is an interesting finding.

4. CONCLUSION

Overall, the case studies give information of the state of the art for the use of IED methods and the implementation of the DGNB criteria in projects at a Danish architectural firm. As *Figure 3* indicates, the IED method only covers a limited number of DGNB criteria because its focus is solely upon energy consumption and indoor climate in the operation phase of the building. IED covers important elements in the initial design phases, but is clearly insufficient as a stand-alone approach to sustainable design which is now much more broadly defined. The good news for IED is that it seems to have become an implicit approach in most design processes, and designers' attentions are now moving on to cover new levels of complexity. The further development of the IED method with an increased focus upon LCC and LCA might be one way of automatically increasing the number of fulfilled DGNB criteria. For IED to expand in this way and fulfil a larger number of sustainability criteria, DGNB has to be made easier to use during the design process. At the present time, the DGNB system is often implemented in the later design process as a checklist or as documentation rather than an integral part of the design method used for design decisions.

The case study at the Danish architectural firm shows that the IED method is widely used even where it is not a deliberate strategy. This indicates a general state of the art with great focus on energy demands and indoor climate in the operation of the building. Furthermore, the software industry has developed a wide range of simulation tools that facilitate the rather limited number of design parameters in the IED design method. Several of the DGNB criteria and related parameters are currently being estimated rather superficially or with simple Excel-based tools.

Nevertheless, the results of the case study also indicate a broad fulfilment of the DGNB criteria, *Figure 4* can be interpreted as showing increased focus upon sustainability and DGBN in these cases over the past year. The smaller study in *Figure 5* of the relationship between building typology and the DGNB criteria shows no correlation, which suggests that this focus on sustainability is a more general feature in all projects rather than specific to certain areas. But the design of quantifiably sustainable buildings in the DGNB sense requires an increased focus upon the integration of DGNB.

From this study, we can conclude that the IED method is very much in use and integrated in the design processes at this Danish architectural firm. Furthermore, the case studies show an increased focus upon sustainability in the framework of DGNB at the Danish architectural firm, but the spread and variation in the DGNB-related parameters that are addressed in the projects manifest a lack of systematic design method and software tools that can facilitate the design process. In the DGNB system, LCC and LCA offer more holistic methods of quantifying sustainability in terms of monetary costs and environmental impacts. Both methods include the results generated by IED in the design process. Integrating these methods into the early design phases in the way that IED has done for energy calculations and indoor environment is the new challenge for practitioners and researchers in design methods. This will be the subject of further studies in the field.

To make it possible to increase the use of DGNB in design projects from the early design phases, new design methods and tools are needed. The dramatic increase in the number of parameters compared to IED renders the DGNB process much more complex, but the rapid development of software today means that simulation tools capable of dealing with that complexity can now be produced in accordance with the new design methods.

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APPENDIX B

PAPER (2)

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How does sustainability certification affect the design process? Mapping final design projects at an architectural office

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ABSTRACT

The context of the study is the very strict regulation of energy consumption for operating buildings in Denmark. It is difficult to meet the requirements by system optimisation in the final design phase, so recent research has focused on ways of meeting the target by adapting the whole design process and informing the industry of them. This has led to optimised design processes such as Integrated Energy Design, in which many decisions related to energy consumption and indoor climate are made in the early design stages. The current tendency is to use an expanded notion of sustainability, derived from the sustainability certification system itself, and to apply it even in the early design process. This perspective emphasises all phases of the life cycle of a building. The goal of the present study was to map how a Danish architectural office approached sustainability in the projects they undertook in the course of a year. All the projects concerned were intended to conform to the German Sustainability Certification System DGNB. We developed a mapping tool to document these case projects and found that different sets of certification criteria were used in each project. This demonstrates the complexity of using them as design parameters in practice, but also that it was successfully achieved.

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KEYWORDS
Integrated energy design; DGNB; sustainability; case study; mapping

Introduction

The adoption of very ambitious political goals for energy reduction in the building industry has put pressure on the Danish building industry (Klima- og Energiministeriet, 2011). Denmark has decided to reach fossil-free energy production by 2050 (Christiansen, 2009). This political goal will require considerable investment in renewable energy production, and it will be impossible without also reducing energy consumption. The building sector is by far the largest consumer of energy (Christiansen, 2009). This has been known for decades and the 1990 goals for minimising greenhouse gas emissions by 2015 were among the most ambitious in the world (Danish Energy Agency, 2015; Energistyrelsen, Danish climate policies & Energistyrelsen, n.d.). In 2005, in Denmark as in many other countries, it became obligatory to document energy consumption in kWh per m^2 in order to obtain a building permit (Energi Styrelsen, 2007). Research performed in this period at universities in Denmark and internationally (Brunsgaard et al., 2014; Koch & Buhl, 2013) demonstrated that a large reduction in energy consumption could be obtained by addressing the overall building geometry, building orientation and window façade proportion at an early design stage. This requires the adoption of new design processes and digital tools for optimising both energy use and indoor climate. These were labelled Integrated Energy Design (IED) (Nielsen, 2012; Strømann-Andersen, 2012).

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The purpose of the present paper was to determine the extent to which IED had been implemented in an architectural office specialised in sustainable architecture, by examining over a 12-month period the projects that had focused on sustainability. A secondary question was to what extent IED can be considered to be a part of the German sustainability certification system DGNB. The Danish Green Building Council chose DGNB as the preferred sustainability certification system for the Danish Building industry (DK-GBC) (Mortensen et al., 2010). By mapping IED and DGNB parameters, it is possible to identify the changes that Danish architectural offices must make to address DGNB in the early stages of a design process. This will also contribute to determining what would be required to move from a focus on indoor climate and energy consumption (IED) to an expanded notion of sustainability.

IED and DGNB

Sustainability was introduced and defined for the first time as being equally vital for economic, environmental and social development in the Brundtland Report (Brundtland, 1987). This understanding of sustainability has since been developed as a natural part of sustainability certification systems such as the German Sustainable Building System (DGNB), which adopted a holistic approach by taking all sustainability parameters into account at the same time (Eberl, 2010). Although DGNB was developed in Germany, it has been implemented by 'green building' councils worldwide. In Denmark, it was implemented in 2010 when, after a thorough analysis of several certification systems, it was chosen by the Danish Green Building Council as the main system to be used and further developed in Denmark (DK-GBC) (Mortensen et al., 2010).

Before DGNB, the method used in Denmark was the Integrated Design Process (IDP), which was intended to provide better management of the many disciplines involved in the various design phases (Löhnert et al., 2003; Sanvido, Norton, & Sanvido, 1994). This developed into the IED method (Intelligent Energy Europe, 2009). The purpose of IED was to focus on the design process on reducing energy use in buildings. Research had shown that most savings and cost reductions are achieved in the early design phases, so IED focuses on them. It was developed in the framework of the INTEND project, whose goal was to take energy demand into account from the very beginning and throughout all subsequent building design phases (Gramkow, 2007; Jørgensen & As, 2010). This led to increased optimisation, with many decisions related to indoor climate and energy consumption being made in the early design phase following an iterative design process that included the technical considerations (Lewis, 2004; Svendsen, Petersen, & Anker Hviid, 2007). IED therefore became an important design factor for both architects and engineers. Because of the very strict Danish legislation concerning energy use, IED is widely implemented in the Danish building industry. The increased focus on indoor climate and energy consumption in buildings in the early design phases led to an increased use of design tools that can provide rapid and precise feedback to the design team (Gramkow, 2007; Oliveira, Marco, Gething, & Organ, 2017). The use of IED as a method of handling indoor climate and energy consumption has become widespread in Denmark, although the degree to which integrated design is used could still be improved (Brunsgaard & Larsen, 2015). The IED method was therefore chosen as a reference for the present research on the new design processes that architects must now use to address the much broader range of parameters in the DGNB sustainability certification process.

For the IED method to expand in this way and fulfil a larger number of sustainability criteria, DGNB must be made easier to use through all design phases. At present, the DGNB system is often implemented in the later design phases as a checklist or as documentation, rather than forming an integral part of the design method on which decisions are based on. However, the DGNB can also be used in the early design phases, as seen in the PRO1.3 criteria, where extra points are given if the design process has introduced the certification system from the very earliest design phase and all through the design process (DK-GBC, 2014). The DK-GBC also emphasises the use of the DGNB system from the very first design phase (DK-GBC, 2014). Despite these good intentions, nobody knows how to apply DGNB in the early design phases, and there is no such explanation of how this should be done. The opposite is true of IED, so it is already applied in the early design phases.

The present research attempted to map how many of design parameters that were considered were taken from the IED and from the criteria of the DGNB certification system to document the overlap of the two approaches. It was found that using IED as a design method emphasises the DGNB criteria and vice versa.

Focus from energy consumption to documentation of sustainability in an expanded perspective

The overall political goal for Denmark is to stop using any fossil fuels by 2050, to reduce CO_2 emissions. Previous research has shown that the potential for energy savings in this connection is 60–80% for new and existing buildings (Tommerup et al., 2009). By producing green energy and reducing energy use, society will be able to adjust to the elimination of fossil fuels (Tommerup et al.,2009).

The building regulations in the EU and Denmark are driving a development in which the built environment is obliged to take more responsibility for the high amount of carbon emission from the energy used in the operation of buildings. The Danish Building Regulations for 2020 mandate a reduction in the maximum allowed emissions from buildings to below what is required by the EPBD (Energy Performance of Buildings Directive), and this will ensure that the building sector can adapt to market requirements in Denmark even before the EU 2050 requirements come into force (Pohl, 2016). One specific initiative in the Danish Building Regulations is to improve daylighting conditions, requiring either a minimum of 3% Daylight Factor on average in the building or, if its light transmittance is higher than 0.75, that the glazed area should be at least 15% of the floor area. Another is that the maximum transmission loss through the thermal envelope should be 3.7 kW/m^2 for single-storey buildings, 4.7 W/m^2 for buildings with two floors and 5.7 W/m^2 for taller buildings (Danish Building Regulation, 2014).

Sustainability certification systems were first introduced by the British Building Research Establishment (BRE) in 1990 in the form of the BRE Environmental Assessment Method (BREEAM). Like many other certification systems from the same period, BREEAM focused on reducing the energy consumption of the building mass, a focus which defined the first generation of sustainable assessment tools (Ding, 2008; Ebert, Eßig, & Hauser, 2011). In the second generation of sustainable assessment tools, economic and social aspects were also included (Ebert et al., 2011). Among the second generation is the DGNB certification system, which was developed in Germany in 2007 (DGNB, 2016).

There are various versions of DGNB certification, defined by the building typology (Green Building Council Denmark, 2013). For this study, we used the version for office buildings because it is the oldest and provided the most projects for our study. The DGNB certification system has five categories, of which the economic, environmental, social and technical criteria have equal weighting

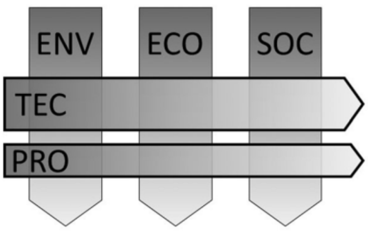

Figure 1. DGNB's five main categories of criteria illustrated by the diagram. The environmental, economic and social criteria are crossed by the technical and process criteria because they affect all three of them (DK-GBC, 2014).

(22.5%), while the process criteria are weighted as only 10% of the total, as shown in Figure 1 (DK-GBC, 2014).

The tendency now is to widen the perspective on sustainability to cover design decisions in all phases of the entire life cycle of a building. Environmental sustainability, including Life Cycle Assessment (LCA), is increasingly being used in the design process to make it possible to meet the overall aim of reducing CO_2 emissions and the overall environmental impact of the building industry. Previous studies underline the use of LCA at different levels of detail throughout the design process of a building to emphasise the design decisions and to decrease total emissions in the life cycle of the building (Takano, Winter & Hughes, 2014). In this development, the complex and wide perspective of sustainability certification systems such as DGNB become a realistic approach for early-stage design phases (Ding, 2008) However, as previously mentioned, the DGNB is used mainly as a checklist at the moment, so an operative tool is required to handle the increased complexity of taking into account all three perspectives of sustainability – environmental, economic and social – in the design process.

Method

The working hypothesis was that IED is effectively implicit in DGNB. The research required to verify this hypothesis was essentially an investigation of the state of art for implementing the IED method and the DGNB certification criteria in design projects in practice. The underlying idea was that increasing the information level behind early-phase design decisions is the key to reaching a well-documented and high-level sustainability in all three of Brundtland's areas of concern: social, environmental and economic. The research analysed recently completed projects at an architectural office specialising in sustainability.

Selection of projects

We mapped how a Danish architectural office had integrated sustainability into their projects over a period of a year. The office was representative of the category of architectural offices in Denmark that specialise in sustainability. The requirement was that the office should have a full-time employee sustainability expert, at DGNB auditor level, and have DGNB-certified projects within the case-year. With these criteria, the projects represent the highest level of sustainability in Denmark. All the projects we selected were intended to be sustainable within the framework of the DGNB certification system. The final project folders for each of the cases formed the material of the study. The research was intended to highlight the complexity of using IED parameters and DGNB's criteria as design parameters in practice. Our approach was to see whether they were used and if they were, to which degree. The case project design teams were not introduced beforehand to IED.

Mapping as method

The overall method was to use a mapping process in the form of tables summarising the main foci of the IED method. The mapping was carried out on the tables developed for the current research and tables that reflected both the IED method and the DGNB certification system. The mapping process consisted of literature-based inquiries into IED and DGNB and the final project folders of the case, and was divided into three different studies as follows.

First, an overall, general literature study was made of the IED method in the framework of the Danish version of the DGNB certification system, to provide an overview of the sustainability criteria that directly and indirectly linked the two (*General mapping of IED in the framework of DGNB*).

Second, 10 projects carried out over a year at an architectural office in Denmark that used both the IED method and the DGNB system were treated as case studies and mapped as described above. Project materials from the final project folders submitted to architectural competitions were investigated to discover whether the use of the DGNB system was evident in the final competition material and if there was any coherence between them (*Mapping IED in case projects*).

Third, the same project material was analysed in terms of the extent to which DGNB criteria had been met (*Mapping DGNB criteria in case projects*).

Results

The methods used – and the results of the mapping

General mapping of IED in the framework of DGNB

The IED method was analysed and compared to the framework of the DGNB, which differs from the IED design method. A distinction was made between the DGNB criteria that are directly related to IED (and are 'automatically' fulfilled during the process of using the IED design method), and the indirect DGNB criteria, which will only be fulfilled to the extent that the design team actively changes the early-phase design process specifically to address these DGNB criteria. The IED parameters evaluated are shown in Table 1.

An important tool for the IED method is the Kyoto Pyramid, which was intended as a passive energy design strategy (Intelligent Energy Europe, 2006). The Kyoto Pyramid has since been further developed and simplified, underlining the three steps in the design process: Reduce, Optimize and Produce. This simplified version of the Kyoto Pyramid, shown in Figure 2 (Kongebro, 2012), was the version used in this study. The IED method explicitly focuses on the bottom level of the pyramid – the early design phases – arguing that 'reduce' is the most efficient way to reduce the energy consumption for operating buildings. The 'reduce' part concerns the early design process, achieved by careful geometry: orientation, windows and façade design (Kongebro, 2012). This illustrates the importance of moving more decisions related to energy and indoor climate that is traditional to the early design phases.

The first step in the IED design process is to 'reduce' by focusing on geometry and orientation. Next, the buildings are further detailed and optimised with regard to indoor climate and energy consumption. Finally, additional renewable energy production may be required to conform to the energy framework (Intelligent Energy Europe, 2009). The IED parameters listed in Table 1 can vary from case to case, but can be seen as a step-by-step indication of the optimal process for designing a building, with the main focus on low energy consumption and an optimal indoor climate. The technical information is calculated and simulated at each step of the design process by using various simulation tools, and this is then implemented in an iterative process to inform the design process.

Table 1. List of IED parameters based on the simplified and further developed version of the Kyoto Pyramid used in this research (Kongebro, 2012).

IED process	IED parameters	Description
Reduce	Context	Overall alignment in the geographical context
	Orientation/placement	Overall strategy in accordance with the near surroundings
	Geometry	Volume and surface area are considered
	Daylight	Concept of daylight strategy for the geometry
	Façade design	From knowledge about previous steps and indoor climate
	Zone programming	Matching the qualities of the building and the functional need
	Structural concept	Best solution for specific building to achieve the parameters
	Energy concept	Reduce the energy consumption and adopt passive strategies
	Use of roof area	Extra useful square metres and direct light source
Optimise	Windows	Type, thermal properties, colours, coating, etc.
	Lighting	Artificial light due to daylight, function, etc.
	Ventilation	Improved indoor climate through optimised systems
	Cooling/heating system	With regard to structure, function and energy considerations
	Automation/controlling	To limit energy consumption
Produce	Renewable energy	Can be needed as a last step to fulfil the energy requirements
	Passive heating/cooling	Special conditions can require further passive strategies

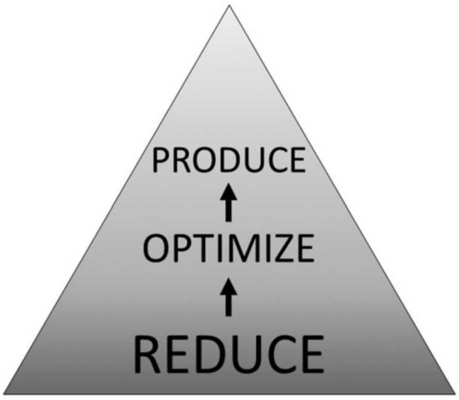

Figure 2. The Kyoto Pyramid is the main diagram of the IED method. It illustrates the design steps starting from the bottom with Reduce, Optimize and Produce.

The DGNB criteria for office buildings are divided into five main categories: Environmental, Economic, Social, Technical and Process. All the criteria are listed in Table 2, which provides an overview of the framework for the study (DK-GBC, 2014).

Because the main focus of the IED method is on optimal indoor climate and minimal energy use in the building, we carried out a further mapping in the operation phase. Here the focus was expanded to include the entire life cycle of the building, but still focused on the primary energy balance. Finally, to complete the first study, environmental impacts were included to assess the extent to which the DGNB criteria had been fulfilled.

The mapping was conducted in the form of a table as a synthesis of data. The table was transformed into graphical form to underline and illustrate the findings. In the first two columns of Table 3, the IED parameters are listed in relation to the three design steps: Reduce, Optimize and Produce. The third column contains the directly related DGNB criteria for primary energy consumption, distinguishing between DGNB's main criteria and its indicators. The last column contains the indirectly related DGNB criteria and indicators, and the environmental impact categories.

Table 2. The criteria of the DGNB certification system (DK-GBC, 2014).

Environmental		Technical	
ENV 1.1	LCA – Environmental impacts	TEC 1.1	Fire safety
ENV 1.2	Local Environment impact	TEC 1.2	Sound insulation
ENV 1.3	Responsible procurement	TEC 1.3	Building envelope quality
ENV 2.1	LCA – Primary energy	TEC 1.4	Adaptability of technical systems
ENV 2.2	Drinking water demand and waste water	TEC 1.5	Cleaning and maintenance
ENV 2.3	Land use	TEC 1.6	Deconstruction and disassembly
Social		**Economic**	
SOC 1.1	Thermal comfort	ECO 1.1	LCC
SOC 1.2	Indoor air quality	ECO 2.1	Flexibility and adaptability
SOC 1.3	Acoustic comfort	ECO 2.2	Robustness
SOC 1.4	Visual comfort	**Process**	
SOC 1.5	User control	PRO 1.1	Comprehensive project brief
SOC 1.6	Quality of outdoor spaces	PRO 1.2	Integrated design
SOC 1.7	Safety and security	PRO 1.3	Design concept
SOC 2.1	Design for all/accessibility	PRO 1.4	Sustainability aspects in tender phase
SOC 2.2	Public access	PRO 1.5	Documentation of facility management
SOC 2.3	Cyclist facilities	PRO 2.1	Environmental impact of construction
SOC 3.1	Design and urban quality	PRO 2.2	Construction quality assurance
SOC 3.2	Integrated public art	PRO 2.3	Commissioning
SOC 3.3	Plan layout and disposal		

Note: ENV: environmental qualities; ECO: economic qualities; SOC: social qualities; TEC: technical qualities; PRO: process qualities.

Table 3. Mapping IED in the framework of DGNB.

		Primary energy		Environmental impacts	
IED process	IED parameters	Direct DGNB criteria	Indicators fulfilled	Indirect DGNB criteria	Indicators fulfilled
Reduce	Context	SOC 1.4	1 + 2	ECO 1.1	
	Orientation/placement	ENV 2.1	B6	ECO 2.1	1
	Geometry			ENV 1.1	A1 + A2 + A3 + B4 + B6
	Daylight			ENV 1.2	
	Façade design			ENV 1.3	
	Zone programming			PRO 1.3	
	Structural concept			SOC 3.3	1.1 + 2.3 + 2.4
	Energy concept				
	Use of roof area				
Optimize	Windows	SOC 1.1	1–8	ECO 1.1	
	Lighting	SOC 1.2	2	ENV 1.1	B4 + B6 + C3 + C4 + D
	Ventilation	ENV 2.1	B6	ECO 2.2	
	Cooling/heating/system			TEC 1.6	
	Automation/controlling			PRO 2.3	
Produce	Renewable energy	ENV2.1	B6	ECO 1.1	
	Passive heating			ENV 1.1	B6 + C3 + D

Notes: The table contains the IED parameters from the Kyoto Pyramid in the first two columns. The third and fourth columns contain the results of the mapped DGNB criteria related to primary energy and environmental impacts.
ENV: environmental qualities; ECO: economic qualities; SOC: social qualities; TEC: technical qualities; PRO: process qualities.

Taken together, Table 3 and Figure 3 give an overview of the results of the mapping. Figure 3 was designed as a simplified version of the DGNB evaluation graph, in which the percentage it represents of the total certification is given for each criterion (DGNB – German Sustainable Building Council, 2013). In this way, a difference in the various steps of the IED method directly and indirectly related to DGNB criteria can easily be measured, so that the mapping is quantified within the framework of DGNB.

Figure 3 shows the number of DGNB criteria that will be affected when the sole focus is on the primary energy of the operation phase, as opposed to when the focus is extended to the entire life cycle and to environmental impacts, in which case the Life Cycle Costing (LCC) and LCA become the main parameters. Since such a small number of the DGNB criteria are affected, it

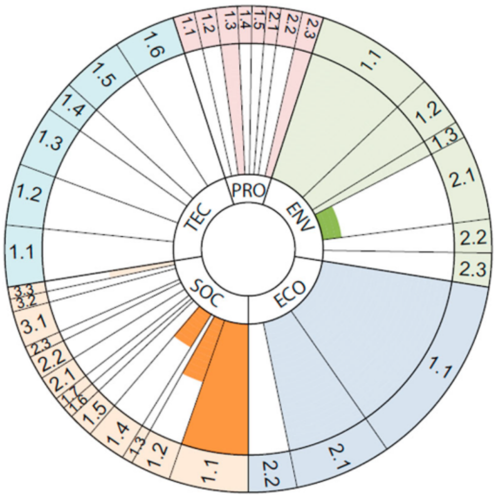

Figure 3. DGNB evaluation graph of IED in the framework of DGNB illustrated in the DGNB wheel diagram, where the bright-coloured cells indicate the direct DGNB criteria and the pale-coloured cells indicate the indirect DGNB criteria fulfilled by the use of the IED process. The diagram segments are labelled with the numbers related to the full names in Table 2.

seems clear that the use of the IED method alone is not enough to ensure a sustainable design or to decrease CO_2 emissions as intended. It can be argued, however, that it is an important step towards a sustainable design method because it has a direct focus and guides design decisions during the process towards that focus. Furthermore, LCC and LCA tools are available for use by the building industry, which makes the step more reasonable.

Mapping IED in case projects

The entire mapping process was carried out at a Danish architectural firm that specialises in sustainable buildings. The case projects were of various types, ranging from schools and residential projects to town halls and homes for the care of the elderly, but they all had the goal of creating sustainable buildings in terms of the DGNB system (Table 4). Theoretical projects were not studied.

All the case projects selected were carried out during 2015 and shared a common focus on sustainability. The number of projects complying with this framework in 2015 was 10. The design teams for all 10 cases were structured alike, with an internal sustainability manager advising and guiding each project during the process. The sustainability manager also prepared the sustainability-related description and diagrams in the final folders submitted for the competitions. In this respect, the dictums of IED were respected (Gaardsted, Kamper, & Højbjerg, 2007). The mapping of IED parameters was carried out by scanning the material available from all the final folders submitted. The mapping identified whether the IED method was used in all cases and whether all parameters were taken into account. The purpose of the mapping was to define the state of the art in using the IED method in design processes in practice, as described previously.

IED is not the only approach used at the firm but was used as the basis for this study, so it was possible to see to what extent the design teams complied with this design method.

The results from the mapping process were intended to quantify sustainability in the design method of IED, which is indicated by the strict definitions and grid for the process. Table 5 shows the mapping of the 10 case projects in relation to the IED method and parameters. The cases are labelled C01–C10, as in Table 4. All the cells marked with '●' have the related IED parameters integrated within the design of the given case project.

The case study indicates the degree to which the IED design method was used in the design process. Analysis of the results shows that 6 out of 10 cases included 75% or more, 3 out of 10 cases addressed at least 56% of the design parameters and 1 out of 10 cases included only 19% of the design parameters of the IED method. The study shows that although IED is not exclusively used, the IED approach to design was nevertheless implicit in the design process of most projects. Only in one case (C05) does a completely different approach seem to have been used for the design process, as very few IED parameters were addressed.

The results show that even though the architectural office did not explicitly address the IED method, the use of DGNB had the effect of inducing a focus on IED parameters.

Mapping DGNB criteria in case projects

To take the study a step further, the 10 cases were then analysed with regard to the DGNB certification system. The mapping distinguished between DGNB criteria that were directly and indirectly

Table 4. List of the case projects used and their type from an architectural firm in Denmark.

Case number and building typology	
C01 – Homes for the elderly	C06 – Hospital
C02 – Town hall	C07 – Residential buildings
C03 – Residential buildings	C08 – School
C04 – Homes for the elderly	C09 – School
C05 – Office building	C10 – Homes for the elderly

Note: Cases are identified by C and a number.

Table 5. The results of the mapping of the use of IED in the case projects at the architectural firm.

IED process	IED parameters	C01	C02	C03	C04	C05	C06	C07	C08	C09	C10
Reduce	Context	●	●	●	●		●	●	●	●	●
	Orientation/placement	●	●	●	●		●	●	●	●	●
	Geometry	●	●	●	●		●	●	●	●	●
	Daylight	●	●	●			●	●	●	●	●
	Façade design	●	●	●	●		●	●	●	●	●
	Zone programming	●	●	●	●		●	●	●	●	●
	Structural concept	●			●	●	●	●	●		
	Energy concept	●	●	●	●	●	●	●	●	●	●
	Use of roof area	●	●	●	●			●		●	●
Optimize	Windows	●	●	●	●			●		●	●
	Lighting	●	●		●			●		●	●
	Ventilation	●	●	●			●		●	●	●
	Cooling/heating system		●	●		●	●	●	●	●	●
	Automation/controlling		●						●		
Produce	Renewable energy	●	●	●				●	●	●	●
	Passive heating										

Note: '●' indicates a relation between IED and the given case.

fulfilled and examined to what extent the sustainability parameters were taken into account, regardless of when or how in the design process. We investigated whether the full life cycle of the building was taken into account and whether all five main criteria of the DGNB system were included. We also investigated whether building type had any significant influence on the integration of DGNB criteria into the design process.

Topics outside the IED method but included in DGNB were also mapped to examine the overall focus on sustainability. Such topics were present in most of the project cases, and Table 6 provides an overview of them. The table illustrates the mapping of the additional parameters marked with an '●'.

The 10 case projects were then described in the framework of DGNB. Figure 4 shows the percentage of the total number of DGNB criteria that were taken into account.

It is clear that the case projects included many DGNB criteria directly by using the IED method, but many more indirectly, indicating the complexity of the topic. Considering the projects only in terms of DGNB criteria, Figure 4 makes clear how many were not included in the IED, namely ENV1.1–ENV2.1, which are related to LCA and environmental material properties, and ECO1.1 related to LCC. Both LCA and LCC were used extensively to address the environmental and economic aspects of sustainability.

The present study determined the extent to which each DGNB criterion was met, but it also provides a general idea of the mindset of the design teams involved and their attitude to sustainability. The working hypothesis was that it is possible to achieve a higher level of sustainability by using the methods developed in the IED framework, with its focus on the early design stages, and still be able

Table 6. The results of the mapping of the use of DGNB criteria in the case projects at the architectural firm.

Additional parameters	C01	C02	C03	C04	C05	C06	C07	C08	C09	C10
Acoustics/Noise	●	●		●			●		●	
Flow	●	●	●	●					●	
Accessibility	●	●	●	●		●			●	●
Identity	●	●	●	●		●	●		●	●
Materials	●	●	●	●	●	●	●		●	●
Flexibility		●				●			●	
User interaction			●			●				
View			●						●	●
Site (Local Drainage of Rainwater, biodiversity)	●		●	●			●	●	●	
Green facades							●			
Renovation		●		●				●		
Energy monitoring		●	●							
Rainwater collection		●	●				●			

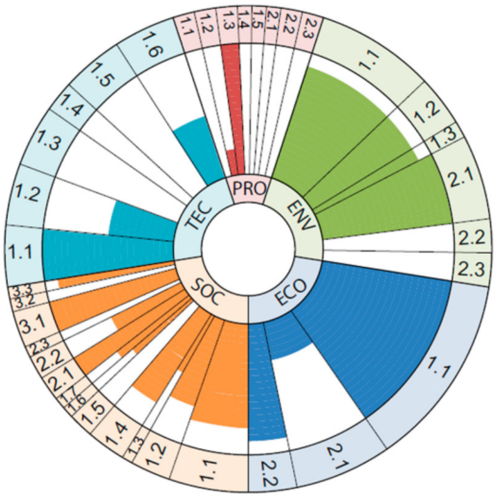

Figure 4. The DGNB wheel diagram illustrates the percentage of fulfilled DGNB criteria in the cases. The bright-coloured cells indicate the DGNB criteria fulfilled. The diagram segments are labelled with the numbers related to the full names in Table 2.

to handle a much larger degree of complexity. It shows how to develop an early-phase design method that includes more sustainability parameters and is therefore able to handle greater complexity without losing the benefits of IED.

The 10 cases studied included several different building types (Table 2). The graph in Figure 5 shows building type related to the DGNB criteria, where the criteria are grouped into the five categories.

It shows that DGNB was employed irrespective of the type and nature of the building.

The extent to which the DGNB system was used seems to have been determined by the individual cases than by building type. This was the case for C01, C04 and C10, which are all of the same type but vary in their environmental, social and technical compliance with the DGNB.

Discussion

Overall, the case studies provided information on the state of the art in the use of IED methods and the implementation of DGNB criteria in projects at a Danish architectural firm and the relationship between the IED method and the DGNB certification system.

As Figure 3 indicates, the IED method covers a limited number of DGNB criteria, because its focus is solely on energy consumption and indoor climate in the operation phase of the building. IED covers important elements in the initial design phases but is insufficient as an approach to advanced sustainable design according to the DGNB and Brundtland definition, which involves many more parameters. The good news for IED is that it seems to have become an implicit approach in most design processes, and designers are now moving on to cover new levels of complexity.

Further development of the IED method by requiring an increased focus on LCC and LCA might be one way of 'automatically' increasing the number of fulfilled DGNB criteria.

It was apparent that the IED method is being widely used even where it is not a deliberate strategy. This indicates a considerable focus on energy requirements and indoor climate in the operation of each building, even in the early-phase design processes, in the Danish building industry. It also shows that this leads to the implementation of DGNB in the early design phases, where there are many more opportunities to influence the design and ensure both economic and environmental benefits than there are in the later design stages.

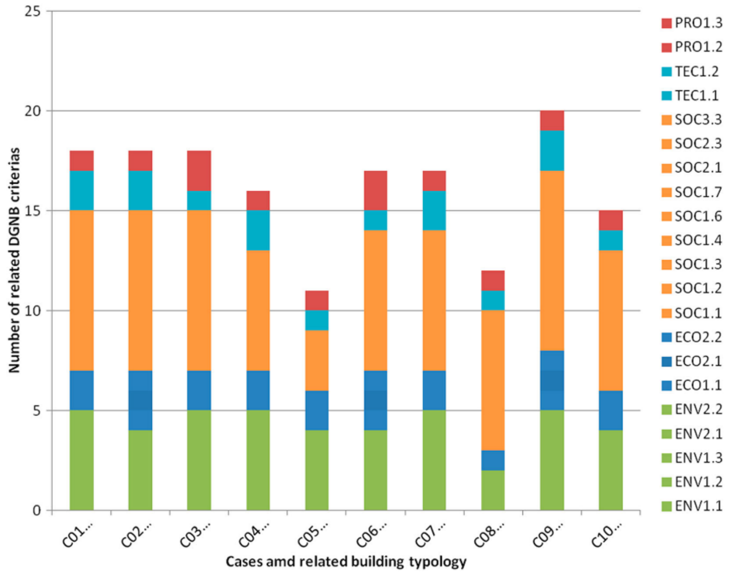

Figure 5. Building types related to the DGNB criteria, with each criterion counted individually and grouped into the five categories. The results are illustrated in this column diagram.

Figure 4 can be interpreted as showing increased focus on sustainability and DGBN in over the past year. The smaller study in Figure 5 of the relationship between building type and the DGNB criteria shows no correlation, which suggests that the focus on sustainability is a general feature in all projects and not specific to certain building types.

From this study, we can conclude that the IED method is very much in use and is integrated into the design processes at this particular Danish architectural firm. However, the mapping does not show how well each topic was integrated into the design, but just which topics were. The spread and variation in the DGNB-related parameters addressed in the projects are symptomatic of the lack of a systematic design method for addressing DGNB. However, the research shows that the design process is affected when certification systems are used because new parameters have to be in focus from the very early design phases. In the DGNB system, LCC and LCA offer more holistic methods and tools for quantifying sustainability in terms of monetary costs and environmental impacts. Both LCA and LCC include the energy consumption results generated by IED in the design process. Integrating LCA and LCC into the early design phases in the way that IED is integrated for energy calculations and indoor environment is the new challenge for practitioners and researchers, and should be the subject of further field studies.

New design methods and tools will be required to increase the use of DGNB in the early phases of building design. This will increase the complexity of the design process, as the number of parameters that must be considered will increase, but the rapid development of software means that simulation tools capable of dealing with that complexity are already feasible.

Conclusions

The 2010 regulations requiring energy balance calculations and indoor climate calculations had ensured that IED was very well integrated into the design process at this particular Danish architectural firm even though it was not implemented explicitly.

DGNB certification is not in the building regulations but its adoption by the green building council has already had an impact: DGNB certification had led to an increased focus on sustainability, although the spread and variation in the DGNB-related parameters considered show that it had not yet become the basis of a systematic design method.

One of the most prominent differences between IED and DGNB is the extension to include both LCC and LCA. They both encourage the adoption of a more holistic method with a wider array of parameters and tools for quantifying sustainability in terms of monetary costs and environmental impacts.

LCA and LCC are linked to and dependent on the energy consumption results generated by IED in the design process. Integrating LCA and LCC into the early design phases will be the next challenge for practitioners and researchers as IED is already being used to include calculations related to energy and the indoor environment.

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APPENDIX C

PAPER (3)

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Integrated Energy Design and Life Cycle Assessment in Refurbishment Design Processes

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Abstract

This paper investigates the state-of-art for using the DGNB Sustainability Rating System, Life Cycle Assessment, and Life Cycle Costing in the Danish building industry, and how well this use is aligned with the Integrated Energy Design process in refurbishment projects. An optimal method for including all aspects of sustainability in the design process is developed based on a literature review, interviews of professionals, and a mapping of design processes at a Danish architecture firm that specializes in sustainable architecture. Finally, the paper reflects upon the final design process presented in this work, considers what is needed to implement this design process, and envisages the impact of this practice on the building industry.

KEYWORDS

Life Cycle Assessment, Life Cycle Costing, Integrated Energy Design, Refurbishment

INTRODUCTION

In recent years, the world has seen serious environmental changes caused mainly by human activities (Vitousek et al. 1997) (IPCC 2008). Worldwide, 40% of emissions are generated by the building industry and the operation of buildings. The Kyoto Protocol, which was adopted in 1997, states a common goal to lower the overall greenhouse gas levels in 2020 to at least 20% below those from 1990. The EU has a goal to reach 30% below 1990 levels. The intention in Denmark is to be fossil fuel free by 2050 (ECEEE 2010). To ensure that this commitment can be kept, new and existing buildings must fulfill stringent requirements concerning energy consumption (Hansen et al. 2014). In order to meet these requirements, it is not enough to insulate and optimize systems. Great care must be invested in the design process. Research conducted from 2007-2009 through the EU INTEND project (Intelligent Energy Europe 2009) demonstrated that decisions made during the early design phases have the greatest impact on energy consumption. As a result, researchers began to focus on developing highly informed and interdisciplinary early phase design processes (Savido et al. 1994). For example, the Integrated Energy Design (IED) method was investigated and improved at the Technical University of Denmark and other universities in the 2000s (Löhnert et al. 2003; Cole 2005). The IED method focuses on so-called passive strategies (in contrast to mechanical control of indoor climate) in the early design phase, followed by calculations and simulations to ensure a comfortable indoor climate and improved energy efficiency of the building. Optimized systems and PV cells are only added later if necessary. This IED-inspired design process has been widely implemented in the Danish Building Industry (Holanek 2008), resulting in a widespread use of indoor climate and energy simulation tools in the early design phases.

Previously, the main focus was on new buildings. However, new buildings only account for 1% of annual building activity in Denmark. Therefore, the focus has moved to include the existing building mass as well (Regeringen 2014). Improving the quality of existing buildings to reduce their environmental impact during operation is referred to as 'Energy Renovation' (IED implemented in a refurbishment project), and is an important step to be able to reach the Danish and EU goals by 2050 (Regeringen 2014). The use of the IED method in a refurbishment design process could start with an elaborate simulation. Simulation of the thermal comfort of a building provides knowledge about the risk of overheating in the building, while a daylight simulation shows the daylightfactor. If daylight is limited and overheating is an issue, a dilemma is formed. Likewise, more insulation will increase the need for ventilation and cooling (Papadopoulos 2016). The IED method and the ASHRAE GreenGuide are developing world wide to help professionals cope with the complexity of energy efficiency and sustainability (ASHRAE 2013).

During the past two years, the entire life cycle of a building has gained ground in the design process due to the success of IED in reducing the energy consumption for operation. In Western Europe, 8-12% of the total CO2 emissions are from building material production (Nässén et al. 2006). Through Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), the emissions related to material production can justify refurbishment instead of demolition and new construction (Haugvaldstad et al. 2016). One of the drivers for adding LCA and LCC to the already well established IED design process is the increase in sustainability certification of buildings such as the German certification system called the DGNB, which will hereafter be called the "Rating System" since this is the focus of this paper. LCC calculates the total economy of design decisions in a 50-year perspective and LCA calculates the impact on the environment in terms of CO2 emissions (and other impacts on human health and natural systems). The first generation of sustainability certification systems, the American LEED and the British BREAM, were mainly focused on environment and economy (Ding 2008; Schweber 2013). These were followed by a second generation of certification systems that use a holistic approach based on Brundtland's definition of sustainability (Brundtland 1987). For example, the Rating System includes environmental, economic, social, technical, and process criteria (Kreiner et al. 2015). The Rating System was adapted to Danish standards in 2010 (Birgisdottir et al. 2010). The first version of the Rating System adapted in Denmark was for new office buildings. This was followed by versions for residential buildings, institutions, and urban districts (DK-GBC 2014). Since the number of new buildings in Denmark is so limited, a version for existing buildings was established and launched through a pilot project in 2016 (DK-GBC 2016).

METHOD

Literature review

The literature review compared the Rating System manuals for new office buildings and for existing office buildings to identify the differences concerning the LCA and LCC criteria. This was done because sustainability ratings and the documented environmental impact of buildings are strong design drivers of sustainable design.

Interviews

Ten interviews were conducted with professionals from the building industry in Denmark. The interviewees were specialists in sustainable buildings with knowledge about LCA and LCC. The interviewees included one individual from the Municipality of Copenhagen, one professional researcher from the Danish Building Research Institute, three professionals from Danish engineering consultancies, and five professionals from Danish architecture consultancies. BIM and 3D scanning experts were also interviewed. The interviews were based on an interview guide, with open approach to include the professionals' perspective and experience. The main questions from the interview guide were:

1. What have you experienced with the use of LCA and the need for handling the data?
2. Which methods and programs do you use?
3. Are there limitations with the process of conducting LCA? In relation to available technologies or interfaces?
4. What is the optimal design refurbishment process like when LCA / LCC are integrated with IED?

Participants were also asked specific questions related to their specialization, depending on their knowledge and experience with IED, LCA, LCC, 3D modeling, interfaces between programs, and 3D scanning.

Mapping

As a part of the interview process, two types of mapping were conducted. Firstly, the interviewees mapped the use of LCA considerations onto a graphical figure illustrating a timeline with six phases of a building life cycle (Table 1). Normally the phases used for LCA are the ones indicated with black arrows, but the last two phases (End of Life and After Life) are important when focusing on renovation, reuse, recycling, and upcycling. The Y-axis of Table 1 is divided into three themes. These relate to Table 1: (A) Indicate the scale of LCA (material, component, or full building scale), (B) Tools used (to indicate the LCA tools used in practice), and (C) Mark the most efficient design phase during which to conduct an LCA in the project.

Table 1. Mapping of A: LCA scales of a design process, B: Tools used, and C: Marking the most efficient design phase for an LCA.

	Prior phase ⟹	Sketch phase ⟹	Detailing phase ⟹	Construction/Operation ⟹	End of Life ○	After life ⟹
A						
B						
C						

Another mapping, also made by the interviewees, related to their use of different tools in their IED design processes (Energy, Indoor Climate, Daylight) supplemented by LCA, LCC, and 3D tools (Table 2).

Table 2. Mapping the use of 8 categories of tools within the IED, LCA, LCC, and 3D approaches, rated from 1 (limited/no use) to 5 (highly used).

	1	2	3	4	5
3D modeling					
LCA					
LCC					
Energy					
Indoor climate					
Daylight					
BIM					
3D scanning					

Case study – observations made during participation in a design team

The case studies were ongoing design projects at the architectural office where one of the authors (who has a background as M.Sc. Eng.) worked as a member of the design team. This work included the use of LCC and LCA tools as well as 'classic' IED tools. The design team worked on refurbishment design projects. A diagram including the process timeline of a design process was used as a mapping tool for all design decisions made in the processes. The figure for mapping is based on the X-axis from Table 1.

RESULTS

Literature review

The Rating System manuals for new office buildings and for the refurbishment of existing office buildings differ in several ways, but the overall structure and holistic approach is kept for both. Table 3 shows the Rating System's criteria for LCA and LCC, including the sub-criteria (DK-GBC 2016). Table 3 is divided into three columns, one for each typology and a middle column indicating commonalities in the two systems.

Table 3. The LCA and LCC criteria for the Rating System - new office buildings compared to existing office buildings and the common indicators.

The Rating System New office buildings	Indicators in common	The Rating System Existing office buildings
ENV 1.1 - Life Cycle Assessment (LCA) - Environmental impact Based upon theoretical data	GWP, ODP, POCP, AP, and EP Tools: Rating system approved LCA tools	ENV 1.1 - Life Cycle Assessment (LCA) - Environmental impacts Based upon real time data from existing buildings
ENV 2.1 - Life Cycle Impact Assessment - Primary Energy (LCA) Based upon theoretical data	Non-renewable primary energy Total use of primary energy Use of renewable energy	ENV 2.1 - Life Cycle Impact Assessment - Primary Energy (LCA) Based upon real time data from existing buildings
ECO 1.1 - Life Cycle Cost (LCC) Indicators: Selected construction costs Selected maintenance and replacement costs Supply data, generic Denmark Cleaning costs Based upon theoretical data	Overall a similarity in focus upon the following indicators, but with a different focus: Construction Technical systems Maintenance	ECO 1.1 - Life Cycle Cost (LCC) Indicators: Budget related use costs Maintenance plan and budget plan Based upon real time data from existing buildings

The differences between the two manuals are that in new buildings, the input concerning electricity, heat, and water is, of course, based on simulations, whereas the real time data of consumption is used for the existing building (refurbishment). Despite the equal criteria for both typologies, there are variations in the definitions of some of them. For example, when looking at ENV1.1 – Life Cycle Assessment, the two typologies will differ as the existing building will already have embodied energy, and therefore the previous life cycle stages for these parts can be neglected. In contrast, the new building will need to include embodied energy. Thus, LCA can give preference to refurbishment by quantifying the much lower environmental impact compared to new construction.

Interviews

From the interviews that were conducted in relation to the current study, there were some main points that will be addressed here.

The Rating System as a driver. All interviewees said that the main driver for using LCA is the Rating System and that they only do LCA if it is required.

Consultants as drivers for incorporating LCA into a design process. The architects underlined that they, as architects, should adopt LCA as a design 'tool', because they are the ones with the overview of the building and know how it is built and with what materials. They also stated that not all architects need to be specialists in LCA, but that they should use it as an indicator like they use simple daylight simulation tools daily in order to add another aspect to the argumentation for material choices, etc.

Inconsistency in the tool interface. The interviewees agreed that before LCA can be used in a design process, the tools must be operational. The interviewees said that existing tools do not have a common interface, so it is not easy to transfer data between the 3D model used in the design project and the LCA tools. To address this issue, some of the interviewees have developed their own software or transfer the data manually.

LCC makes economy a comparable design parameter. Architects have worked with LCC for a long time since cost is a crucial aspect of a project. These calculations have mainly been made using company-developed tools, and therefore differ. Specific LCC tools are a new phenomenon that will make these calculations comparable and will make LCC work as documentation and arguments for choosing better solutions in meetings with the clients. As a general output from the interviews, LCA and LCC were seen as important tools that should be integrated into the design process from the beginning. However, it was reported among the interviewees that this is not being done yet.

Mapping

The optimal use of LCA within the frame of IED is depicted in the process timeline (Figure 1). The timeline indicates when the use of 3D scanning can be useful in a design process.

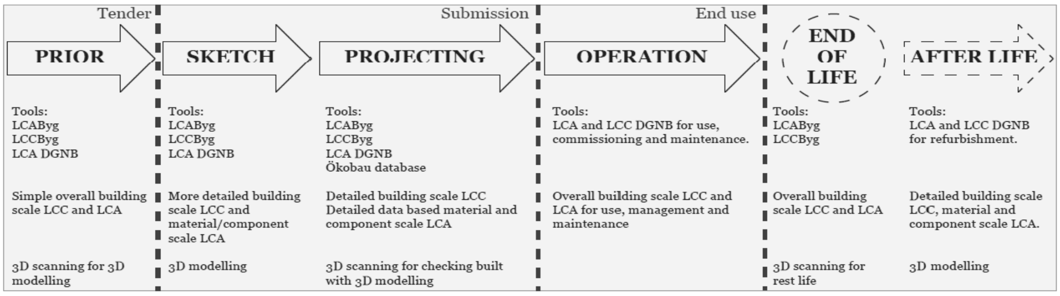

Figure 1. The table shows an optimal design process where LCA is included. The phases of the design process are illustrated, along with the scale, the tools of LCA, and the most influential phases for LCA in the design process.

Figure 2 shows the results of the second mapping concerning the use of tools. The tools are rated on a scale from 1-5, where 1 is limited or no use and 5 is using it a lot. The following diagrams indicate the professions: (A) engineering consultant, (B) and (C) are architects and (D) is an engineering consultant who specializes in 3D scanning with no experience using LCA.

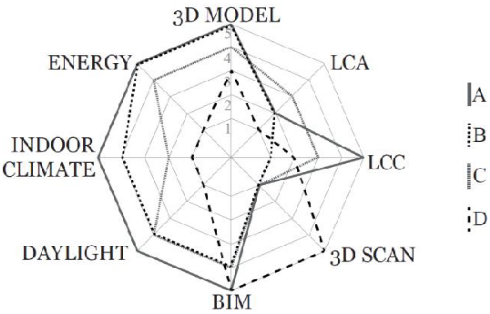

Figure 2. Ratings from 1 (limited/no use) to 5 (highly used), which are seen as the steps in the spiderweb diagram. The professions can be seen in the diagrams: (A) is an engineering consultant, (B) and (C) are architects, and (D) is an engineering consultant who specializes in 3D scanning with no experience using LCA.

This study shows that the professionals interviewed tend to have a limited use of LCA and LCC tools, whereas the 3D modeling, energy, indoor climate, daylight, and general BIM and IED tools are more in use. This can be an indication that the interfaces between 3D modeling tools with the simulation tools for energy, indoor climate, and daylight functioning well when the project doesn't include LCA and LCC perspectives.

Case studies – observations made during participation in a design team

Case studies were conducted at a Danish architecture firm where LCA and LCC were introduced and included by one of the authors (a M.Sc. Eng.). Participants in different stages of the design process showed a willingness to include LCA and LCC in their design processes. Figure 3 illustrates the results of the case studies in the architectural company. In one case, the LCA and LCC programs were used before the first design phase to decide whether the existing building should be renovated or, as another option, be demolished and built new. In the other case, the programs were used in the same phases in the process to decide the optimal method for refurbishment by investigating the different renovation typologies simultaneously to select the best method concerning costs and environmental impacts. As seen in Figure 3, LCC seems to be especially useful as a tool for decision making from the very first phase before design begins. This can be a direct reflection of a building industry where cost is the primary factor. LCA was used for decision making at different stages of the design processes to justify the selection of one material over another. The environmental impact embodied in the main building structure was surprisingly more favored when using LCC rather than the LCA tool because it is very costly in Denmark to demolish buildings. However, both LCA and LCC were important tools in defining further steps and the direction of the project.

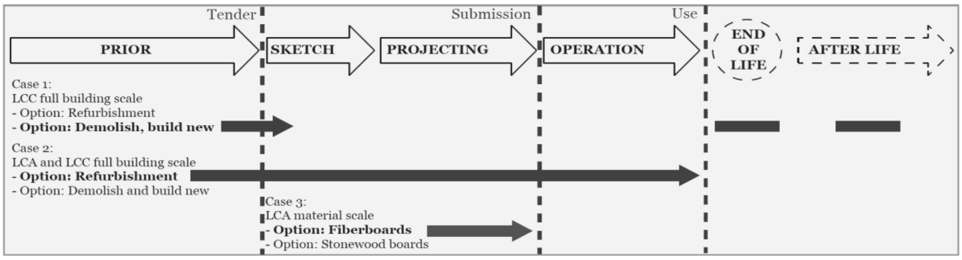

Figure 3. Three case studies using LCA and LCC to decide how to proceed in regard to the process timeline. The black arrows indicate the decision made and the next step for the design process.

The ideal design process

Figure 1 illustrates the ideal design process based on the use of IED including LCA and LCC tools to ensure a holistic approach towards more sustainable buildings. It is clear that a focus on LCA and LCC has to be included from the very first sketching phases, just like the IED method includes a focus on energy consumption and indoor climate from the very beginning. Therefore, they can be used as active design tools to help define and direct the ongoing design process. The optimal base for LCA and LCC is for the architects to use the tools in refurbishment projects as justifications for their decisions on a building and material scale, followed by the sketch and project phases where the tools will help to ensure that the choices for materials and components will be environmental friendly within a 50-year economic frame. This process needs data from the consulting engineers and the client that is not commonly included. A close collaboration and an interdisciplinary team will be preferable to optimize the process.

The ideal process is therefore not only dependent upon the use of tools, but is just as much about the interaction with the professions within the design team. To be able to handle the complexity of integrating energy, indoor climate, LCA, and LCC as design parameters, a certain general knowledge is needed in the team. All aforementioned design parameters will, to some extent, influence the others. In IED theory, an 'integrator' is an important team role. However, the design team will be the ones evaluating the outputs of the different tools and justifying one direction or decision over another. In this complex decision making context, general knowledge within sustainability and buildings will be important ahead of the divided knowledge within each profession. The design team will therefore benefit from having specialists and generalists in one mixed group to ensure that the ideal design process will occur.

As the interviews of professionals in the Danish building industry indicated, there is no real consistency in the LCA and LCC programs used. Instead, they indicated a broad use of different tools and methods. Figure 1 and Figure 2 revealed limited options for interfaces to handle data transfer between the programs. Instead, the iteration happens with manual transfer of data. When data transfer is handled manually between the tools, the professionals need an overview to know which type of data is needed where.

The issues related to getting the correct inventory data of materials and their quantities results in a rather time consuming process, even if a BIM model is used, especially when working with refurbishment. In several consulting companies, these limitations are handled by developing their own tools to facilitate the process of collecting data from 3D modelling software and transferring it to parametric LCA tools as well as to more simple and official LCA tools. However, different technologies are rapidly improving, and design processes and workflows suitable to the profession are developing within various companies. The case study of a M.Sc. Eng. who was participating with LCC and LCA tools in a design team of architects showed that integration is possible.

The interface between the LCA tools and the 3D modeling tools therefore needs to be streamlined for all to use directly and easily in the design process. The 3D models are also far from perfect. Often, they are missing a lot of data needed for LCA, LCC, and indoor climate simulations. Each simulation that addresses different aspects of the design needs information from the 3D model in a specific way to feed the appropriate data to the programs correctly. This is a missing link if all simulations and calculations should be based on the same 3D model and thereby be a common tool for the design team. However, the common wish is to have a more simplified interface/transitional tool that can easily transfer data back and forth between the LCA tools and the 3D model. The individual developments from different companies show the importance of developing such tools in the future.

3D scanning can be a tool in the first design stage to scan the existing building and thereby ensure that the basis model for further design is based upon real built measurements instead of old drawings, which are often missing data. Scanning the existing building at a later stage can ensure that new components fit the existing building. The 3D model can thereby feed the LCA and LCC at the same time. Specific knowledge about the building will be used for simulations of energy efficiency and indoor climate, as well as for daylight calculations.

IED is the basis for handling passive strategies from the beginning, including the LCA at smaller scales, such as the material level, and having the LCC as the starting tool to define the direction of the refurbishment.

CONCLUSION

From interviewing the different professionals, the preference is a wide interest from different professions to use LCA and LCC as extra parameters in the IED method. However, the Rating System seems to be the reason for most of the LCAs conducted in the Danish building industry at the moment, as this is the only real requirement for LCA and LCC. The architects interviewed seem to have interest in using LCA and LCC as equally important tools as the IED-related tools to compare specific materials and components to other materials and components in order to select the right ones. Since only a limited number of buildings in Denmark are new, the existing building mass contains a high amount of embodied energy and CO2. LCA and LCC can assist the sustainability decisions regarding the two scenarios of either demolition and building new versus refurbishment of the existing buildings. There are parallels to the findings from the IED, where the first design phases are very important for decision-making – this goes for the LCC and LCA assessments as well. According to this study, LCA can be used for new buildings as well as for existing buildings, however there is a difference in the required data (theoretical or 'real time') for the two typologies. The need for actual consumption data from the existing building can be a limitation for the Rating System in design refurbishment processes since it can be difficult to get the required data for the LCA in the time frame of the given project. In competition projects, time is an important parameter in the process. Therefore, different simulations and calculations of energy, indoor climate, and LCA are important to optimize according to design changes. In this design phase, real time inventory data can therefore limit the project in time and process.

The use of the design process developed in this paper will build on the already established interdisciplinary workflows from IED, however supplementing with LCA and LCC will alter the pros and cons of specific design decisions. The international race towards 2030 and net zero energy buildings will therefore include a much broader approach to sustainability resulting from a holistic design process.

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APPENDIX D

PAPER (4)

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Mapping the communication of engineering knowledge using visuals to improve interdisciplinary design team performance for sustainable building design

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Abstract

At government and political levels, restrictions and requirements have been tuned and tightened to force the entire building industry to move towards energy efficiency and thereby reduce the environmental impacts of operating buildings. At the same time, there has been an increased focus upon emissions during the entire life cycle of a building, including upon the emissions related to the materials used for constructing buildings. Environmental buildings are now defined by low emissions over the entire life cycle of the building. Due to an increased complexity in building physics, products and technologies, more specialized knowledge has to be taken into account for every building design, which requires greater common understanding and cooperation between the various stakeholders – thus an interdisciplinary team from first design phases. The simple and intuitive communication of technical information is an important factor in the interdisciplinary design team and one vehicle for this is visual communication. Two professions, architecture and engineering, are starting to increase their focus on interdisciplinary and better communication with each other however, it is often rendered in transparent how the actual interdisciplinary takes place in the design team. Focus on visual communication opens up for a study of what take place in the integrated design team.

The aim of this research was to define and describe the effect of visual communication of engineering knowledge to architects and other stakeholders participating in the interdisciplinary design team in the early stages in a building project. The research is based on extensive project materials consisting of presentation material, reports, simulation results and case studies. The material was derived from one of the largest European Engineering Consultancies and a large architectural office in the field of sustainable architecture in Denmark. Inquiries into the project material have resulted in a mapping of communication concepts from the practice the material represent. In addition to this, the researchers with competences in both engineering and architecture took part in ongoing design teams which contributed additional information to the mapping of how engineering knowledge is communicated, received, and affects the design process. The research shows that visual communication by engineers' increase the frequency in which architects base design decisions on technical knowledge, which is a prerequisite for the ability to reach the goal of buildings with low environmental impact. In reverse, the quantification of architectural quality improves the understanding by the engineers and their acceptance of the work by the architect. An interdisciplinary approach is thereby reached from two bridging sides by switching the methods, which are more traditionally opposite of each profession, with each other.

Keywords: Visual communication, Case study, Interdisciplinary design, Low environmental impact buildings, Quantitative architecture

1. Introduction

Increasing the development of sustainable buildings, which are highly complex, will require more professions to be dependent on the decisions of one another, which again will require and lead to further development of interdisciplinary communication. Visual communication is moving to the fore of engineering education because interdisciplinary design teams require close corporation to ensure a holistic and uniform final product [5].

In an integrated design process engineers are expected to be able to proactively influence early design decisions in the interdisciplinary design team, however industry is uneven in its willingness to alter the traditional roles of consultancy [4]. The fact that traditional consultancy roles linger on in industry influences the design process and forms a barrier for interdisciplinary early phase design processes [4]. However, a number of engineering consultancies are challenging these traditions by focusing on new communication strategies through visual communication [6]. Traditionally, visuals are a part of the schools of architecture (e.g. through modelling, diagrams, visualizations, renderings, 3D models, and sketches) [1]. The increased focus on early integration of technical knowledge in design decisions and the frequent aim of achieving sustainability certification of buildings call for architects to consider the communication of architectural quality. Quantification of architectural quality is challenging and some architects would claim that it is not possible however it could be one way of accommodating this request [14]. DGNB (Deutche Gesellschaft für Nachhaltiges Bauen) is a German sustainability certification system addressing Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) as add-ons to the legal- and regulation-based focus on indoor climate and energy calculations. Thus it is expected that also LCC and LCA are considered from the early design phase. This means that architects need to develop quantifiable and knowledge-based design decisions [11] to be made in the early design phases. Therefore, classical engineering tasks are introduced to the architects, who have to take them into account if a sustainability certification is the goal. As a result, the architects gain knowledge of the engineering fields [1].

2. Method

2.1. The two case study consultancies:

There has been an increased focus on the importance of early design decisions since research has shown that the economic influence of early design decisions is high. For the last decades, this knowledge has set the demand for changing the mind-set and work processes for both architects and engineers; these processes are now rapidly evolving [4]. In the following, the quest to inform early design decisions with technical scientific knowledge and the ways that architects and engineers try to create a common ground is investigated by looking at the role of visual communication first in a large engineering consultancy and then in the quantification of design decisions in a large architectural office. The paper is based on several case studies. However, three were selected for discussion in this paper. These case studies are derived from two companies in Denmark: a large architectural office with a focus on sustainable buildings, and the Danish part of a large European engineering consultancy. The engineering consultancy has more than 1000 employees in Denmark and around 15,000 worldwide [8]. It is organized in special units. Each unit has deep specialist knowledge in their field. A selection of these units is shown in the organization diagram in Table 1.

Table 1. Organization diagram showing a selection of the units and some of the related subjects in the engineering consultancy [8]

Architecture	Building Eng.	Energy	Management services	Environment	Water
Accessibility	Buildings	District heating	Commissioning	Building contamination	Adaptation to climate change
Architecture	Energy labelling and energy optimization	Energy efficiency	FM	Nature conservation	
BIM	Renovation	Solar energy	Sustainability	Waste	
Lighting design			Work environment		

The architectural office has around 80 employees and is organized in three main units - City & Housing, Learning & Culture, and Business & Health - with a range of different specialist knowledge. A selection of this knowledge is shown in the organization diagram in Table 2 [9].

Table 2: Organization diagram showing a selection of the many subjects at the architectural office [9]

City & Housing	Learning & Culture	Business & Health
Public housing	Day care	Hospitals
Care Centres	Schools	Laboratories
Renovation	Colleges	Business
Landscape	Universities	Landscape

2.2. Engineering approach – Visualizing engineering knowledge

The engineering consultancy has developed their own tool called 'Game Changer', which is a set of technical guidelines meant to serve as tools to facilitate early phase dialogue. It is based on a report conducted by a group of anthropologists [6], who observed the working processes in the engineering consultancy. They detected three challenges within the routines at each organizational level that affected how the clients experienced their interactions with the engineers. The three organizational levels are the leader level, the project leader level, and the technical specialist level. In this work, only the challenges related to the technical specialists are considered. The diagram in Figure 1 shows the challenges at the Technical Specialist level. This has been the starting point for the company to understand the relationships between the potential behaviours of the employees and the resulting client experience.

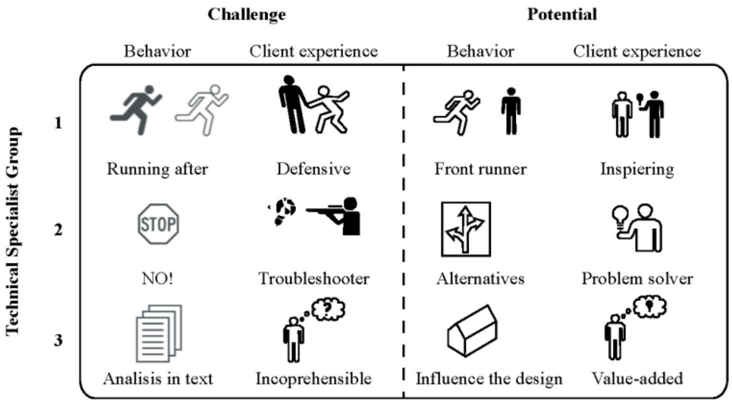

Figure 1. The Technical Specialist level and the three related challenges [6]

One of the challenges defined by the anthropologists at the Technical Specialist level is "Analysis in text". Clients feeling that "Analysis in text" is incomprehensible, since they do not share a common medium for dialogue. Here, visuals may be a potential medium for communicating the engineering tasks and making the expert knowledge more comprehensible; however, this would require a different work strategy [6]. When changing work strategies, it is not always enough to offer an introductory course and a list of guidelines. The entire routine-based workflow and mind-set of each employee has to be taken into account. Emotional intelligence (EQ) also has a great impact on the capability for utilizing communication tools, therefore EQ is an important qualification for employees to work within the complex environment of interdisciplinary design teams in the building industry [2]. By visualizing the complexity of the general technical issues in the guidelines, they become a qualitative description of design principles instead of quantitative values in a report. This is more easily incorporated into the design process and invites dialogue for an open range of design decisions [6]. Visuals as a tool for communication can be an advantage since they are easier to understand and to remember than text, as they engage the imagination and increase creative thinking [3].

2.3. Architectural approach – Quantification of design decisions

At the architectural office, there was no explicit aim to make communication more visible since they already work very visually. However, the increased number of interdisciplinary design teams and the demand for sustainability certification of buildings has introduced a need to quantify design decisions.

At the architectural office, the DGNB certification system is used as a basis for the definition of sustainability, which leads to an increased focus on resources, consumption, and emissions in relation to LCA, as well as on the economic aspects related to LCC. Internal changes are in development for the architectural office, where the entire mind-set of the classical architect has to be modified and an awareness of the benefits of quantification as the background for their design decisions has to be introduced. The DGNB system proactively pushes this development at the architectural office by requiring 10 early phase sustainability concepts to be developed in interdisciplinary teams as seen in Figure 2.

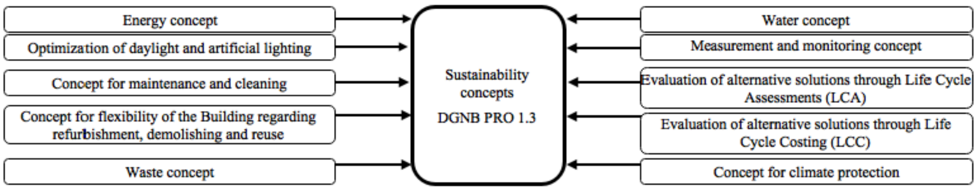

Figure 2. DGNB, PRO1.3 – New office buildings criteria: the 10 introduced concepts that give points [11].

2.4. Method of research

Although several case studies have been conducted, two case studies were selected as being illustrative for influencing the initial design phase, prior to actual design: one at the engineering consultancy and one at the architectural office. The third case study illustrates the influence in the schematic design phase at the architectural office. The results of the case studies are compared, categorized, and reflected upon in relation to the visual communication of engineering knowledge, quantified design decisions, and the DGNB certification system. The case studies were conducted based upon the active research approach of four steps; planning the process, action through involvement in design teams, observing and collecting data, and reflection upon the findings [16].

2.5. Case 1

Two engineers participated in the first initial meeting of a project with the entire design team. The design team consisted of engineers and architects. At the meeting, the engineers presented technical guidelines as visuals and after the meeting they reflected on what worked and what did not. The case study is based on Figure 1, “Analysis in text” at the ‘Technical Specialist Level’. The current project has an open beginning, where the architect develops the building mass. This gives the engineers the possibility to include their knowledge from the very beginning. For the first meeting, all of the specialists brought their most relevant technical guidelines to be presented. The technical guidelines consisted of visualisations of the technical issues, which could be the result of the selected design decision and the adjacent list of the pros and cons for the specific design.

2.6. Case 2

One engineer employed at an architectural office participated in the initial design phase to assist the design team with the quantification of their scenarios for the project definition. The project started with a request from the project leader to quantify the economic value of two scenarios for an existing building through LCC calculations. The two scenarios were either to demolish and rebuilt the building or to renovate it. For the calculations, a simple tool developed in Denmark called LCCByg was used [12]. The available material for the existing building was rather limited; the necessary data for the calculations was derived from old drawings. Included in the calculations were new components, maintenance and operation, supply, and cleaning.

To assist the LCC calculations with the environmental and social aspects of the two scenarios, a simple tool from the Municipality of Copenhagen called the MBA (Environment in Buildings and Construction) was used [13]. The client requested its use since the project focused on a public building. The feedback based on the quantified data and the following responses were observed from the client for the current case study. The case study was mapped in a large matrix developed to align cases in regards to sustainability criteria, technical inputs, influence by the technical inputs, design decision, and level of sustainability. The matrix is seen in Table 3 below.

Table 3: Matrix for case studies at the architectural office.

Case No.	Case 2	Case 3
JJWs role	-	-
JJW included design phase(s) (Description of Service)	-	-
Sustainability focus	-	-
Technical inputs (my inputs) Requested by	-	-
Technical inputs (my inputs)	-	-
Technical tools	-	-
Design variations and decision	-	-
Reason for design decision	-	-
Level of sustainability	-	-

2.7. Case 3 – Informing the design process through visuals

The third case was derived at the architectural office as well, by quantifying design decisions during the design process. Also here the data was collected based upon the matrix in Table 3. Here a number of daylight simulations were conducted by the sustainability team and submitted to the design team through reports and presentations. The daylight simulations done were testing the influence from type of glazing, solar shading, and depth of balcony overhang, and ceiling surface, upon the daylight conditions in the room and thereby the number of workspaces possible due to requirements of daylight conditions on workspaces of 2% daylight factor [15].

3. Results

3.1. Case 1 – Visuals at an engineering consultancy

Figure 3 shows a representative technical guideline illustrating the placement of the toilet cores in a multi-storey building. The guideline also includes lists of the pros and cons related to the technical installations.

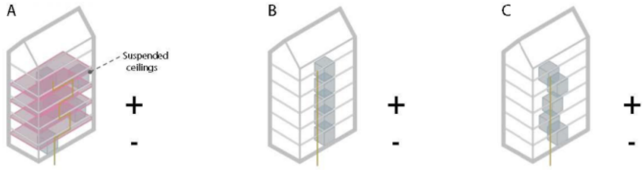

Figure 3. An example of the technical guidelines; these are always accompanied by text for the pros and cons: (A) Suspended ceilings result in high flexibility in the plan layout; the toilet cores can be placed in various locations. (B) Centred toilet cores on all floors ensure minimal routing for pipes. (C) Flexibility in plan layout with centralized routings. [6]

Planning and action: Addressing the issue of toilet core placement in a multi-storey building at the first meeting before the design processes started was intended to avoid a common challenge of technical installations that arises from a lack of organization of the cores.

Observations: Some of the attendees at the meeting found the information banal and narrowing. However, the simple visual and adjacent text made the point precise and clear, and ensured that those who were not experienced understood and could use the information. The mapping indicate the different types of feedback on the guideline, which provided a basis for collaborative dialogue.

Reflections: The engineers decided to further develop the visuals so that they would support an open range of solutions instead of suggesting just one solution space (the technical cores), and in this way accommodate the critique by the architects.

3.2. Case 2 – 'Quantification' at an architectural office

Planning and action: A report was exported from LCCByg showing the results of the calculations through column diagrams. The final sustainability ranking from the MBA (Environment in Buildings and Construction) [13] was included as well and illustrated through a circle diagram. These diagrams can be seen in Figure 4. The results show that the economically preferred scenario is 'demolish and built new' due to the very poor conditions of the existing building. The sustainability ranking supports the economical preference based on more environmentally friendly materials, improved possibilities for maintenance, and improved functionality of the building (since it will better fulfil the needs of the users). The calculations and sustainability ranking ensured a thorough investigation of the scenarios and ensured a design solution based on both quantified data and qualitative data.

Observation: The project leader brought the outputs from Figure 4 to a pre-meeting with the client. The client expressed that they were impressed by the thorough investigation and very clear visualized outputs. The analysis done here convinced the client to follow the advice from the architects to demolish the existing buildings and build new due to poor existing quality and high costs to renovate.

Reflection: Hence it is public buildings limited economy is available and costs thereby is the highest factor, therefore this was a crucial aspect to document from the architects perspective to quantify from the initial design phases.

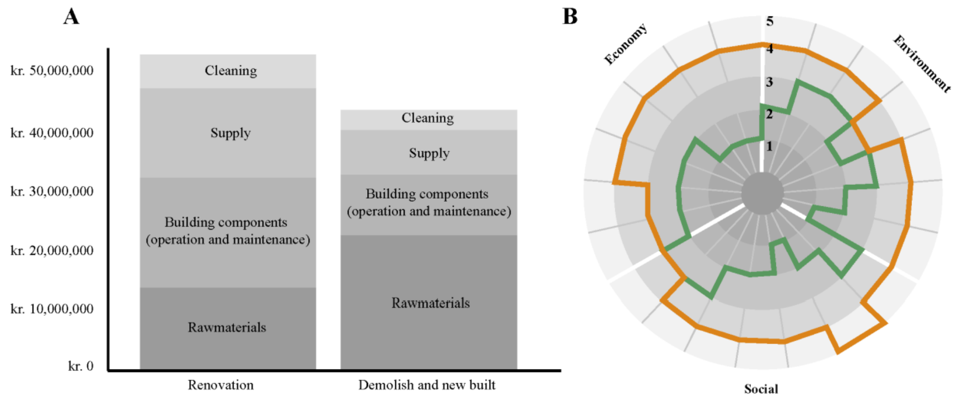

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Figure 4. (A) The column diagram shows the costs for each process for the two scenarios from the LCCByg report. (B) The circle diagram illustrates the social, economic, and environmental ratings as outputs from the MBA. The orange represents the new building and the green represents the renovated building.

3.3. Case 3 – Informing the design process through visuals

Planning and action: One output of the daylight simulations is seen in Figure 5, having the limit of 2% daylight factor illustrated on the floorplan of the room, for easier communication to design team and client.

Observation: The design loops and design decision parameters were collected in the matrix for case studies. The design team aimed for a design to ensure highest possible number of work places in the room having no additional solar shading to the balconies. This was argued to be possible through the daylight simulations, however only with white plane surface of the ceiling. The design team accepted and included the output from the daylight simulations through the design process to ensure best possible conditions of final design.

Reflections: Each iteration of design suggestions was followed by a daylight study to inform the design decisions. Mostly the aesthetic was the source for decision, however where the daylight simulations could argue for more workplaces in the room, this was the design decision factor.

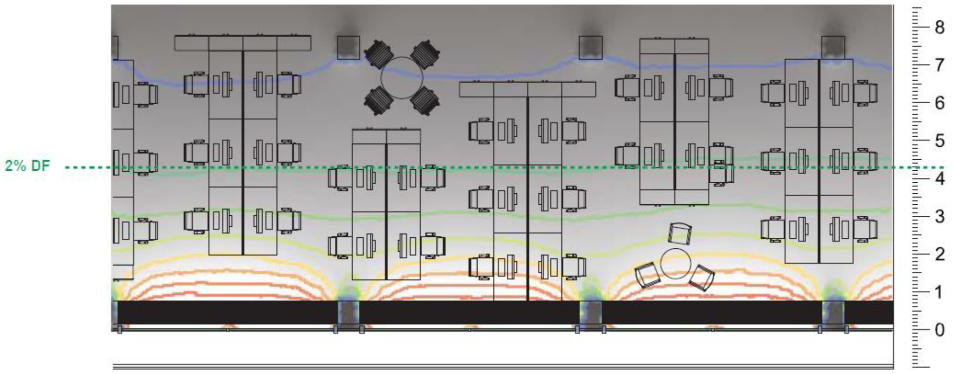

Figure 5. The figure shows the daylight simulation of the room, having the green line as the 2% daylight factor limit in the room. On the right a scale showing the depth of the room in meters from the façade.

4. Discussion

Requirements for more sustainable design and increased use of interdisciplinary design teams led both engineers and architects to alter their means of communication. The engineers focused on simpler and more visual communication strategies that helped avoid predictable problems by influencing how the architects organized the building masses during the early design phases. The architects, in turn, aimed to quantify their design approaches so they could influence decisions that would otherwise be determined by the engineers and financial considerations. This study also show the importance of the disciplines individual methods supplemented by the other disciplines method to increase the level of knowledge based design and not just a change in methods.

The engineers succeeded in including technical knowledge simply and clearly from the initial design phase. However, some experienced architects felt that the discussions were banal and that this process limited in their solution space. This feeling is crucial to address in the future since it can limit creativity in the design process. By being up-front with quantified design decisions, the architects were able to make important decisions that underlined their concept and visions, and ensure an open range of solutions, as illustrated by case 3. This makes the architects receptive to engineering knowledge in the early design phases.

All three case studies illustrate the impact of visualising technical knowledge to ease communication between professions and to ensure informed design decisions in practice. The use of visuals are important in all design phases as illustrated here both in the initial phase and the schematic design phase. As well as the need for quantification of design decisions to shape it based on informed design decisions.

All case studies expanded the range of communication means and made the aim for sustainable buildings and low emission buildings easier to approach.

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APPENDIX E

PAPER (5)

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NEW PARADIGM IN URBAN DEVELOPMENT: LIFE CYCLE THINKING AND SUSTAINABILITY

Decision support for large-scale remediation strategies by fused urban metabolism and life cycle assessment

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Abstract

Purpose This paper seeks to identify the most environmental friendly way of conducting a refurbishment of Broendby Strand, with focus on PCB remediation. The actual identification is conducted by comparing four remediation techniques using urban metabolism fused with life cycle assessment (UM-LCA) in combination with information relating to cost and efficiency of the compared techniques. The methodological goal of our paper is to test UM-LCA as a decision support tool and discuss application of the method in relation to large refurbishment projects.

Methods To assess the environmental performance of PCB-remediation techniques, the UM-LCA method was applied. By combining UM and LCA methodologies, the total environmental impact potentials of the remediation techniques were calculated. To build an inventory for each technique, we contacted and interviewed experts and studied existing literature, cases, and projects in order to compile information on practical details of the techniques. To process the collected inventory data, we used the simplified product system modeling software Quantis Suite 2.0 (QS2.0). In order to validate the results from the simplified software, we carried out the exact same analysis using a more complex tool—OpenLCA 1.5. Based on the assessment results, we compared the remediation techniques and identified the techniques with the smallest and largest environmental impact potentials.

Results and discussion The results obtained are presented, and the technique with the smallest impact identified. A comparison between the two software tools applied is made, and differences between the two are discussed in detail. Further discussed is how possible inventory errors affect the results and if any assumptions should be considered as critical for the final results. Furthermore, are the remediation efficiencies of each technique and the cost of each method considered and compared. Finally, UM-LCA's ability to work as a tool for decision support is discussed and possible ways of implementing the method in sustainable decision-making is considered.

Conclusions In this study, it is found that the most environmental friendly PCB-remediation technique is thermal desorption, whereas the technique with the largest environmental impact potential is sand blasting, due to the environmental impacts induced in relation to disposal of the building waste. It is concluded that the UM-LCA method can be applied as a tool for decision support, and if economic aspects are incorporated, the UM-LCA approach could be an essential approach for designing sustainable buildings.

Keywords Decision support · Hazardous building materials · PCBs · Remediation techniques · Renovation · UM-LCA

1 Introduction

In the 1950s to 1970s, polychlorinated biphenyls (PCBs) were used in many industries, building materials, and in products such as sealants, capacitors, paint, and oil (Dansk asbestforening 2010). PCB was a useful additive because of its chemical properties including fire resistance and softening abilities. Of the PCB used worldwide, the use in sealants was the most common (Dansk asbestforening 2010). However, through the 1970s, the use of PCB was prohibited due to its inherent toxic properties, which may cause effects in the

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Table 1 Action values/air concentrations defining when to act on PCB in the indoor climate (Sundhedsstyrelsen et al. 2014)

Above 3000 ng/PCB m3 air	Long-term stay will cause a significant increased health risk, and the concentration should be minimized immediately.
Between 300 and 3000 ng/PCB m3 air	Can cause a health-risk at long-term stays. The risk should be handled as soon as possible.
Below 300 ng/PCB m3 air	Health risk is insignificant and no action is needed.

environment and affect human health (Sundhedsstyrelsen, Trafik- og Byggestyrelsen, Miljø- og Fødevareministeriet, Arbejdstilsynet, and Udlændinge 2014). If materials containing PCB are disposed of incorrectly, the PCB in the waste may be discharged into the environment where it accumulates and eventually may end up in marine animals, some of which are part of a human diet (Dansk asbestforening 2010). Hence, PCB poses a challenge to human health. In addition to the behavior of PCB in the ambient environment, PCB may pollute the indoor environment where it can be absorbed in the human body and once again via an additional exposure pathway pose a threat to human health (Dansk asbestforening 2010). Today, PCB is declared among the ten most hazardous substances in the world (Sundhedsstyrelsen et al. 2014). The risks associated with PCB demand awareness on how to handle materials containing PCB, which is why The Danish Health Authorities have determined a set of PCB action values, see Table 1, defining when to act on PCB in the indoor climate (Sundhedsstyrelsen et al. 2014).

A housing estate located in the suburban area of Broendby Strand, 15 km southwest of Copenhagen, Denmark, was studied. The housing estate consists of 12 high-rise buildings with 16 floors, 66 building blocks with four floors, and eight terrace houses with two floors (Ellgaard 2018). Five of the 12 high-rise buildings are contaminated with PCB to such an extent that the threat posed by the PCB should be handled immediately according to the action value proposed by the authorities and presented in Table 1. Thus, this paper focuses on these five buildings (Ellgaard 2018), which hold around 300 apartments (Gudmand 2015).

In the contaminated apartments, the primary sources of PCB are located in flexible joints around windows and in sealant residues on the floor (Sparvath and Trap 2014). The primary sources are indicated in Fig. 1. The sealant used in the apartments contains up to 250.000 mg PCB/kg (around 25% PCB), which is a considerable concentration (Sparvath and Trap 2014).

Since PCB spreads to both the indoor and ambient environment, the interior of the apartments has been contaminated with PCB meaning that paint, wall materials, floors, doors, and furniture have become secondary sources of PCB. Thereby, all rooms are considered contaminated with tertiary sources of PCB due to the contamination of indoor air by the primary and secondary sources. The contaminated rooms include rooms such as WCs and hallways that are not in direct contact with the primary sources of PCB. Some apartments contain high levels of PCB in the indoor air, and the residents living in these critically contaminated apartments have thus been rehoused (Andersen 2013). The residents in the five high-rise buildings in Broendby Strand are currently awaiting

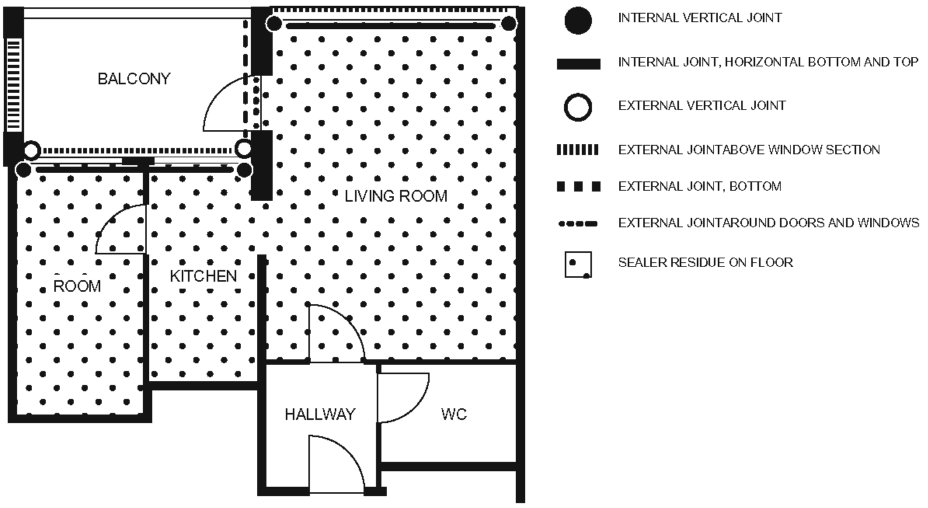

Fig. 1 Illustration of an apartment in Broendby Strand with the PCB sources highlighted (Sparvath and Trap 2014)

a renovation strategy to be decided upon. Meanwhile, a pilot project has been initiated and three compared remediation strategies—thermal desorption, steel blasting, and sealing—were tested in vacant apartments in order to test which technique is the most cost efficient (Sparvath and Trap 2014). Our paper investigates four remediation techniques considered for Broendby Strand:

- Thermal desorption
- Steel blasting
- Sealing
- Sand blasting

The four remediation techniques were chosen since these are among the most commonly used in Denmark. Our paper is based on the assumption that the primary PCB sources (typically sealant) are removed before any of the four remediation techniques are applied.

By heating materials containing PCB to at least 50 °C, the PCB volatilizes from the material to the air, and by subsequently using an air filter, the PCB can be removed from the air compartment of an apartment—this technique is called thermal desorption (Koch et al. 2013). The techniques called steel blasting and sand blasting are very similar techniques. Both techniques use fine steel or sand particles which are blown at a surface at high speed, thereby stripping the contaminated material (Timm 2018) of the surface. The major difference between the two blasting techniques is that the sand grains can only be used once or twice whereas the steel grains can be reused up to 800 times (Interview: Kim Østergaard J Jensen A/S 2016). Olsen and Nerum Olesen (2015) found that there is a great variety of blasting materials used for blasting. To cover this range in our study, it was necessary to investigate two cases of both sand blasting and steel blasting—one case using a minimum amount of blasting material and one case using a maximum amount of blasting material.

The last technique assessed in our paper, sealing, simply works by applying a sealant to a surface and by doing so creating a permanent barrier layer that prevents the PCB from migrating to the indoor climate (Koch et al. 2013).

The selected remediation techniques differ significantly from each other in terms of labor effort, energy demand, etc., which inevitably will make the environmental footprints of these techniques vary. To minimize the environmental burden of the renovation of Broendby Strand, it is relevant to identify the most environmental friendly way of conducting a PCB remediation. To do so, the fused method of urban metabolism coupled with life cycle assessment (UM-LCA) was applied to the case of renovating Broendby Strand. The idea is thereby to quantify the induced effects for each technique and life cycle stage. UM-LCA will hence be used as a tool to identify the most environmental friendly remediation technique and thereby function as a possible decision tool when choosing among PCB remediation strategies. Since cost and technical efficiency are the most important factors when choosing a remediation strategy, these aspects will also be investigated, and advantages and disadvantages for each technique will be identified and highlighted. By considering the technical, environmental, and cost-efficiency aspects of remediation techniques, a more holistic perspective on all remediation techniques should ideally be provided.

2 Methods

To assess and prioritize the PCB-remediation techniques mentioned in the previous paragraph according to their environmental performance, a combination of the methodology "urban metabolism" (UM) and the "life cycle assessment" (LCA) framework was applied. In a traditional UM study, the city is typically depicted as a black box where upstream- and downstream-induced burdens are kept outside of the study's scope (Goldstein et al. 2013). A UM study most often account for the material and energy flows necessary for a city to conduct its "metabolism" thereby yielding a liveable urban space. The metabolism and hence provision of the urban space can be compared to the "use stage" of an LCA. As illustrated in Fig. 2, when the UM and LCA methodologies are combined, the LCA part is intended to account for environmental impacts of all life cycle stages by aggregating and characterizing the environmental loadings induced by inputs and emissions of the urban system conducting its metabolism (Goldstein et al. 2013). In our paper, we apply the UM-LCA definition in accordance with the definition proposed by Goldstein et al. 2013. For our case, specifically, the UM-LCA term is used to reflect that the neighborhood undergoing renovation/remediation can, in accordance with the UM definition proposed by Wolman (1965), be regarded as a metabolic entity defining the foreground system of our LCA. The metabolic entity in UM-LCAs is hence controlling a range of value chains feeding the metabolic entity and handling the waste streams emitted by the metabolic entity. The metabolic entity and thus the foreground are therefore not representing a specific life cycle stage in a single value chain. The metabolic entity is moreover representing a range of life cycle stages within each value chain exploited by the metabolic entity. The UM-LCA is hence a way to apply long-defined (urban) system assessment perspectives (i.e., urban metabolism) to describe a specific type of LCAs relying on a specific system perspective. By applying a combination of these two methods (UM-LCA), it is possible to calculate the environmental impact potentials of, e.g., remediation techniques applied on urban or large neighborhood level. In our study, the areas of interest are the five iconic PCB-contaminated

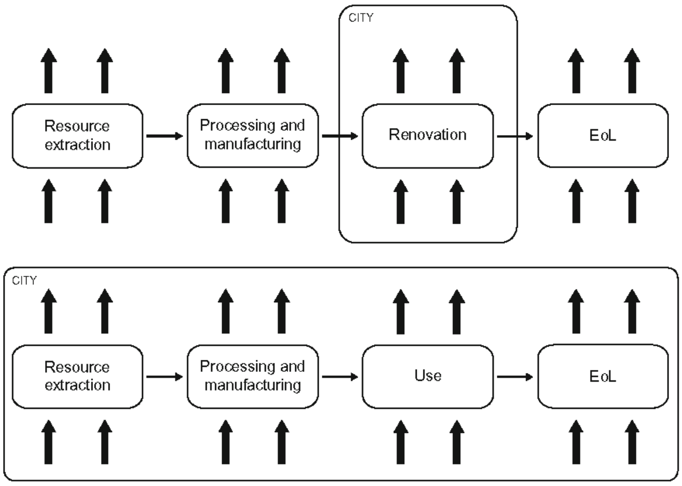

Fig. 2 Simplified illustration of how the scope of an urban LCA study can differ from system flows of materials at macroscale (top) and microscale (bottom). This study is done by considering the flows at macroscale, where the physical delineation of the city/neighborhood forms the system boundaries of the renovation LCA. Based on Goldstein et al. (2013)

buildings located in Broendby Strand close to Copenhagen in Denmark. Due to the scale of the buildings, these were in our study considered as a *neighborhood.* Only processes directly linked to the remediation are accounted for in our study. The included processes are summarized in Table 2.

The goal of our assessment is to quantify the environmental impact induced by a number of PCB remediation techniques in order to provide a qualified decision support regarding the choice of refurbishment strategy. When carrying out such an assessment, it is essential that the acquired data are based on the same unit (Jolliet et al. 2016). To ensure this, a functional unit was defined. In our assessment, the functional unit was defined as provision of 1 average m^2 remediated floor area with a PCB-concentration below the lowest action values, i.e., below 300 ng PCB/m^3 air.

Hence, an inventory quantifying all extracted resources and emissions to the environment had to be made (Jolliet et al. 2016). Since the goal was to be able to compare the four remediation techniques, an inventory containing detailed data for each technique would be needed. All data were thus sorted according to product system of origin and location within the three life cycle stages—"raw materials," "execution of refurbishment," and "disposal." An example of such a product system can be seen in Table 3. In order to model these product systems in a comparative manner, we interviewed experts to collect information on how the techniques are applied. The experts were not able to provide sufficient information on the techniques in order to build a complete inventory. Hence, to fill out the data gaps, assumptions relating to the actual application of each technique had to be made. We made these assumptions based on existing literature, cases, and projects. It was possible to find a relatively large amount of information in the literature; however, some details were simply not described or documented anywhere. Therefore, some of the data used in the simulations had to be based on assumptions made in accordance with our best judgment.

The data collected for the inventories of the remediation techniques were subsequently used to model a product system for each remediation technique. For this purpose, we used the software Quantis Suite 2.0 (QS2.0). QS2.0 is a simplified LCA product system modeling software that calculates environmental impact potentials supported by background data from the Ecoinvent 2.2 inventory database (Humbert et al. 2012). Contrary to most other product system modeling software, QS2.0 does not allow for choosing between different

Table 2 The phases and process groups relevant to the PCB remediation. The processes highlighted in bold are included in the LCA's carried out in this paper

Life cycle stages	Process	
Product phase	**A1**	**Extraction of raw material**
	A2	Transportation for manufacturing
	A3	Manufacturing of materials
	A4	**Transportation to building site**
Refurbishment	B1	Stripping of fixture
	B2	**Sealing off**
	B3	**PCB-remediation**
	B4	**Cleaning**
	B5	Installation of fixture
	B6	**Water consumption**
End-of-life	**C1**	**Transportation to disposal**
	C2	**Incineration/landfill**
Next inventory	D	Recycling/reuse potential

Table 3 Representative remediation inventory: inventory for the technique "thermal desorption"

	Raw materials	Execution of renovation	Transportation		Disposal (kg)	Transportation (tkm)
			To construction site (tkm)	From construction site (tkm)		
Rock wool	0.79 kg	–	0.006	–	0.79	0.09
Plywood	0.002-7 m^3	–	0.011	–	1.365	0.16
Gloves	0.0019 kg	–	0.0099	–	0.0497	0.006
Coverall	0.038 kg	–				
A2P3 filter	0.0093 kg	–				
Charcoal filter	0.001-5 m^3	–	0.0135	–	0.075	0.0089
Aircleaner, charcoal	–	1.8 kWh	0.0002	0.0002	–	–
HEPA filter	0.13 kg	–	0.032	–	0.013	0.015
Aircleaner, HEPA	–	1.8 kWh	0.00018	0.00018	–	–
Calorifere	–	3.36 kWh	0.0011	0.0011	–	–
Oil furnace	–	37.3 MJ	0.0003	0.0003	–	–
Fan	–	0.84 kWh	0.00086	0.0022	0.019	0.0022
Vacuum cleaner	–	0.04 kWh	0.00013	0.00013	–	–

impact assessment methods, and using QS2.0 means having to rely solely on the IMPACT2002+ impact assessment methodology (Humbert et al. 2012).

Since QS2.0 relies on an older version of Ecoinvent and is a simplified product system modeling tool and since the systems being modeled are quite complex, we decided that it is necessary to validate the results and hence the decision support provided by QS2.0. In order to validate the results from QS2.0, we carried out the exact same assessment in a more complex tool, OpenLCA 1.5. It was chosen to use a more recent version of Ecoinvent for the validation, here Ecoinvent 3.2. By choosing a more recent version of Ecoinvent, we intended to make sure that the decision support provided by QS2.0 not only aligns with more complicated product system modeling software but also more recent data. When using OpenLCA, it is possible to choose between different impact assessment methods. Here, we chose to use the ReCiPe 2000 midpoint and endpoints comparable to the results obtained from QS2.0. OpenLCA is an open source software and hence provided free of charge, which makes it an economical reachable tool to use in practice for architectural offices and other consultancies. However, the complexity of the tool can make it difficult and time-consuming to use in design processes where the aim is to promote and facilitate knowledge-based design decisions. Therefore, the current study emphasizes to investigate whether the complexity of OpenLCA is comparable to the results, and hence if QS2.0 would be an acceptable choice of software to be used for simple and quick calculations in relation to building design practice.

One of the challenges encountered in relation to comparison of the four techniques was that in practice using only one remediation technique is rarely enough to lower the PCB-level below action levels (Koch et al. 2013). As earlier mentioned, usually, several remediation techniques are used simultaneously, and it is almost impossible to predict exactly how the preparations for a PCB remediation will take their course (Interview: Kim Østergaard J Jensen A/S 2016). In our case, we decided to investigate the techniques separately. Some denominators common to all remediation techniques were not included. The common denominators are the stripping of existing fixtures, removal of flooring, and removal of the primary sources of PCB in each apartment. These are all actions that will represent an environmental impact when carried out—for instance, the disposal of all PCB-contaminated building materials will induce significant environmental effects—but since these actions are carried out *before*, any of the techniques can be applied, and since the actions are common to all techniques, it can be argued that the environmental impacts induced by these actions will be equally divided between the techniques and thus have negligible influence on the remediation technique comparison.

Even though the four remediation techniques all vary in the way they handle PCB contamination, they share some further

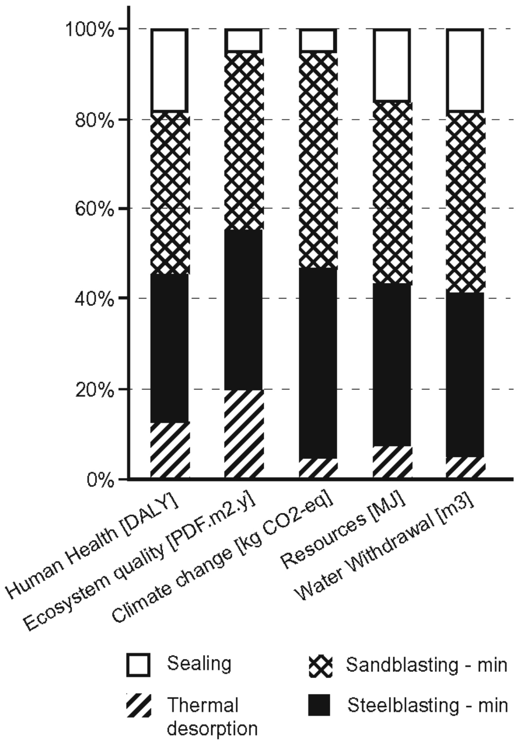

Fig. 3 Comparison of the considered PCB remediation techniques, assuming use of minimum amounts of blasting material for the two blasting techniques, Quantis Suite 2.0

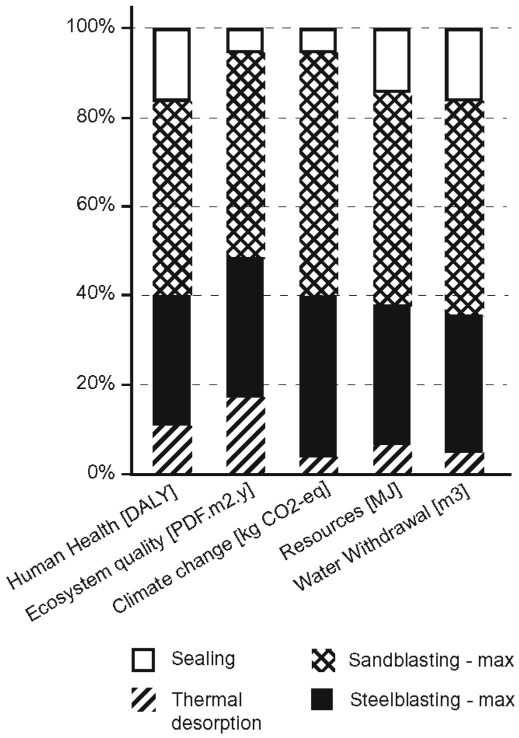

Fig. 4 Comparison of the considered PCB remediation techniques, assuming use of maximum amounts of blasting material for the two blasting techniques, Quantis Suite 2.0

elements that we have chosen not to include in the comparison of the techniques. Identical elements of the techniques will not have any relative influence when comparing the results (Jolliet et al. 2016); they will only make the calculations more extensive and will require further data. An element which reoccurs in every technique is, e.g., an on-site changing room for workers, which ensures that traces of PCB on clothes are not spread. In Denmark, having an on-site changing room is compulsory when dealing with dangerous substances, and therefore this changing room is an element identical for all remediation techniques.

Finally, we chose not to include activities, which—by our estimates—only induce minor/negligible environmental impacts. These activities include manufacturing of safety equipment and cleaning of handheld tools after the refurbishment of all apartments is finished.

The assumption that all of the above-mentioned elements can be left out of the simulation has helped limiting the data processing needs. Besides this, limiting the number of activities simulated, so that only the activities differing across scenarios are left, can be considered an advantage in terms of result interpretation. It is easier to identify weaknesses and strengths for each remediation technique and thereby exposing possible ways of optimizing the techniques if only differences are compared. However, it is important to keep in mind that the estimated environmental impact potential for each technique is hence a relative measure and smaller than the "absolute" impact potential associated with a PCB-remediation technique. The *absolute* environmental impact potential could be calculated by adding environmental impacts associated with the activities *not included* in our results for each technique.

The focus of our paper is the environmental impact potentials associated with various PCB-remediation techniques; however, decisions relating to refurbishment strategy are, as earlier mentioned, rarely based on environmental performance arguments. Deciding which remediation technique(s) to use will in most cases be determined by cost (Interview: Kim Østergaard J Jensen A/S 2016; Interview: Flemming Correll Frank 2016; Interview: Kathrine Birkemark Olsen and Lene Dalvang 2016). Rough estimates of the price for two out of the four techniques were found; however, as earlier mentioned, it is difficult to predict how the exact course of a PCB

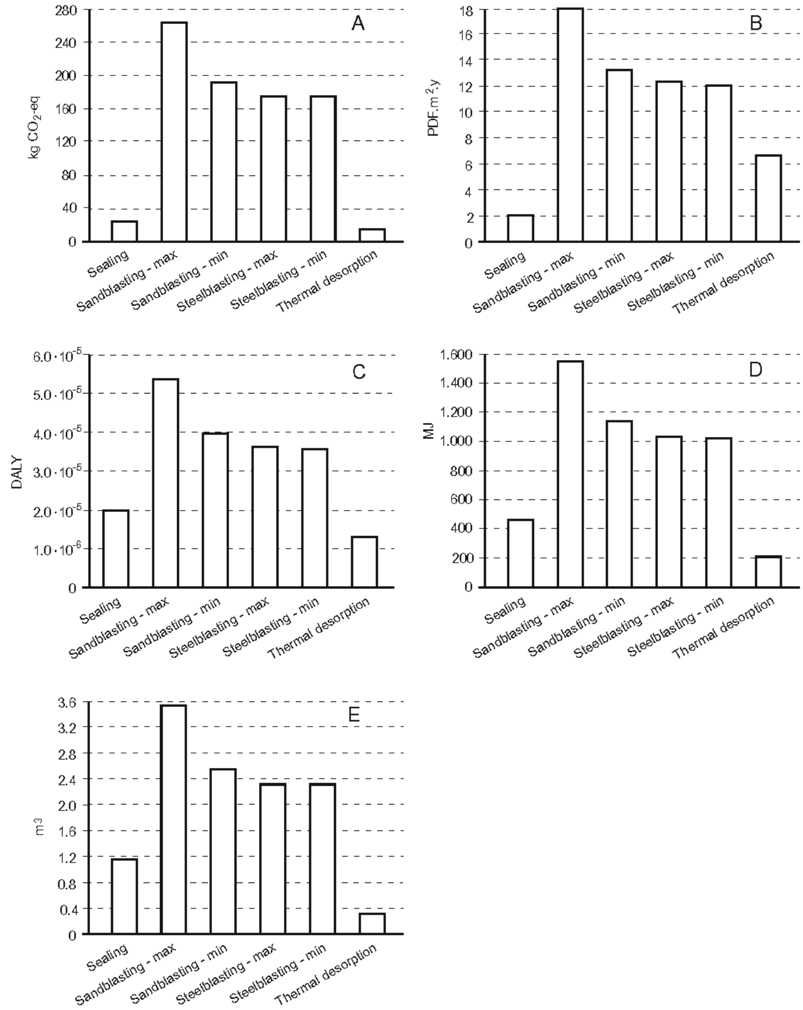

Fig. 5 **a** IMPACT2002+ endpoint climate change, **b** IMPACT2002+ endpoint ecosystem quality, **c** IMPACT2002+ endpoint human health, **d** IMPACT2002+ endpoint resources, **e** IMPACT2002+ endpoint water withdrawal

remediation will be which is why it is also difficult to predict the cost of a technique in advance.

3 Results

As mentioned earlier, this study considers two quite similar cases of the sand blasting and steel blasting techniques. For these techniques, two subscenarios were assessed representing the use of a minimum amount of blasting material and a case where a maximum amount is used (Olsen and Nerum Olesen 2015).

Figure 3 presents the overall results for the case where a minimum amount of blasting material is used for the blasting techniques, whereas Fig. 4 illustrates the environmental impact potentials induced by the four techniques in the case where a maximum amount of blasting material is used. The two figures compare the four techniques and their environmental impact potentials. Figure 5a–e compares the environmental impact in each endpoint category.

In Figs. 3 and 4, it can be seen that the technique thermal desorption is the remediation technique with the best environmental performance across most endpoint categories. The technique thermal desorption has the advantage that it does not produce any waste, which is an important reason for the environmental performance. As seen in Fig. 6, it is the life cycle stage "execution of refurbishment" that exhibit the largest environmental impact potentials caused by the energy

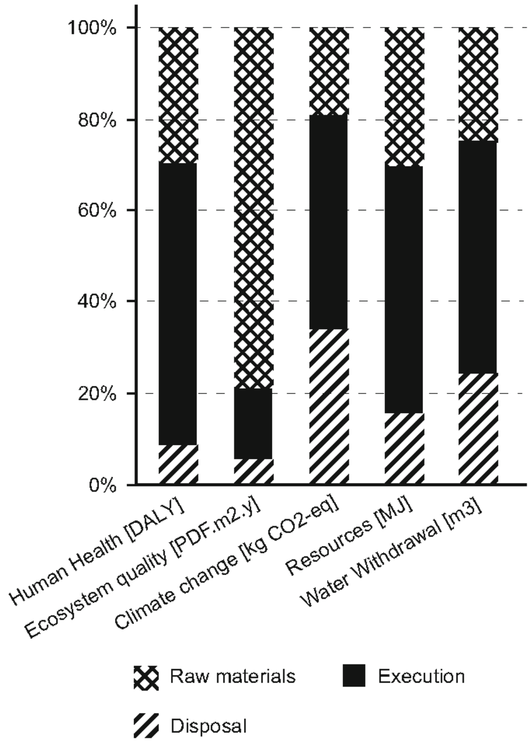

Fig. 6 Overview of the origin of the environmental impact potentials associated with thermal desorption, Quantis Suite 2.0

consumption induced by the elevation of the temperature in the building to minimum 50 °C. The life cycle stage "raw materials" represent a large environmental impact as well. A way of optimizing this stage could be to choose different materials than plywood as shielding during the remediation, due to a great environmental impact generated by the glue used in plywood (Teknologisk Institut 2009).

Figures 3 and 4 clearly illustrates that sand blasting is the technique inducing the largest environmental impact potentials in both cases using either minimum or maximum amounts of blasting material. As it can be seen in Fig. 7, the life cycle stage "disposal" is clearly the life cycle stage exhibiting the largest impact potentials. Further analysis reveals that the majority of impacts, induced by sand blasting, are associated with the amount of construction waste and blasting material that needs to be disposed of as hazardous waste. Compared to the impacts from the construction waste, the blasting material constitutes only a minor part of the total environmental impact of sand blasting. From this, it can be seen that it would be relevant to optimize the method of disposal and thereby reduce the environmental burden associated with the technique sand blasting.

Similar to sand blasting, the technique steel blasting has a great environmental impact. As it can be seen in Fig. 8, the life cycle stage "disposal" is the most injurious to the environment. The great environmental impact in the disposal stage is a result of the amount of construction waste that needs to be disposed of as hazardous waste.

Eventually, in Figs. 3 and 4, it is observed that the technique sealing has a noticeable low environmental impact. Figure 9 clearly illustrates that the life cycle stage "raw materials" causes the greatest impact associated with the use of surface sealant. The surface sealant is based on epoxy resin, which is known to be environmentally (both ambient and work) problematic (Huang et al. 2012), and it would hence be relevant to use a surface sealing alternative that is less problematic. An advantage of choosing this technique is that this solution does not produce any waste, just like the technique thermal desorption, which turned out to be an important factor having considerable influence on the total environmental impact of the compared remediation techniques.

Since QS2.0 is a simplified product system modeling software, the exact same simulation conducted in QS2.0 was reproduced in OpenLCA using the same inventory data for all four techniques/foreground systems—sealing, sand blasting, steel blasting, and thermal desorption. The results obtained from the two modeling approaches are hence not

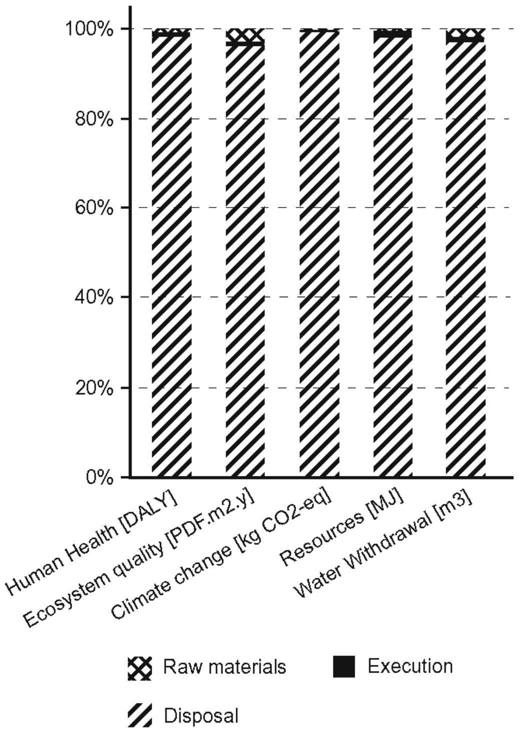

Fig. 7 Overview of the origin of the environmental impact potentials associated with sand blasting, Quantis Suite 2.0

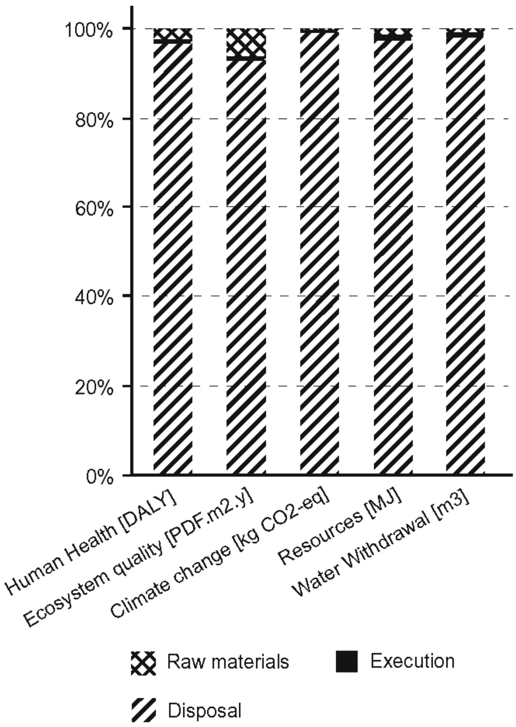

Fig. 8 Overview of the origin of the environmental impact potentials associated with steel blasting, Quantis Suite 2.0

directly comparable for all impact categories (however, assuming more or less direct comparability of simpler impact indicators such as GWP); however, it is considered valid to compare the environmental ranking obtained for the remediation techniques considered and hence the decision support provided by the two product system modeling software.

Figure 10 presents the environmental impact potentials obtained for the four techniques for the cases where a minimum of blasting material is used, while Fig. 11 shows the environmental impact of the four techniques for the cases where a maximum amount of blasting material is used.

Figure 12a presents the environmental impact potentials for climate change and Fig. 12e shows water depletion for all six remediation strategies. Figure 12b presents the ReCiPe endpoint categories for ecosystems, Fig. 12c human health, and Fig. 12d resources. All five ReCiPe result sets are compared with the results obtained from QS2.0.

The compared remediation strategies are for the product system modeling software comparison divided into the three phases: “raw materials,” “execution,” and “disposal.”

Figure 13 shows the environmental impact potentials induced by thermal desorption, Fig. 14 from sand blasting min, Fig. 15 from steel blasting min, and Fig. 16 presents the relative environmental impacts from surface sealing.

3.1 Efficiency of the techniques

As mentioned in the paragraphs “Introduction” and “Methods,” deciding on a remediation strategy will in most cases be based on *cost* and *efficiency* of the remediation strategies (Interview: Flemming Correll Frank 2016, Interview: Kathrine Birkemark Olsen and Lene Dalvang 2016, Interview: Kim Østergaard J Jensen A/S 2016). As earlier mentioned in this paper, a project where the efficiency of three compared remediation strategies had been tested. Determining the efficiency of a technique is challenging, due to the fact that the efficiency of a technique is highly dependent on *which* material the PCB needs to be removed from as well as the *amount* of PCB in the material. The next paragraph describes how the remediation of two apartments where carried out step-by-step.

Initially, the primary sources of PCB were removed from the apartments, which caused the concentration of PCB in the indoor air to decrease with 57% in one apartment and 71% in a

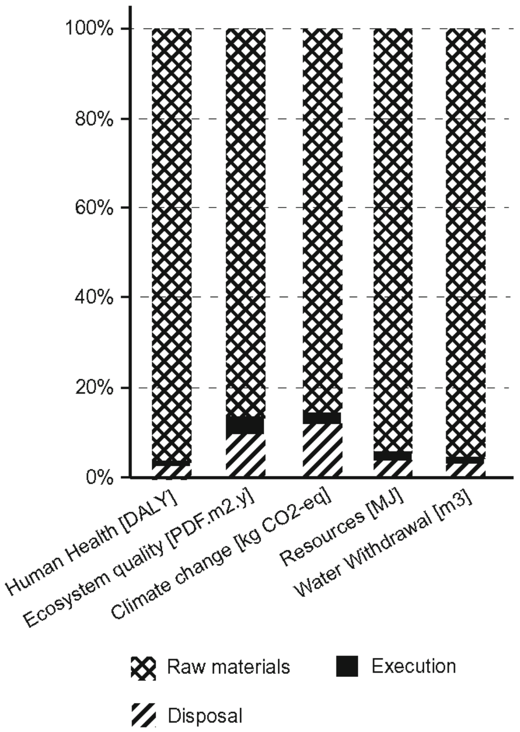

Fig. 9 Overview of the origin of the environmental impact potentials associated with surface sealing, Quantis Suite 2.0

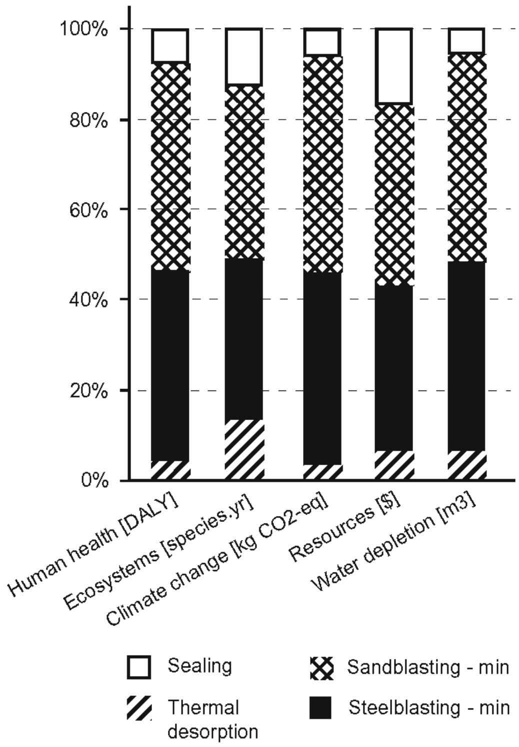

Fig. 10 Comparison of techniques, minimum amount of blasting material, OpenLCA

second apartment (Sparvath and Trap 2014). After removal of the primary sources, a steel blasting of all walls in the apartments was performed, which, at first, further lowered the PCB concentration with additionally 2%, but in one of the apartments, the concentration rapidly increased again—possibly due to a mobilization of the PCB (Sparvath and Trap 2014). After the steel blasting of the apartments, a thermal desorption was conducted in one of the apartments, which made the concentration initially decrease with additionally 14% (Sparvath and Trap 2014). Over a longer time span, the PCB concentration in the indoor air however increased again, which may be due to the fact that an increase in temperature can mobilize the PCB and thereby cause an increase in PCB concentration in the indoor air. In the second apartment, a surface sealing was carried out which decreased the concentration with additionally 10% (Sparvath and Trap 2014). The combination of removal of primary sources, steel blasting, and a thermal desorption or a surface sealing, respectively, yields a total decrease in PCB concentration of 49% (final = thermal desorption) in one apartment and 73% (final step = surface sealing) in another (Sparvath and Trap 2014). The total decreases presented here accounts for the unintended increases in concentration associated the steel blasting and thermal desorption techniques.

4 Discussion and conclusions

During this project, it was challenging to locate the data necessary to conduct a UM-LCA on each technique. Because of this, a range of assumptions had to be made which has introduced uncertainties in the obtained via our assessment, and this fact needs to be accounted for in the interpretation of the result.

Our study indicates that the least environmentally burdensome technique is thermal desorption (see Figs. 3 and 4). Some sources of errors could be that, in most cases, it will be necessary to perform a thermal desorption more than once as well as elevating the desorption temperature beyond 50 °C (Koch et al. 2013) in order to obtain sufficient desorption. The higher temperature will inevitably cause a higher energy consumption and thereby make the technique more environmentally taxing. Through our assessment, it has been made clear

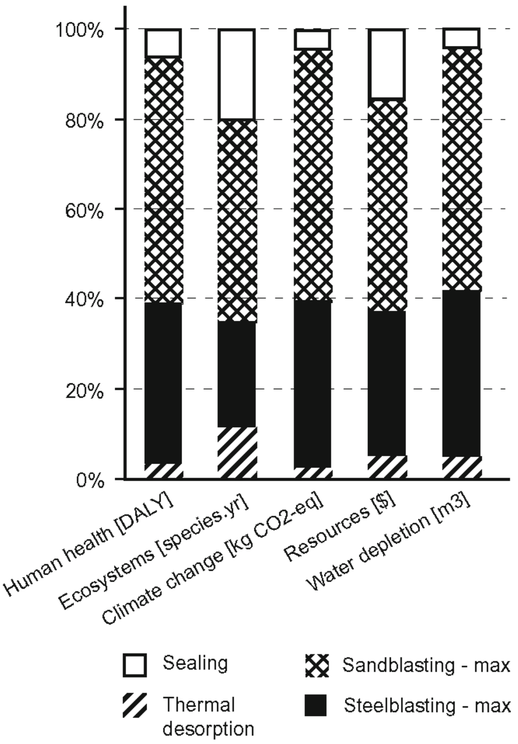

Fig. 11 Comparison of techniques, maximum amount of blasting material, OpenLCA

that disposal of waste has a considerable influence on the total environmental performance of a remediation technique which provide the techniques generating the lowest amount of waste—an environmental advantage.

The fact that the steel grains used for blasting in the technique steel blasting can be reused up to 800 times, was not, as initially expected, an advantage. This is due to the environmental impacts induced by the disposal of waste. Steel blasting is a relatively new remediation technique making it difficult to locate adequate data needed to conduct the assessment and thereby considerable uncertainties arise. In our project, many of the assumptions regarding steel blasting are based on data found on sand blasting.

For sand blasting, as was the case for steel blasting, it is the amount of disposed waste that affects the environmental performance the most. For both techniques, the amount of waste depends on the PCB contamination levels and hardness of the contaminated material to be blasted, which yields uncertainties regarding the amount of waste for disposal.

Finally, the technique surface sealing encloses the PCB in the material and prevents it from migrating to the indoor environment. Thereby, the PCB will migrate further into the materials and over time contaminate a greater volume of the material (Koch et al. 2013). This will in the end increase the amount of hazardous waste to be disposed of when the contaminated building is demolished, and it will hence be more difficult to separate the non-hazardous waste from the hazardous waste. However, new techniques might appear in the future, which will make the environmental impact associated with waste disposal smaller and justifying temporary solutions such as surface sealing. It would have been relevant to include the future demolition of the buildings and calculate the total environmental impact. Had this been included, it is expected that the surface sealing technique would have performed significantly worse compared to the other techniques.

Comparing the two pieces of product system modeling software, QS2.0 and OpenLCA, underlines the efficiency of the simple tool QS2.0 as the results obtained from the two tools more or less are the same, with a maximum of 10% of variation. At the same time, by verifying the results obtained from QS2.0 by comparison with results obtained from OpenLCA, it is ensured that the results remain unbiased and partially validated. The results obtained from OpenLCA proved in general to be lower than the QS2.0 results. An important difference lies in the impact assessment methods applied in the two programs resulting in different impact categories for quantification of the environmental performance of the remediation systems. It is concluded that the simpler simulation software QS2.0 is just as suited for the UM-LCA task as the more complex software OpenLCA, and application of the tool may prove beneficial in practice due to ease of use and license price. However, the limitations (i.e., in terms of data resolution, e.g., midpoints; choice of characterization method; availability of compatible inventory data) of QS2.0 also have to be taken into account when conducting a UM-LCA. Therefore, it is considered crucial to include a validating comparison applying a more conventional product system modeling software, here OpenLCA. Such a comparison ensures objectivity and hence validity of the statements made regarding QS2.0.

4.1 Discussion of cost and efficiency

As mentioned earlier, the remediation techniques thermal desorption, steel blasting, and sealing reduced the PCB contamination levels in two identical apartments with 73 and 49%. Since the two apartments were identical, the results should ideally not vary much. The noticeable variation in the results underline the difficulty in predicting the efficiency of the techniques, and it is considered necessary to measure and validate the efficiency of each remediation technique in the respective apartments to get a clearer picture of exactly how efficient they are. The pilot project involving the two test apartments illustrates that the removal of primary contamination sources is the most efficient method and that the remediation

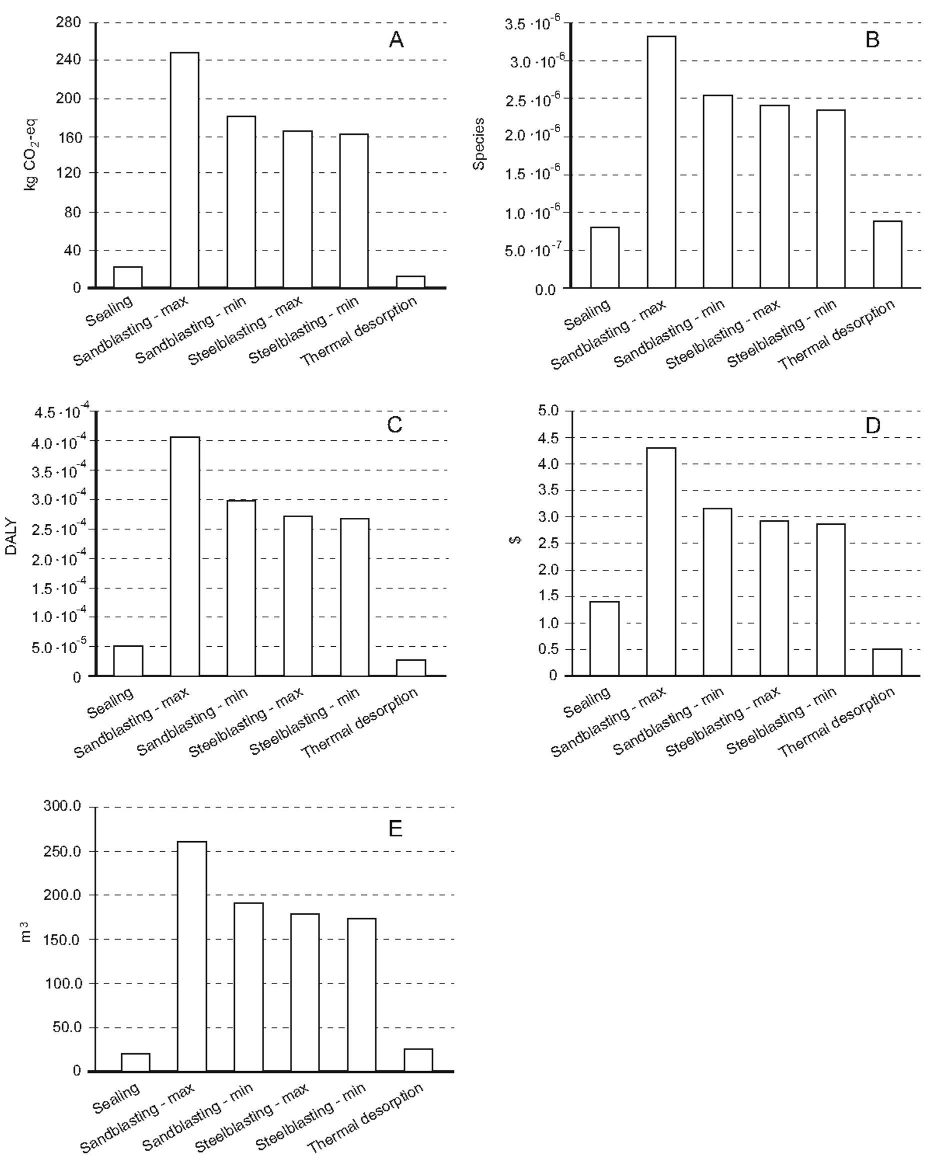

Fig. 12 **a** Climate change, OpenLCA; **b** ecosystems, OpenLCA; **c** human health, OpenLCA; **d** resources, OpenLCA; **e** water depletion, OpenLCA

techniques do not necessarily provide acceptable PCB contamination levels and hence acceptable low air concentrations. The best results can most likely be obtained through removal of the primary sources followed by a combination of the different techniques. Furthermore, the pilot project states that the remediation techniques thermal desorption and surface sealing are the most efficient techniques, but the risk of the PCB contamination forcing its way deeper into the construction materials needs to be considered.

Predicting the remediation cost is just as difficult as predicting the efficiency. The expenses related to the technique sand blasting varies from 450 DKK/m^2 to 2.455 DKK/m^2. The fact that data are available on this technique is due to the fact that this method is fairly common, and it is

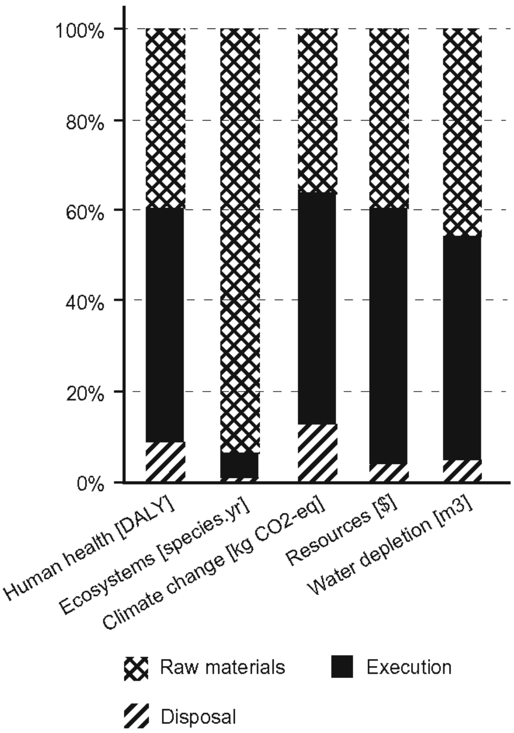

Fig. 13 Overview of the origin of the environmental impact potentials associated with thermal desorption, OpenLCA

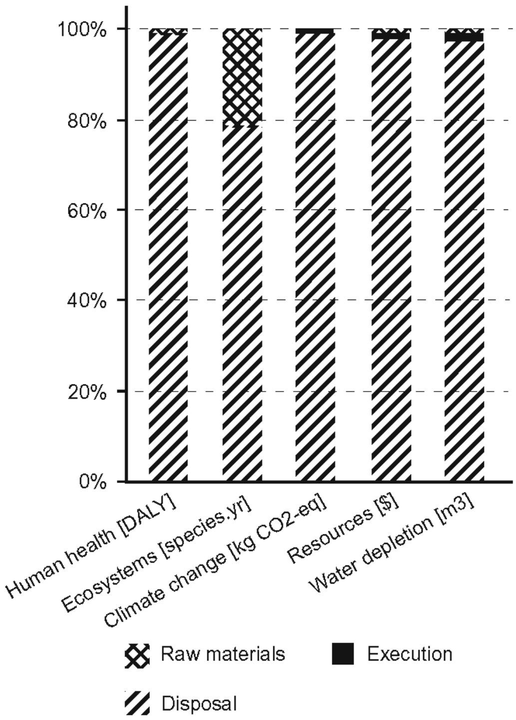

Fig. 14 Overview of the origin of the environmental impact potentials associated with sand blasting (minimum), OpenLCA

therefore easier to obtain estimates of the expenses related to it. On the contrary, there is currently only one Danish contractor applying the technique steel blasting, and they reported that the average expenses related to the technique are 871 DKK/m^2, which puts the expenses related to steel blasting within the price range of sand blasting yielding a clouded picture in terms of economic advantage of any of the methods.

It has not been possible to find reliable prices on the remaining techniques, thermal desorption and sealing, which complicates an economic and hence a more holistic comparison.

4.2 UM-LCA as a decision tool

One of the goals of this paper was to investigate how the method UM-LCA can function as a decision support tool in relation to a PCB remediation and if a simplified readily available product system modeling software is up for the task. The benefit of coupling UM with LCA is that the LCA will ensure that upstream and downstream burdens are included in the assessment, and the result will thereby become more accurate. In the same manner, the UM framework compliments the LCA framework by providing a valuable and long-defined (Wolman 1965) urban assessment framework perfectly compatible with a specific way of assessing (product) systems and, in our case, more specifically, urban subsystems.

In this study, it has become clear that the amount of hazardous waste that needs to be disposed of by application of blasting-based remediation techniques is a very relevant factor when prioritizing remediation techniques according to environmental burden. Since disposal of waste is an example of a downstream process that would be left out of a traditional UM study, it can be concluded that without the combination of urban metabolism and life cycle assessment, the final result of this study could have been too narrow and hence misleading.

Applying the UM-LCA approach to the case of comparing different techniques has worked well and has successfully given an overview of which techniques are the best seen from an environmental point of view. Another way of assessing the environmental impacts of the renovation is described in the recently introduced Danish industry guidance for LCA on retrofit projects "Branchevejledning i LCA ved renovering" (see Worm et al. (2016)). Here, three levels of LCAs are proposed for retrofit projects. For each of the three levels, different life cycle stages are included in the assessment. The

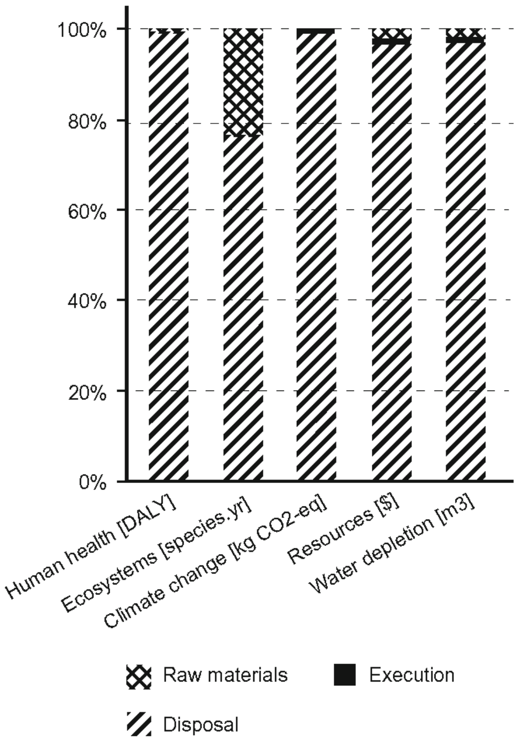

Fig. 15 Overview of the origin of the environmental impact potentials associated with steel blasting (minimum), OpenLCA

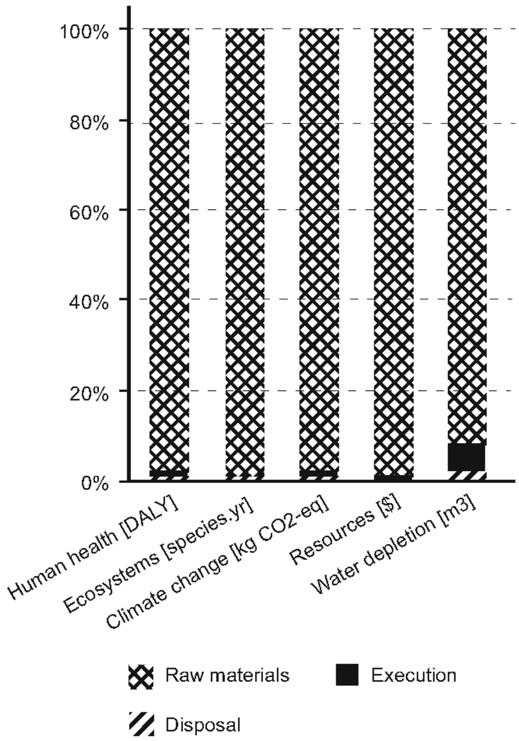

Fig. 16 Overview of the origin of the environmental impact potentials associated with surface sealing, OpenLCA

applied UM-LCA methodology in this study would be (approximately) comparable to a level 2 LCA according to the new guidance; however, since the study described here was carried out as a comparative LCA, certain life cycle stages that the guidance normally recommends to include were purposely left out (since these are assumed equal for the systems compared). Examples of life cycle stages that could be left out in our comparative LCA are, e.g., disposal demolished building materials and the PCB-contaminated floor boards and window frames. A UM-LCA is roughly speaking merely a specific form of (building) project LCA relying both on the LCA framework and the already defined (Wolman 1965) UM framework in order to project the correct system perspective applied for the assessment. When comparing the considered techniques, the result is straightforward and easy to comprehend and communicate with little or no prior knowledge of LCA required. As a part of our consideration of UM-LCA as a useful tool for decision support, four experts were asked about their opinion on the possibility of incorporating results from an LCA in a remediation decision process (Interview: Kim Østergaard J Jensen A/S 2016; Interview: Flemming Correll Frank 2016; Interview: Kathrine Birkemark Olsen & Lene Dalvang 2016). Of the four experts, three were dismissive of the idea and argued that cost and efficiency of a refurbishment strategy always would be the determining factors. Only one of the four experts was open to the idea of including UM-LCA as a support tool for decision-making. It was suggested that performing an LCA could be a service that consulting engineers and architects offer a building contractor. Given that three out of four responses were negative, it is clear that if environmental factors should gain priority when planning future refurbishment of large-scale projects, further (potentially legislative) incentives are needed.

A possible way of motivating contractors, consulting engineers, architects, and building contractors to implement UM-LCA as a decision support tool could be to establish a financial incentive as is the case with DGNB certification. A study done by the World Green Building Council shows that the general perception in the Danish building industry is that sustainable buildings or "green" buildings cause higher expenses than what they really do (World Green Building Council 2013). The same study disproves this perception by describing how a DGNB-certified building generally causes lower energy costs and fewer expenses related to operation and maintenance while at the same time increasing the rental income and sales value of the building and inducing higher efficiency amongst employees as a result of a better indoor climate (World Green Building Council 2013). A Danish DGNB certification was first introduced in 2012, and in the spring of 2015, 50 projects were certified or in the process of being certified (Green Building Council Denmark 2016). In April 2016, the Danish Green Building Council performed a market investigation, where 55 persons from 45 different companies answered a questionnaire about their opinion on sustainable buildings and DGNB certification. Eighty percent of the participants answered that they expect that the demand for sustainable buildings will increase, and 0% answered that they expect a decrease (Green Building Council Denmark 2016).

With the above-summarized study in mind, it can be argued that sustainability is and will most likely be a relevant parameter to most contractors in the future, but most likely only as long as some sort of financial gain is associated with the sustainability "tag." It is hence considered if the environmental impacts of a renovation or remediation technique could be incorporated as a parameter in a (renovation) certification such as DGNB. If one of the requirements for reaching a high (renovation) DGNB core—and thereby gaining the possible financial reward associated with a DGNB-certified building—was documenting that the most environmental friendly renovation strategy had been chosen; contractors, consulting engineers, architects, and building contractors would have an incentive for investigating and choosing the technique with the smallest environmental impact. Furthermore, it could be a criterion that the documentation should be in the form of a (UM-)LCA.

Finally, it can be concluded that UM-LCA is a highly applicable and highly illustrative tool that *can and should* be used as a decision support tool for building renovation/remediation and has the potential to be essential in the future of designing sustainable buildings, if some sort of economical aspect could become incorporated in/associated with the method.

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APPENDIX F

PAPER (6)

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Integrated design processes – a mapping of guidelines with Danish conventional 'silo' design practice as the reference point

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Integrated design processes – a mapping of guidelines with Danish conventional 'silo' design practice as the reference point

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ABSTRACT

This research maps various Integrated Design Processes (IDPs) with Danish conventional silo Design Practice as the reference point. The intention was to identify generic elements that are common among IDPs. The mapping was based on a literature study of a number of IDP guidelines. Eight IDP guides from the last two decades were selected for mapping. The Danish Description of Services functions as a typical representation of a conventional silo Design Practice (CSDP) and as a 'scale' against which to map the selected IDP guides. The results indicate a limited consensus on what constitutes an IDP but a possible consensus core that is shared by them all. One commonality is that technical knowledge must inform design decisions, and not simply be used to validate them, but on the other hand, it should not drive them. Another main trait is the interdisciplinary character of these processes, where several professions must be a part of the process from the beginning. The study also found that all IDP guides have a 'black box problem', where the desired inputs and outputs of the process are known but no explanation is given regarding the mechanisms of how the integrated design decisions are to be made or how to facilitate this decision-making in an interdisciplinary design team. These findings can explain the slow adoption of IDPs in the building industry and they can be used to improve IDPs and increase their implementation in integrated building design.

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KEYWORDS
Integrated design process; sustainability; building design; mapping

Introduction

The information available to designers has increased due to the advent of digital tools that can apply centuries of engineering knowledge. Building Information Models, together with these tools, form a new framework for building projects and it is evident that design processes should be improved as a result. The family of 'Integrated Design Processes' reflect this development and provide answers to how the new information that has become so readily available can assist in efficiently achieving sustainable buildings.

Background

A new focus on the energy consumption and environmental impact of the building industry has resulted in more strenuous requirements for building performance, which has inevitably resulted

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in more complex building design processes (Brunsgaard et al., 2014; Intelligent Energy Europe, 2009; Keeler & Burke, 2016; Koch & Buhl, 2013; Urup, 2016). Building regulations concerning energy consumption have been tightened and tuned in Denmark, which now has one of the world's most ambitious energy regulations for building operation. This has led to an increased focus on the process of achieving sustainable building performance (Brunsgaard et al., 2014; Intelligent Energy Europe, 2009; Koch & Buhl, 2013; Reed & Gordon, 2000; Urup, 2016).

The quest for sustainable building practice has been a common thread in research and legislation for three decades. In this period, it was realised that sustainability goals cannot be achieved simply by adding technological components (such as PVs) to a finished architectural design (Brunsgaard et al., 2014; Intelligent Energy Europe, 2009; Koch & Buhl, 2013; Urup, 2016). Instead, achieving sustainability goals requires a focus on the entire building, and on the synergies and trade-offs between various design decisions. Research also showed that if a reduction in the energy consumption for building operation is the goal, the most efficient approach is to focus on early design decisions (Intelligent Energy Europe, 2009; Nielsen, 2012; Strømann-Andersen, 2012). These include their basic geometry, window-façade ratio, and orientation – decisions that are often made by architects. Such architectural decisions greatly restrict the range of solutions available to HVAC engineers. The background for the present study of integrated design processes is the complexity that arises from these new circumstances.

Traditionally the design process is divided between the silos of professions, having architects in one silo and engineers in another silo. In the Conventional Silo Design Process – (CSDP), the architect designs the building first and the engineers then equip it with technical systems. CSDPs are linear processes where the architect and client agree on a design concept consisting of the volume/geometry, orientation, window/façade ratio, and so on (Urup, 2016). Next, the engineers suggest and implement the technical systems necessary to allow the design to function correctly, e.g. to achieve an acceptable indoor climate (Intelligent Energy Europe, 2009). The contractor then calculates the costs and begins construction. Building design in CSDPs is like a baton being passed from one stakeholder to another.

As mentioned above, research show that the performance and sustainability of a building are greatly influenced by the decisions made in the early design phases. This challenges the linearity and work division of CSDPs (Brunsgaard et al., 2014; Koch & Buhl, 2013), and makes CSDPs unsuitable for the complex task of optimizing a building in its entirety and creating sustainable buildings (Brunsgaard et al., 2014; Busby Perkins + Will, S.C., 2007; Intelligent Energy Europe, 2009; Koch & Buhl, 2013; Larsson, 2009; Urup, 2016). The MacLeamy Curve (Figure 1), which is widely used in research focusing on IDPs, demonstrates the importance of early intervention in the design process to ensure a positive influence on the sustainability of the design and to limit the expenses incurred (AIA, 2007; Buvik & Hestnes, 2008).

Recent developments in sustainability certification systems such as DGNB (The German Certification system – Deutche Gesellshaft für Nachhaltiges Bauen) show evidence that IDP elements are partially included in the Process Criteria: PRO 1.1-1.4 (DK-GBC, 2014).

Problem, aim

In many ways, the Danish context is an ideal environment for the implementation of IDPs. For example, engineering education in Denmark has broadly included IDPs in the curriculum since 2003 (Rammer Nielsen, 2003). In addition, IDPs require a collaborative and interdisciplinary work culture. Denmark has a well-documented culture of trust, which is one of the basic requirements for establishing a collaborative and interdisciplinary work culture (DANSKE ARK and FRI, 2012; Löhnert, Dalkowski, & Sutter, 2003; Urup, 2016). Additionally, educational programs in Denmark, from Kindergarten to the PhD level, are project-based and group-work oriented, and this prepares students to work in a collaborative work culture. The financial advantages of IDPs have been thoroughly researched and documented through large EU-financed projects such as Task 23

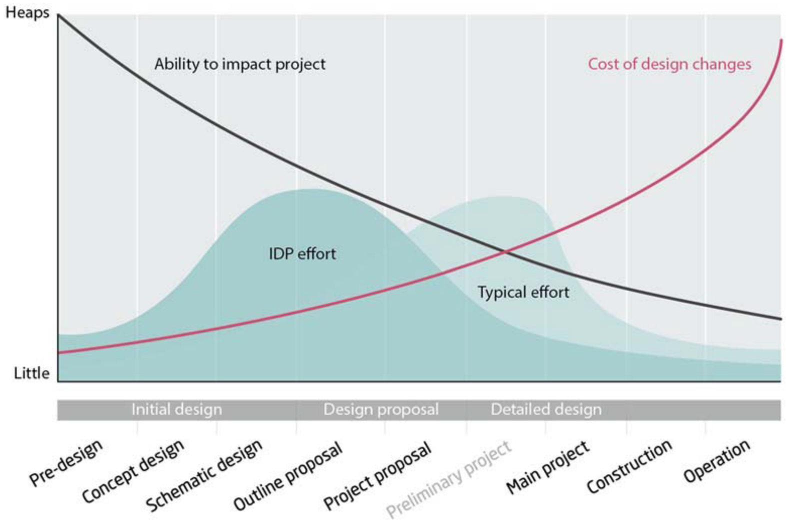

Figure 1. MacLeamy Curve, visualizing that the ability to impact projects is greatest in the early design phases and that the cost of changes is the largest in the late design phases. This highlights the importance of integrating technical knowledge in the early design stages. The red curve indicates the cost of design changes. The black curve indicates the possibility of influencing the project.

(Löhnert et al., 2003). Finally, some of the largest engineering consultancies in Denmark and Europe have made IDPs an explicit part of their company strategies (Arup, 2018; Wohlenberg & Jakobsen, 2018). Sustainability certification systems encourage the use of an IDP through DGNB PRO 1.1-1.4, as previously mentioned. However, there is no description of how collaboration in the interdisciplinary design team should take place. In addition, DGNB historically required 10 concepts to be developed in the early design phases, by an interdisciplinary team. There is considerable variation in the understanding and implementation of IDPs in the Danish building industry. In the process of preparing this paper, a questionnaire to 8 architectural offices specialized in sustainable architecture was send out, and a series of interviews was performed to supplement the survey. This showed that although many architectural offices in the Nordic Countries use an implicit IDP approach or at least elements of it, few conduct projects explicitly according to an IDP guideline (Landgren & Jensen, 2017; Wohlenberg & Jakobsen, 2018). In conclusion, the overall adoption of IDPs in Denmark continues to be slow.

Aim, objective

Through a comparative study of a selection of IDP descriptions and best-practice guidelines for IDPs published over the past two decades, a mapping was performed in order to determine if there was a generic design content, e.g. a core of parameters in or a consensus among the different guidelines and methodological descriptions of IDPs. The mapping used a common 'scale' (the Danish Description of Services) that represents the conventional silo design practice (CSDP). The mapping seeks to identify gaps, insufficiencies, or other weaknesses in the IDP definitions, frameworks, or best-practice guides that could be partially responsible for the relatively slow implementation. The mapping adds to the findings of Kanters and Horvat (2012), which addressed the implementation of IDP through an international literature review and by means of interviews, experience, and case studies. They performed a series of interviews with practitioners concerning IDP implementation, although they did so without referring to specific guidelines (Kanters & Horvat, 2012).

Methods

This work is based on a mapping of literature that define methods and propose guidelines for Integrated Design Processes. The IDP guides were developed by different institutions, researchers, and companies during the past two decades and cover the state of the art for IDP approaches. To compare the various definitions of IDP, a mapping strategy was developed to ensure consistency and comparability.

The building industry has numerous norms, many of which are tacit and some of which simply reflect tradition. To minimize the impact of bias and historical practice, the design process mapping in this work was a theoretical analysis based solely on the methods and methodologies in the IDPs as described in writing without consideration of their implementation. As a part of the mapping, these descriptions were compared to the milestones in the Danish Description of Services (which can be used as a typical CSDP) to show how the IDPs facilitate a process that differs from the norm. The Danish Description of Services is used as a foundation for parts of this mapping for several reasons. First, there is no standard, national IDP in Denmark (or anywhere else) to use as a baseline. Second, the Danish context is theoretically optimal and conditions in the Danish building industry are ideal for the use of IDP in practice (as explained in the Introduction). Finally, the Danish Description of Services is sufficiently similar to the American Description of Services (as seen in Table 2) for mapping against one to be equivalent to mapping against the other.

The selection and mapping of the IDP guides are described in detail below.

Criteria for the selection of the IDP guides

The guides for IDPs that have been developed and published over the past two decades can be divided into three generations of design methods (Hybertson, 2009). The first and second generation are the most commonly used in the building industry, and present different views on how to reach a solution. Engineers mainly use the first generation, which are problem-oriented and based on technical knowledge, while architects use the second generation, which are solution oriented and based on empirical knowledge. The third generation is a reaction to the first two generations and claims that defining problems and developing solutions are parallel activities that support each other, so these IDPs are a mix of the two previous generations (Hybertson, 2009). In this paper, the generations were considered in the initial selection and mapping of IDPs to provide an overview of the similarities and differences in their approaches to reaching a solution.

IDP guides are rooted in various professions, and most IDPs were created by agencies or associations within these professions. This means that the methods are rooted in how the specific profession works and collaborates across disciplines. All of the published guides are thus both descriptive and prescriptive, and each one goes into detail for some, but not all, elements of the proposed IDP. The IDP guides investigated and analysed here were chosen to include those from architects, engineers, and contractors – the key actors in the building industry's collaboration – to obtain a wide perspective on IDP guides. The selected IDPs are all well regarded and most of them have been internationally implemented, so a wide range of IDPs was preferred for the purpose of the analysis.

Overview of the selected IDP guides

Eight IDP guides were selected for mapping:

The Integrated Project Delivery Guide (AIA, 2007) conducted by the American Institute of Architects, is widely recognized in the global building industry. It is aimed at architects. It focuses on the management of design teams and the legal framework for collaboration between companies. *TASK 23*: Integrated Design Process is a guideline for sustainable and solar-optimized building design (Löhnert et al., 2003). It was one of the first to explore the role of IDP in enabling buildings to achieve sustainable performance. It was developed by academic experts and practitioners (architects, engineers, and contractors) from Norway, the Netherlands, Switzerland, Canada, Germany, Sweden, Denmark, Austria, Finland, Japan, USA and Spain. *INTEND*: Integrated Energy Design (IED) (Holanek, 2009) is based on and summarises good practice in Norway, Austria, Denmark, Greece, Poland and the UK. It was developed as a European Commission founded project. It is intended for architects, engineers, clients, and developers and focuses on the early design stages. *MATRID*: Integrated Design Process Guide (Intelligent Energy Europe, 2014) builds on INTEND but has a wider focus that includes the whole design process. The core developers were the same group that developed INTEND and also a Europe Commission founded project. *The Integrated Design Process (IDP AAU)* is a so-called 'holistic' approach to sustainable architecture and was created in Denmark by academics in collaboration with partners in industry (Hansen & Knudstrup, 2005). It is internationally recognized for being radical in its way of embracing the second-generation models and thus broadens the perspective in the mapping of this work.

The method for integrated design of low energy buildings with high quality indoor environment, IDP DTU (Svendsen, Petersen, & Anker Hviid, 2007), was written from an engineering perspective in Denmark, and has had a large impact on the Danish Building Industry. It is radical in the way it embraces the first-generation models' technical approach. It was developed by engineers but is aimed at both architects and engineers. It focuses on energy balance and the indoor climate in design processes. *The Integrated Design Build Method* (*IDBM* MT Højgaard) (Urup, 2016) from Denmark, was chosen because it was developed from a contractor starting point. It was created by a researcher with a background in both architecture and engineering and is aimed at contractors and their collaborators (architects and engineers etc.) in design-build projects. It focuses on the management of building projects. *An Architect's Guide to Integrating Energy Modelling in the Design Process* (AIA, 2012) from the American Institute of Architects shows the architects' approach to integrating energy modelling in the design process. It was developed by architects and is intended for architects.

The Danish description of services as a common baseline

The Danish Description of Services (DDS) outlines the design phases and the services that are required by building designers in each of the phases of a building design project and it is used as a financial and legal framework. According to the DDS, there are four main phases in a building project: initial design, project design, construction, and operation (DANSKE ARK and FRI, 2012; DANSKE ARK and FRI, 2017; Koch, 2011). The project design phase is often divided into two parts: Design proposal and detailed design. The phases are listed in Table 1, which includes a description of the content and milestones from the phase.

The Danish context was selected for this study since it is viewed as an optimal context (as described in the introduction). Since this study was conducted in a Danish context, the Danish Description of Services was used as the common foundation and acts as a scale for all the IDPs that are mapped and compared in the study. It is however to some extent generic or typical of CSDPs (Table 2).

Comparative mapping method

The IDP guides are described and assessed in terms of their legibility, content, context, and the degree to which they focus on collaboration or knowledge sharing. Brunsgaard (2009) mapped three IDPs based on the following eight criteria:

Table 1. The design phases as described in the Danish Description of Services (DANSKE ARK and FRI, 2012; DANSKE ARK and FRI 2017).

Phase	Description
Initial design	The client develops the building program. The main consultant (lead architect/project manager) consults with the client to determine the project goals and requirements. The main consultant summarizes the client's requirements and wishes for the building project and lists the necessary conditions for further development of the project. Milestones: > Pre-design > Concept design The initial architectural design is developed, e.g. architectural competition proposal in General Contract projects or tenders in Design – Build Contract projects. > Schematic design – Architectural proposal and possibly other requirements, depending on the call for tender.
Design proposal	The design is developed further with the initiation of engineering design. Milestones: > Outline proposal – The outline proposal is a substantiated proposal for the completion of the project, including a description and sketches of design principles and the main systems for technical installations. > Project proposal – The project proposal is a revision of the approved outline proposal to the extent that all pivotal decisions for the project have been made and are included in the proposal.
Detailed design	The building design is completed and the tend.er documents are prepared. Milestones: > Preliminary project (regulatory project) – The prelimina1y project (regulatory project) is a revision of the approved project proposal to the extent that it can form the basis for approval by the authorities. > Main project – The 1nain project describes the project precisely and at a level of detail that forms the basis for final clarification of the conditions contained in the planning pennission, as well as for tendering, contracting, and construction.
Construction	The contractor builds the project and 'as built' services are provided to bring the project documentation to a level that is consistent with the building.
In-use	Operation, maintenance, and.inspections, e.g. a five-year inspection, of the building.

Table 2. Overview of the American and Danish definitions of the phases and milestones in a building design project and how they correspond.

American phases	Milestones in the Danish Description of Services	Phases in the Danish Description of Services
Project Brief	Pre-design	Initial design
Concept design	Concept design	
Scematic design	Schematic design	
Design development	Outline proposal	Design proposal
	Project proposal	
	Preliminary project	Detailed design
Construction documents	Main project	
Construction documents	Construction	Construction
Commissioning	Operation	In use

Motivation and goal for development of the design process
Short description of the characteristics of the method
The key stakeholders in the process
Design phases
Process development
Design goals/parameters
Tools
Strengths and weaknesses

In Brunsgaard's method, it is argued that terms must be objective. In principle, and by definition, a guide should not just be easily understood – it should be impossible to misunderstand. In the present study, these criteria are combined with criteria that can place each IDP guide in context, based on Lasswell's model of communication that dictates '*who, says what, in which channel, to whom, and with what effect*' (Lasswell, 1948). The terms used are thus not always consistent between different

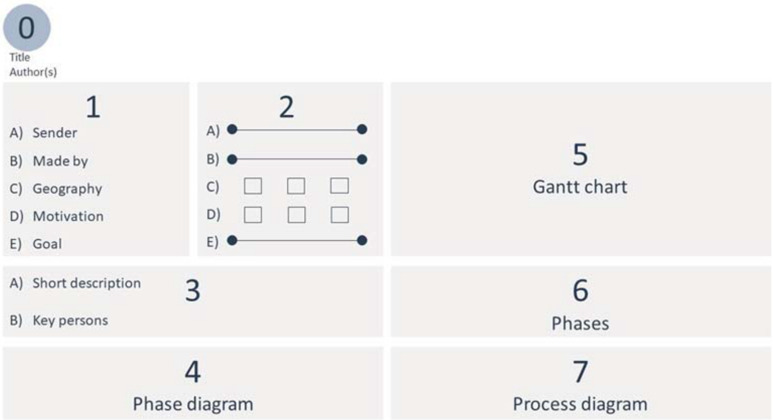

Figure 2. The mapping guide with seven categories used to compare the selected IDPs.

guidelines and, occasionally, within an individual guide. Lasswell (1948) himself underlined the subjectivity of his model. The mapping also includes the following key aspects:

The names of the participating stakeholders described in the IDP
Whether the presence of a stakeholder/profession is mandatory in a given phase
Whether the description is fully developed and complete
Whether another word is used to describe the stakeholders, e.g. 'design consultants' instead of 'engineers'
Whether an action is interpreted as involving the participation of a specific stakeholder/profession

The mapping guide is shown in Figure 2 was developed using this labelling scheme as a foundation, and with the goal of ensuring correspondence between all the selected IDPs. The numbers in the mapping guide indicate how to read a mapped IDP.

The seven categories for mapping based on the above description are shown in Table 3. The numbers refer to Figure 2.

This paper focuses mainly on '2. Classification', '4. Phase diagram', and '5. Gantt chart'.

Results

The Results section is divided into two parts; it begins with an example of mapping (of Task 23). The results and conclusions from all of the mappings are then presented as 'profiles' for each of the IDP guides in Figure 6–12.

Example: mapping of task 23

Only one of the IDP guides, Task 23, is presented in detail, as an example, to explain and document the mapping method. The present section documents the complete mapping of Task 23 to demonstrate the mapping framework.

The first two categories from the mapping '1. Context' and '2. Categorizations' are shown in Figure 3. Task 23 is one of the first generation of IDPs. No information is available about the level

Table 3. The seven categories used for the mapping.

1. Context	The background and motivation of a given guideline described in the sender's o\vn words
2. Classification	Each guideline is rated using 5 separate scales. Rating is done by the authors based on their interpretation of a given guide.
Scale 2. A	is a continuous scale that indicates the level of applicability, ranging from 'theoretical methodology' to 'practical method'. The scale operates over a range from 1–10. The level achieved is defined by an evaluation of the literature. Theoretical methodologies explain why a certain method should be applied, but not bow. Practical methods describe in detail how an integrated process should be performed – ideally nothing is left for interpretation or misunderstanding by the reader The authors have not assessed the real applicability. They have solely assessed if and the extent to which 'the how' is communicated in the guideline.
Scale 2. B	is a continuous scale (defined in the same way as Scale 2 A) that defines the level of knowledge incorporation in the design process, raoging from 'knowledge sharing' to 'knowledge integration'. 'Knowledge sharing' IDPs state that knowledge should be shared, but do not describe how that knowledge should be incorporated into the building design. These IDPs encourage a unidirectional mono log – the pushing of information from one participant to another rather than the encouragement of a dialog between participanb. 'Knowledge integration' IDPs explain how different people with expert knowledge should communicate and collaborate to understand and see the value of each other's work. They encourage dialogue and multi-directional exchange of information.
Scale 2. C	is a discrete scale with 3 checkboxes that categorize the collaborative arrangements of the guide. 'Leader and assistant' means that there is one actor who is more dominant than the others in the design dec.ision making process; information is asked for and delivered. 'Hybrid' is the idea of having multi-disciplinary professions – everyone is both engineer and architect which means everyone has the same in-between role and no one is an expert. 'Equal partners' means that the collaboration has a flat structure where each profession is ranked equally and no one is more dominant than others.
Scale 2. D	is a discrete scale with 3 checkboxes that categorize the design method paradigm by generation. As noted above, the first generation is problem-oriented, based on technical knowledge, and mainly used by the engineering consultancies. The second generation is solution-oriented, based on empirical knowledge, aod mainly used by the architectural offices. The third-generation states that defining problems and developing solutions are parallel activities that support each other, and is an exploration of how architecture was done before the two first generations were described (Hybertson, 2009).
Scale 2. E	is a continuous scale (defined in same way as Scale 2 A) that defines the meaos of implementation of technical knowledge in the,design process, ranging from 'design validator' to 'design informer' to 'design driver'. Validator is the traditional approach where technical knowledge is used to validate the design in retrospect. In this case, the architects design and afterwards the engineer validates the work. In an Informer approach, the technical knowledge informs the design upfront. Here, the engineer is proactive and gives input to make design decisions that are informed by technical knowledge. 'Driver' represents the case where technical consideration is the main driver. Here, engineering knowledge is the basis for all design decisions made in the design team. The means of implementation of technical knowledge is highly related to the collaborative arrangement and the design method paradigm.
3. Descriptions	The characteristics of the IDP guide aod the key individuals or stakeholders in the process.
4. Phase diagram	Specific phases are mapped against the traditional phases of the Danish Description of Services for Building aod Planning. The steps of the IDP guides are therefore compared to the milestones/sub-phases of the Dartish Framework to see where each!DP guide has most of ib design steps.
5. Gantt chart	The activities of participating actors in relation to the Danish framework. The Gantt chart shows the eight most common stakeholders mapped according to the milestones in the Danish framework. The darker colors indicate mandatory actors while the lighter colors indicate optional actors.
6. Phases	Description of the phases of each IDP guide. The phases are labelled with guide-specific terms.
7. Process diagram	A process diagram using both the specific terminology from the IDP guide aod the terminology from the Danish Dese£iption of Service.

of knowledge incorporation and the collaborative arrangements in the guide. Since these categories cannot be evaluated, the headings for these scales are ignored.

The diagram in Figure 4 is a part of the mapping: '4. Phase Diagram'. Figure 4 shows the design process time frame when using Task 23 (lower scale) in relation to the first seven milestones in the Danish Description of Services (upper scale). In Figure 4, the phases for each design process (top and bottom) are shown as being equally distributed along their axes, although they may actually occur over a variety of timeframes. The Danish Description of Services has nine milestones, but only the first seven milestones (Table 2) are mapped in the diagram, to limit the discussion to the design phase and because the last two milestones are not mentioned in most of the IDPs. Here, the first phases are described as being longer for Task 23, so it can be argued that more design decisions are made early in the process.

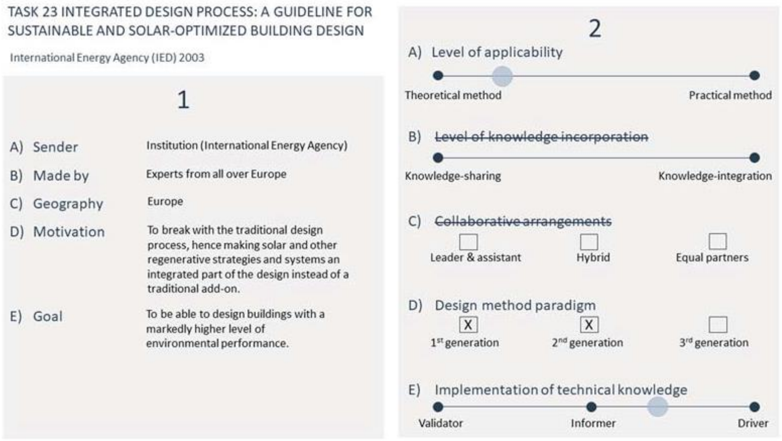

Figure 3. Mapping results for the first two categories for Task 23, '1. Context' and '2. Classification'. Two rating scales were crossed out because the information was not available in the current Task 23 IDP guide.

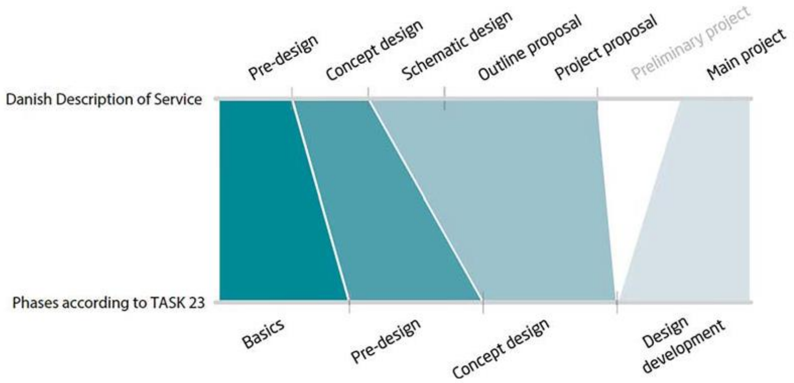

Figure 4. Mapping results for the fourth category for Task 23: '4. Phase diagram'. The top scale shows the milestones of the Danish Description of Services and the bottom scale shows the specific definition of the Task 23 IDP.

Figure 5 indicates that both architects and engineers are mandatory stakeholders in all the design phases. The importance of integrating the two professions from the very beginning leads to a focus on time and iteration of communication and to include more aspects in the projects.

Comparative results

The mapping is a 'profile' of each IDP guide, categorized by: '2. Classification', '4. Phase Diagram', and '5. Gantt chart'. To enable a comparison of the mapped IDP guides, the results were merged into one common diagram per category. Not all IDPs contained information for all of the categories seen in Figure 2, so it was not possible to map all eight IDPs across all categories and sub-categories.

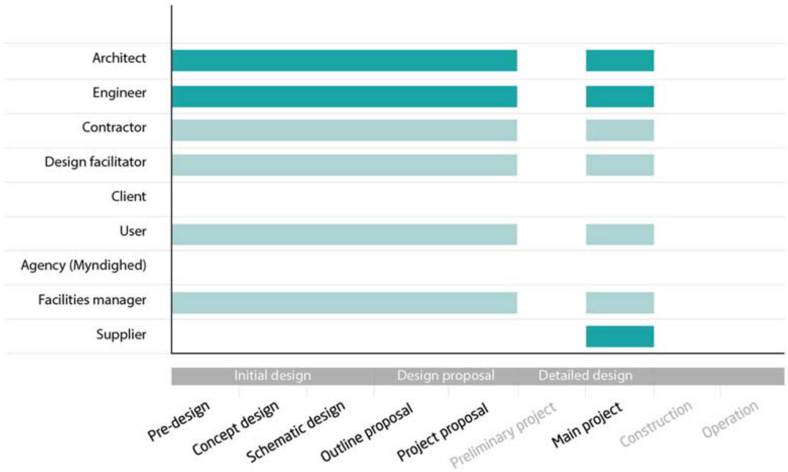

Figure 5. Mapping results for the fifth category for Task 23: '5. Gantt chart'. The darker colour shows the mandatory stakeholders and the lighter colour indicates actors who can be involved if necessary. If there is no colour, the actor was not mentioned in the IDP guide.

Figure 6. IDP level of applicability, ranging from theoretical to practical.

Results based on '2. Classification'

Figure 6 shows the level of applicability mapped across all eight IDPs on a continuous scale of methods ranging from theoretical to practical. It shows that there is a wide range of practicality for the different IDPs, which has been noted in other recent research (Brunsgaard, 2009; Urup, 2016). About half of them are very theoretical. The rest are closer to the middle and tend towards being more practical.

As seen in Figure 6 – Level of applicability, about half of the mapped IDPs take a theoretical approach, while the rest address the 'how' to a large extent and are thus closer to being a practical method. However, none of the IDPs amount to a clearly practical method.

Figure 7 – Of the eight IDP guides reviewed in this work, five can be categorized according to how they approach knowledge incorporation in the team. Figure 7 shows a clear divide between guides that claim that one-way knowledge sharing is enough and those that claim that knowledge has to be understood by the receiver (i.e. that advocate for knowledge integration). Knowledge integration seems to be preferable, although this approach requires more time and skill from the entire team.

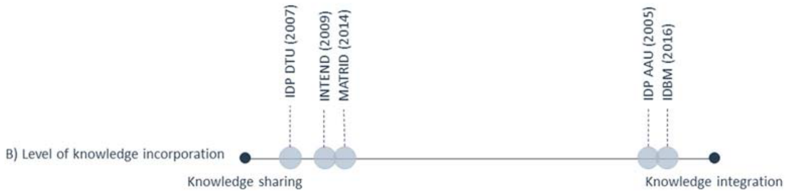

Figure 7. IDP levels of knowledge incorporation from 'Knowledge sharing' to 'Knowledge integration'.

Three IDPs claim that knowledge sharing is enough when working with the IDP, while the two others argue that knowledge integration is right way. Knowledge integration requires that the information be understood by the receiver; this requires more dialog, which is more time-consuming. Given the disadvantages associated with both extremes and the lack of consensus among IDPs, knowledge incorporation within IDPs remains an open research question.

Figure 8 – Collaborative arrangements shows that only five of the eight IDPs defined how partners should collaborate. Three use a design leader & assistant model, in which the design leader decides whether the inputs are relevant for the team. One guide uses hybrids as the preferred arrangement and one prefers equal partners, which means that all decisions must be made on an informed basis and that all approaches emphasize the design.

For three IDPs, a Leader & Assistant relationship was preferred. In addition, one preferred a Hybrid model and only one specified Equal Partners. From this, it is concluded that current IDPs are mainly controlled by a project leader or manager who facilitates the process. However, there is no alignment.

Figure 9 – Design methods generations shows an emphasis on both 1st and 2nd generation paradigms. In practice, this can complicate the cooperation since architects and engineers will naturally be more focused on one design method or the other based on their education. Of the eight IDP guides, five can be categorized according to the design method paradigm (1st, 2nd and 3rd generation) as seen in Figure 9. Three of the IDP guides distinguish between architects and engineers. This means that the different professions may use different methods. These three guides thus belong in both the 1st generation and 2nd generation categories. Since the two methods are not used in collaboration, they cannot be categorized as 3rd generation guides. One IDP guide uses only 1st generation methods, one IDP guide uses 2nd generation methods, and one IDP guide uses 3rd generation methods. As seen in Figure 9, some IDPs include both 1st and 2nd generation paradigms; this is due to their division of architects and engineers into individual 'boxes', each having their own method.

Figure 10 – The role of technical knowledge in an IDP and how it is implemented in the design process has been one of the central research questions of this work. Technical knowledge in the IDPs can be used to *validate* (which is often the case in CSDP), *inform*, or actually *drive* decision-making in the design processes. The eight IDPs suggest integrating technical knowledge in the design process in different ways. To promote close collaboration between architects and engineers,

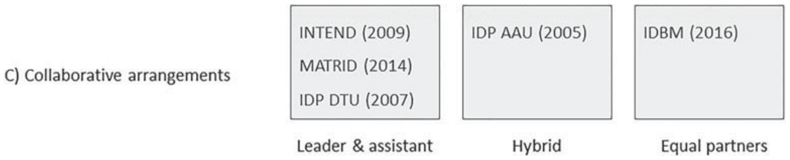

Figure 8. IDP collaborative arrangements. 'Leader & Assistant', 'Hybrid', and 'Equal Partners'.

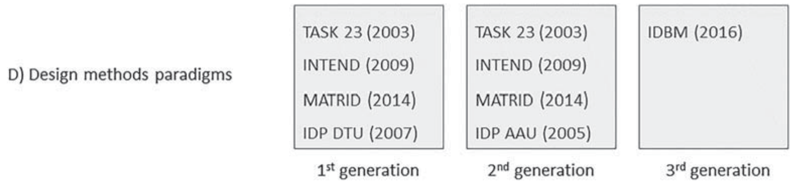

Figure 9. IDP categorization by design method generation.

most IPDs recommend an informed design process where technical knowledge is not the only a driver, nor a mere validator, but can play a variety of roles as seen in Figure 10 – Implementation of technical knowledge. Although the IDP mapping indicated a variety of approaches to using technical knowledge (to validate, inform, or drive the design process), there was a slight tendency to prefer an Informer approach in which the engineers inform the design decisions.

Results based on the '4-phase diagram'

Figure 11 shows an overall diagram of the eight mapped IDPs (lower scale) in comparison to the Danish Description of Services (upper scale). The results indicate an IDP emphasis on more time for the first design phases – the basics, predesign, and concept design – compared to the Danish Description of Services. There is an agreement among the IDPs for an extension of the first two design phases, which is comparable to other research in the field (Brunsgaard, 2009), whereas the later design phases vary more in length between IDPs.

Results based on '5. Gantt Chart'

Figure 12 shows the contribution from each profession using the phases of the Description of Services as the framework. The chart shows the design phases from the Danish Description of Services as horizontal bars; all the professions act vertically. The dark colour shows mandatory actors and the light colour indicates other possible actors that could be involved if it became necessary.

Figure 13 shows the combined mapping from the eight IDP guides merged into one diagram, to provide an overview of the stakeholders and their expected contributions. From the diagram, it is clear that there is no consensus. However, there is a tendency to include architects and engineers throughout the design process. Also, the client is always involved in the initial design phases but not necessarily throughout the entire process. For certain steps related to the financial setup of a project, the contractors are also included throughout the design process. For the other stakeholders, the IDP guides have different views on whom to include, when, and for how long. When compared to Figure 12, it is clear that the IDPs are more complex than CSDPs.

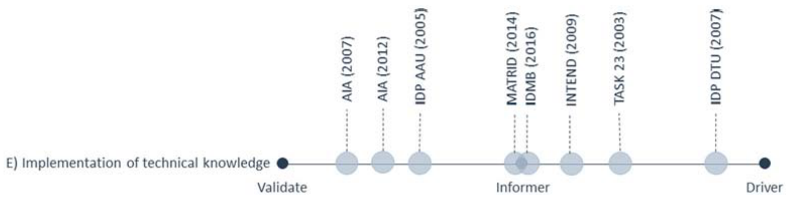

Figure 10. Integration of technical knowledge, ranging from validation, to informing, and driving the design process.

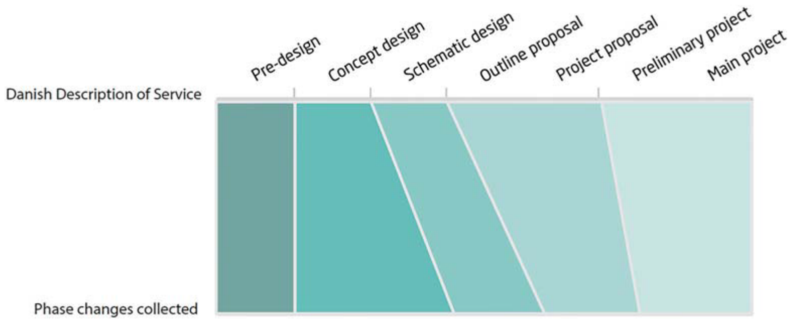

Figure 11. Overview (over layered) diagram of the eight mapped IDPs showing the process timeline in relation to the Danish Description of Services.

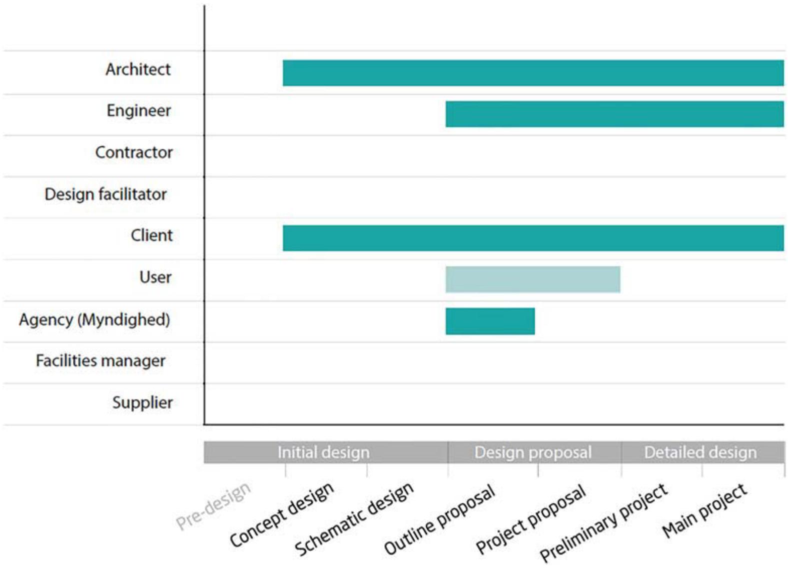

Figure 12. Stakeholders involved in the different design phases as described in the Danish Description of Services. The dark colour shows mandatory actors and the light colour indicates other possible actors that could be involved if it became necessary.

Figure 13 – '5. Gantt chart', which maps the stakeholders in the design processes, shows large differences among the different IDPs on who is to be included and when. However, there is a general agreement that architects and engineers should be included from the very first phase and must continue in close corporation throughout the building design process. The contractor should also be included throughout the process alongside the architects and engineers.

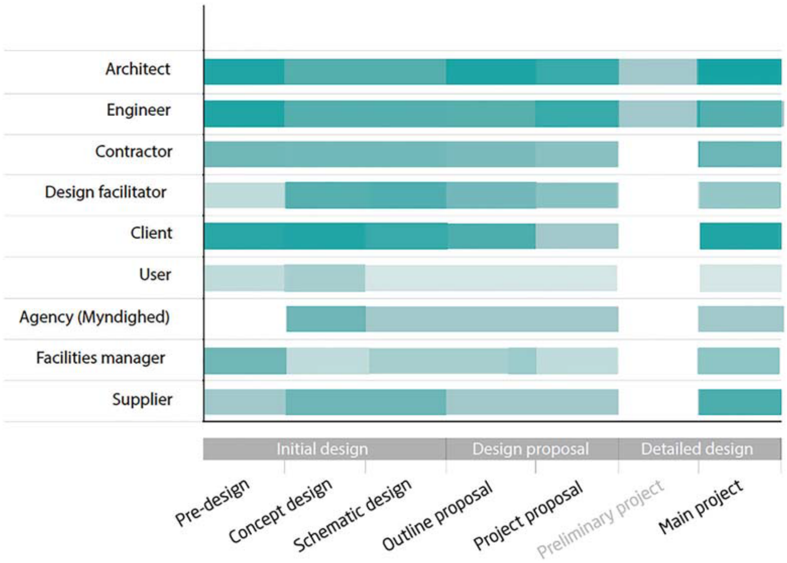

Figure 13. Stakeholders involved in the different design phases of a merged version of the eight IDPs. The dark colour shows mandatory actors and the light colour indicates other possible actors that could be involved if it became necessary.

Discussion and conclusion

Kanters and Horvat (2012) performed a series of interviews with practitioners on IDP implementation, but they did so without referring to specific guidelines. Figure 6 supplements their study by demonstrating that there are differences in the extent to which the IDP guides address applicability.

This paper extends the study of Kanters and Horvat (2012) by highlighting some of the major differences between specific IDP guides. For example, there are differences in the extent to which the IDP guides address applicability. There is a clear divide between guides that claim that knowledge sharing is enough and those that claim that knowledge has to be understood by the receiver (i.e. that advocate for knowledge integration). Communication is an important factor in a design process; it is critical to know how knowledge within an IDP should be communicated and incorporated. A focus on knowledge sharing might not necessarily lead to understanding and it also risks information overload due to an over-emphasis on one-way communication.

In all the IDP guidelines, it is frequently stated that the motivation is to facilitate the change from a CSDP to an Integrated Design Process. However, only a few of the IDPs explain how to change the design process in practice and to what degree it should be changed. There seems to be a consensus in the IDP guides that gathering different professions in a room would somehow 'automatically' foster the necessary collaboration. Physical co-location, in itself, seems to mean that a design team works in an integrated manner according to the IDPs. When the IDP guides leave the process of communication and collaboration up to the individuals involved, individual professions are free to interpret them as they wish. It could be that the delay in implementing IDPs could be due to this because stakeholders could be tempted to fall back into their usual habits without working in an integrated manner. This result is consistent with previous research from Buvik and Hestnes (2008) and Kanters and Horvat (2012).

The mapped IDP guides all describe the integrated design in terms of the desired results, but they do not describe how the process is to be conducted, how integration is to be ensured, how communication is to be managed and which interactions are essential for the stakeholders. In other words, the actual collaboration is a 'black box' in which different professions are gathered in one room but the process of *how* to transform the known inputs into the desired output (integrated design) is not explained. This lack of focus could be due to a need to leave room for interpretation, as there are different contexts, different types of knowledge, and different reasons to use an IDP. It is perhaps sufficient to observe that the actual collaboration processes are insufficiently described in IDP guides (Figures 6–13). The current IDP guidelines consider only why and what, but not how to use the IDP guides.

Related to this observation is that the IDP guides differ in their suggestions for organizational set-up: 'Leader and Assistant' – 'Hybrid' – 'Equal Partners', etc. In general, all the IDPs consider more stakeholders than are considered in CSDP, which is an important difference.

Many IDP guides do not clearly address the mapped topics, so that important basic information is often missing. This indicates that the IDP guides are theoretical in nature and difficult to apply in working situations, as shown in the Task 23 example. This reflects the general picture of the eight IDPs mapped in the present work.

Technical knowledge in the IDPs can be used to validate, inform, or drive decision-making in the design processes. There is no consensus but a small tendency to favour the 'inform' mode, understood as technical knowledge provided as information to designers when needed.

The mapping indicates that there are many differences between the definitions in various IDP guides. However, there is some consensus about the core of IDP in all of the guides. The IDPs all describe which stakeholders to include, that the definition of a design process consists of a series of steps, and emphasize the need for an integrated process. There is also a tendency to allow more time in the early design phases than is envisaged by the CSDP; they all agree on the need for an extension of the first two design phases compared to the CSDP, and this finding supports other research in the field.

Since IDPs are still maturing, it is essential to understand how the Description of Services (CSDP) and the business management in each company influence the challenges of interdisciplinary collaboration and design processes in the building industry, and how they are influenced by social factors, such as the national policy, manifest in the Danish Description of Services, which sustains a CSDP. In addition, the transfer of knowledge and experience from one project to another is not systematised in any of the IDPs, and this could be a good addition to future guidelines.

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APPENDIX G

PAPER (7)

Presented at: 2018 PLEA Conference, Hong Kong

Design process cultures as drivers and obstacles to sustainable architecture

- Identifying the knowledge involved in design decisions at architectural offices in the Nordic countries.

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ABSTRACT: The past decades of focus on sustainability and the decrease of energy consumption in the built environment has led to higher demand for integrated design and implementation of technical scientific knowledge in the design process. This paper aims to investigate the state of the art for the implementation of technical knowledge in architectural offices in the Nordic countries and the degree to which integrated design is performed. This paper reflects a larger survey-based study among architectural offices in Scandinavia that have a focus on sustainability. The paper underlines the diversity of each architectural office through a work profile developed based on the surveys. Although the offices' workflows differ, microclimate comfort, daylight, and energy performance tend to be well-integrated topics in building design processes today. However, life cycle costing and life cycle assessment are new topics in the building industry and are still not included in design processes in practice. There is a discrepancy between how important architects evaluate certain kinds of information and how they include it. Much information is still based on 'experience' and 'intuition' rather than derived from the inclusion of technical scientific methods.
KEYWORDS: Integrated Energy Design, Informing architecture, Technical knowledge, Sustainability, Work profiles

1. INTRODUCTION

The built environment accounts for around 40% of the energy consumption and approximately 36% of the CO_2 emissions in the EU [1]. Thus, for decades it has been a goal to reduce the energy consumption of operating buildings. In recent years, the quantifications of environmental impact categories have been broadened to include the entire life cycle and emissions from material use [2]. Research has shown that the majority of a given building's sustainability level is derived from early phase design decisions such as its orientation, window façade ratio, and geometry [3]. Thus, an important step to accommodate more stringent building energy requirements in practice was the introduction of the Integrated Energy Design (IED) method [4]. In today's building industry, sustainability certification systems such as the German DGNB have become the drivers for Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) [2]. These systems address Brundtland's definitions of sustainability [5]. However, they also increase complexity, which has led to an increased need for communication among different professions and a more systematic and holistic design team approach addressed by integrated design. Holistic, in this context, means an inclusion of both aesthetics and technical scientific information in the design process in order to address sustainability. One way to enhance the holistic approach in practice is to inform the design process with more technical scientific knowledge in architectural offices through integrated design [6]. This paper investigates how technical knowledge is involved in making design decisions in order to outline levels of holistic and integrated design in the architectural offices and thus identify design process culture. The underlying hypothesis is that design process cultures can enhance or hinder the Integrated Design Process (IDP) needed to achieve sustainable architecture.

2. METHODS

This work is based on surveys conducted in architectural offices in the Nordic countries that are either based in Denmark or have a smaller section in Denmark. These companies are all private and have a reputation for sustainable projects. The surveys were distributed to architects who are also sustainability experts through a central contact person at each architectural office. Response rates were at least 30%, (Table 1). The level of feedback is considered acceptable and representative.

Table 1: Survey responses from all offices.

Profiles	Respondents	Sent
Office A	11	21
Office B	12	20
Office C	10	17
Office D	3	9
Office E	9	31
Office F	8	23
Office G	6	14

The survey consisted of 37 questions divided into three main topics: (1) technical knowledge in the design phases (related to microclimate comfort, daylight, energy performance, LCC, and LCA), (2) interdisciplinary collaboration in the architectural office, and (3) inputs about the constellation in the office. The survey included only closed-ended questions to ensure that the responses could be quantified afterwards. Closed-ended questions are commonly used for surveys, as they ensure uniformity and reduce the time to answer and process [5].

3. RESULTS AND ANALYSIS

The graphical output of the survey is represented by the results from Office A, as seen in Figure 1.

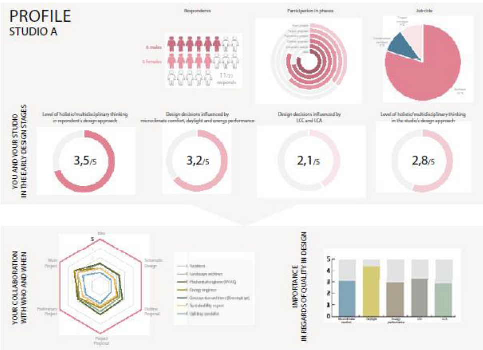

Figure 1: Profile of Office A based on the surveys.

The respondents tended to evaluate their own design processes as being more holistic and more interdisciplinary than the general approaches in their offices. This indicates that individual pioneers are the main drivers for integrated design and that it is not (usually) a top down directive from the offices' partners.

The integration of technical scientific knowledge in the early design phases was uneven; some offices do this and others do not. All offices involve technical scientific information in the later design phases, as defined by the Danish Description of Services [7]. The surveys show that the respondents include knowledge about microclimatic comfort, daylight, and energy performance in the design process equally; however, they mostly work with the topics using rules of thumb and without interdisciplinary collaboration. Very few respondents involve information related to LCC and LCA in their design decisions despite the fact that many find it highly relevant. This limited use can be caused by the lack of national requirements, which persists despite the increased focus from building certification systems. This also corresponds with previous research on the DGNB certification system as a driver for LCC and LCA in design projects in practice [2].

4. CONCLUSIONS

Each architectural office has its own overall design process culture, which is defined by how they involve technical knowledge in their design decisions and by how interdisciplinary their design processes are. The surveys show that there can be a large variation in design practices within an office. In some offices, however, design practices are generally consistent and the overall design process culture corresponds to the individual ones. How and to which degree professions are mixed in the office varies; some have explicit strategies of integration and some do not. There is a tendency for microclimate comfort, daylight, and energy performance to be well implemented in the design process cultures. This may be an effect of strict national building energy requirements and the focus on Integrated Energy Design. It is also clear from this study that LCC and LCA are new fields of knowledge in the building industry, which are discussed more than they are actually addressed in design processes today. From this study, it is clear that more focus is needed on LCC and LCA to better address sustainability in practice. Finally, there is a tendency for interdisciplinary approaches to be applied by the individual experts and not by the offices as a whole, which can limit implementation in practice.

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APPENDIX H

PAPER (8)

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Informing sustainable building design

The importance of visualizing technical information and quantifying architectural decisions

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Abstract

Purpose – In recent decades there has been a focus on reducing the overall emissions from the built environment, which increases the complexity of the building design process. More specialized knowledge, a greater common understanding and more cooperation between the stakeholders are required. Interdisciplinary design teams need simple and intuitive means of communication. Architects and engineers are starting to increase their focus on improving interdisciplinary communication, but it is often unclear how to do so. The purpose of this paper is to define the impact of visually communicating engineering knowledge to architects in an interdisciplinary design team and to define how quantifying architectural design decisions have an impact during the early phases of sustainable building design.

Design/methodology/approach – This work is based on a study of extensive project materials consisting of presentations, reports, simulation results and case studies. The material is made available by one of the largest European Engineering Consultancies and by a large architectural office in the field of sustainable architecture in Denmark. The project material is used for mapping communication concepts from practice.

Findings – It is demonstrated that visual communication by engineers increases the level of technical knowledge in the design decisions made by architects. This is essential in order to reach the goal of designing buildings with low environmental impact. Conversely, quantification of architectural quality improved the engineer's acceptance of the architects' proposals.

Originality/value – This paper produces new knowledge through the case study processes performed. The main points are presented as clearly as possible; however, it should be stressed that it is only the top of the iceberg. In all, 17 extensive case studies design processes were performed with various design teams by the 3 authors of the paper Mathilde, Birthe and Signe. The companies that provided the framework for the cases are leading in Europe within sustainability in the built environment, and in the case of Sweco also in regards to size (number of employees). Data are thus first hand and developed by the researchers and authors of this paper, with explicit consent from the industry partners involved as well as assoc. Professor Lotte B. Jensen Technical University of Denmark (DTU). This material is in the DTU servers and is in the PhD dissertation by Mathilde Landgren (successful defence was in January 2019). The observations and reflection is presented in selected significant case examples. The methods are descriped in detail, and if further information on method is required a more in depth description is found in Mathilde Landgrens PhD Dissertation. There is a lack in existing literature of the effect of visualisation in interdisciplinary design teams and though the literature (e.g. guidelines) of integrated design is extensive, there is not much published on this essential part of an integrated design process.

Keywords Case study, Visual communication

Paper type Research paper

1. Introduction

The rapid development of sustainable buildings, which is highly complex, will require more professions to be dependent on the decisions of one another, which will require the further development of interdisciplinary communication (Brunsgaard, 2009; Lewis, 2004;

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Svendsen *et al.*, 2007; Zimmerman, 2002). Visual communication is moving to the fore of engineering education because interdisciplinary design teams must co-operate closely to ensure a holistic and uniform final product (Rammer Nielsen, 2003; Svendsen *et al.*, 2007; McGrath and Brown, 2005). In an integrated design process, engineers are expected to be able to proactively influence the early design decisions made by the interdisciplinary design team, but the building industry is uneven in its willingness to alter the traditional roles of consultancy (Luyten, 2010). The fact that traditional consultancy roles linger on influences the design process and constitutes a barrier to the use of interdisciplinary processes in the early phase of a design (Luyten, 2010). However, a number of engineering consultancies are challenging these traditions by focusing on new communication strategies that use visual communication (Jakobsen and Wohlenberg, 2016). Traditionally, visuals are used in schools of architecture in the shape of diagrams, visualizations, renderings, 3D models and sketches (Lawson, 2006; Luyten, 2009). The increased focus on early integration of technical knowledge in design decisions and the increasingly frequent need to achieve sustainability certification of a building require architects to consider how to communicate architectural quality. Quantification of architectural quality is challenging, and some architects would claim that it is not possible, but it could be one way of fulfilling this need (Tanga *et al.*, 2006). Deutche Gesellschaft für Nachhaltiges Bauen (DGNB) is a German sustainability certification system that uses life cycle assessment (LCA) and life cycle costing (LCC) as add-ons to the legal- and regulation-based focus on indoor climate and energy calculations (Birgisdóttir *et al.*, 2013; DK-GBC, 2014). This means that both LCC and LCA must be considered from the earliest design phase, so architects must make quantifiable and knowledge-based design decisions (DK-GBC, 2014; Landgren and Jensen, 2018) in the early design phases. Classical engineering tasks must therefore be addressed and accessed by the architects, who have to take them into account if sustainability certification is the goal. As a result, the architects gain knowledge of the relevant engineering fields (Luyten, 2009). The aim of this research is to define and describe the effect of visual communication of engineering knowledge to architects and other stakeholders in the interdisciplinary design team at the early stages of a building project.

2. Method

2.1 The two case study consultancies

There has been an increasing focus on the importance of early design decisions since research showed that the economic and environmental impact from early design decisions is large. In the last decades, this finding has led to a change in the mind-set and work processes of both architects and engineers, and the necessary processes are now evolving rapidly (Luyten, 2010). In this paper, current attempts to base early design decisions on technical knowledge and the various ways that architects and engineers try to create some common ground were investigated by examining the role of visual communication in a large engineering consultancy and in the quantification of design decisions in a large architectural office. The paper is based on several case studies. However, three were selected for discussion in this paper. They were obtained from two companies in Denmark: a large architectural office with a focus on sustainable buildings, and the Danish part of a large European engineering consultancy of around 1,000 employees. It was organized in special units: planning and design, transport and mobility, and water and environment, this research took its base in the first unit. Each unit had deep specialist knowledge in their field (Sweco, 2017). A selection of these units is shown in the organization diagram in Table I.

The architectural office had around 80 employees and was organized in three main units – city and housing, learning and culture, and business and health – with a range of different specialist knowledge (JJW, 2017). A selection of this knowledge is shown in the organization diagram in Table II.

2.2 Engineering approach – visualizing engineering knowledge

The engineering consultancy had developed their own tool called the "Game Changer," which was a set of technical guidelines intended to serve as tools to facilitate early phase dialogue, based on a report conducted by a group of anthropologists, who observed the working processes in the engineering consultancy (Jakobsen and Wohlenberg, 2016). They detected three problems in the routines in use at each organizational level that affected how clients experienced their interactions with the engineers. The three organizational levels are the business leader level, the project leader level and the technical specialist level. In the present work, only problems related to the technical specialists were considered. Figure 1 shows the challenges encountered at the technical specialist level. This was the

Planning and Design	Structures Fire safety Electricity HVAC Energy indoor climate sustainability Light design Facility management

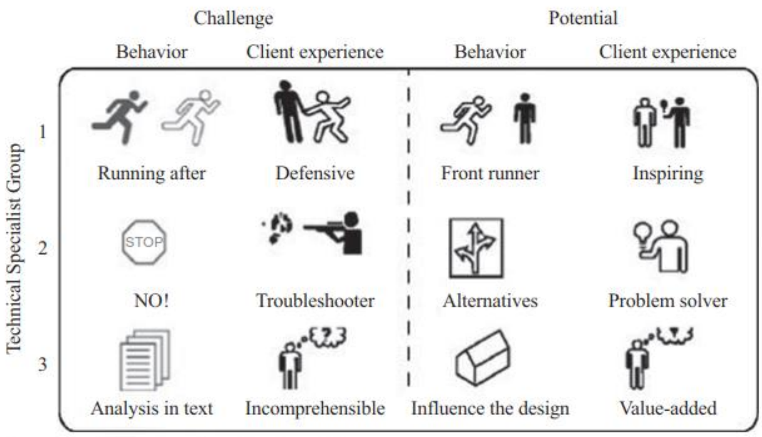
Source: Sweco (2017)

Table I. Organization diagram showing a selection of the units and some of the related subjects in the engineering consultancy

City and housing	Learning and culture	Business and health
Public housing Care centers Renovation Landscape	Day care Schools Colleges Universities	Hospitals Laboratories Business Landscape

Source: JJW (2017)

Table II. Organization diagram showing a selection of the many subjects at the architectural office



Source: Jakobsen and Wohlenberg (2016)

Figure 1. The technical specialist level and the three-related challenges

starting point for the company to understand the relationships between the behavior of their employees and the resulting client experience.

One of the challenges identified by the anthropologists at the technical specialist level was "Analysis in text." Clients felt that "Analysis in text" is incomprehensible, since they do not share a common medium for the dialogue. Here, visuals may be the right medium for communicating information about the engineering tasks and making expert knowledge more comprehensible; however, this would require a different work strategy (Jakobsen and Wohlenberg, 2016). When changing work strategies, it is not always enough to offer an introductory course and a list of guidelines. The entire routine-based workflow and mind-set of each employee has to be taken into account. Emotional intelligence (EQ) also has considerable impact on how well communication tools are used, so EQ is an important qualification for employees who work within the complex environment of interdisciplinary design teams in the building industry (Riemer, 2007). Once the complexity of the general technical issues in the guidelines has been visualized, they become a qualitative description of design principles instead of quantitative values in a report. This is more easily incorporated into the design process and invites dialogue for an open range of design decisions (Jakobsen and Wohlenberg, 2016). Visuals as a tool for communication are easier to understand and to remember than text, as they engage the imagination and increase creative thinking (Woeppel, 2015).

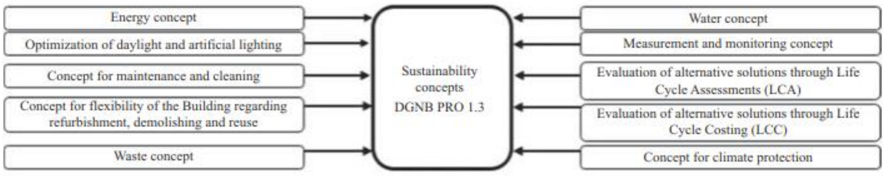
2.3 Architectural approach – quantification of design decisions

At the architectural office, there was no motivation to make communication more visible since they already work very visually. However, the increased number of interdisciplinary design teams and the demand for sustainability certification of buildings had made it necessary to quantify design decisions.

At the architectural office, the DGNB certification system was being used to define sustainability, which has led to an increased focus on resources, consumption and emissions in relation to LCA, and on the economic aspects of LCC. Internal changes were already taking place at the architectural office, where the entire mind-set of the classical architect had had to be modified and an awareness of the benefits of quantification as the background for their design decisions had had to be introduced. The DGNB system mandates this development by requiring ten early phase sustainability concepts to be developed by the interdisciplinary teams, as seen in Figure 2.

2.4 Method of research

Although several case studies were conducted, only two of them were considered to be illustrative of how the initial design phase, prior to actual design, is affected: one at the engineering consultancy Sweco and one at the architectural office JJW Architects. A third case study was used to illustrate the influence of visualization at the schematic design phase in the architectural office. The results of these case studies were compared, categorized and analyzed in terms of the visual communication of engineering knowledge, quantified design decisions and the DGNB certification system. The case studies were



Source: DK-GBC (2014)

Figure 2. DGNB, PRO1.3 – new office buildings criteria: the 10 new concepts that were scored

conducted using an active research approach in four steps; planning the process, action through involvement in design teams, observing and collecting data and a discussion of the findings (Swann, 2002).

2.5 Case 1

Two researchers with architectural engineering background took part in the first initial meeting of a project, together with the entire design team. The project was confidential and is not further described here; only the process related to the use of visuals is described. The design team consisted of engineers and architects. At the meeting, the engineers presented selected general technical guidelines, which the engineers considered relevant for the given project. The guidelines were presented as visuals to emphasize the scope of possible solutions, from which a dialogue on the potential interdisciplinary benefits could be initiated. After the meeting, the engineers identified which visuals had worked and which had not. The case study was based on Figure 1, "Analysis in text" at the "Technical Specialist Level." The project had an open beginning, in which the architect had developed the building mass and defined the building geometry. This gave the engineers the possibility of including their knowledge from the very beginning. At the first meeting, all of the specialists brought their most relevant technical guidelines, as illustrated in the Results section, and presented them. They consisted of visualizations of the technical issues and possible benefits that would result from the selected design decision and a list of arguments for and against alternative designs.

2.6 Case 2

One researcher, an engineer employed at an architectural office, participated in the initial design phase of a project to assist the design team with the quantification of their scenarios and project definition. The project is described only briefly to preserve confidentiality. The project started with a request from the project leader to quantify the economic value of two scenarios for an existing building by making LCC calculations. The two scenarios were either to demolish and rebuild the building or to renovate it. For the calculations, a simple tool developed in Denmark called LCCByg was used (Trafik- og Byggestyrelsen | Statens Byggeforskningsinstitut, 2016). The available material for the existing building was rather limited, so the data required in the calculations were derived from old drawings. Included in the calculations were new components, maintenance and operation, supply and cleaning.

To facilitate the LCC calculations on the environmental and social aspects of the two scenarios, a simple tool from the Municipality of Copenhagen called the MBA (Environment in Buildings and Construction) was used (Municipality of Copenhagen, 2016). The project leader requested its use since the project was a public building. Feedback based on the quantified data was obtained from the client for the current case study. The case study was mapped in a large matrix that was developed to align each case in terms of sustainability criteria, technical inputs, technical inputs influence on design decision and level of sustainability. The matrix is shown in Table III.

2.7 Case 3 – depicting the design process as visuals

The third case study was also undertaken at the architectural office, by quantifying design decisions during the design process. The project was confidential and only limited data can be provided here. These data were also collected on the basis of the matrix in Table III. A number of daylight simulations were conducted by the sustainability team and submitted to the design team as reports and presentations. The daylight simulations examined the influence of the type of glazing, solar shading, and depth of balcony overhang, and ceiling surface, upon the resulting daylight conditions in each room and thereby the number of workspaces that it would be possible to create, given requirement for a 2 percent daylight factor (Trafik-, Bygge- og Boligstyrelsen, 2014).

3. Results

3.1 Case 1 – visuals at an engineering consultancy

Figure 3 shows a representative technical guideline illustrating the placement of the installation cores in a multi-story building. It included a list of the advantages and disadvantages of each technical installation.

Planning and action. Addressing the issue of installation core placement in a multi-story building at the first meeting, just as the design process started, was intended to integrate the technical installations in the initial design, hence avoiding future problems with coordinating core placements and finding space for installations.

Observations. Some of the attendees at the meeting found the information useful in the future design process, while others found it banal and restrictive. However, the simple visual and adjacent text made each point precise and clear, and ensured that everyone understood and could use the information.

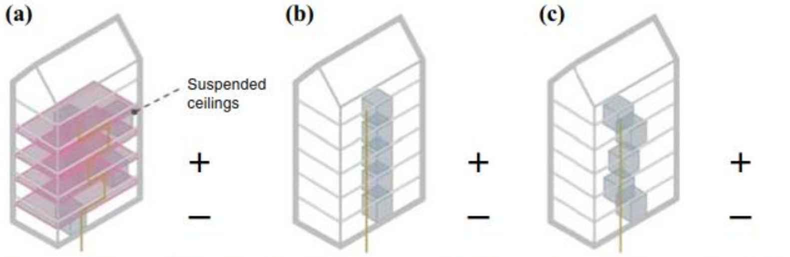
Reflections. The engineers decided to further develop the visuals, as they proved a useful tool for dialogue. A strategy for timing was also discussed internally on the basis of the reactions and feedback from the architects, e.g., it proved important to restrict the number of visuals presented and to tailor them to the meeting context.

3.2 Case 2 – "quantification" at an architectural office

Planning and action. A visualization was generated using LCCByg, showing the results of the calculations for the two scenarios "demolish/rebuild" or "renovate" as column diagrams.

Table III. Matrix for the case studies at the architectural office

Case No.	Case 2	Case 3
JJWs role	–	–
JJW included design phase(s) (Danish Description of Service)	–	–
Sustainability focus	–	–
Technical inputs (made by the PhD researcher) Requested by	–	–
Technical inputs (made by the PhD researcher)	–	–
Technical tools	–	–
Design variations and decisions	–	–
Reason for design decision	–	–
Level of sustainability	–	–



Notes: (a) Suspended ceilings result in increased flexibility in the plan layout; the toilet cores can be placed in various locations; (b) stacked toilet cores on all floors ensure minimal routing for pipes and hence require less space for installations; (c) centralized pipe routings with flexibility in plan layout require less space for installations
Source: Jakobsen and Wohlenberg (2016)

Figure 3. An example of the technical guidelines; these were always accompanied by text listing the advantages and disadvantages

The final sustainability ranking from the MBA (Environment in Buildings and Construction) (Municipality of Copenhagen, 2016) was added as a circle diagram. These diagrams are shown as Figure 4. The results indicate that the most economically advantageous scenario is "demolish and build new" due to the very poor condition of the existing building. The sustainability ranking supports this choice, as it involves the use of environmentally friendly materials, improves the possibilities for maintenance and improves the functionality of the building (since it will better fulfill the needs of the users). The calculations and sustainability ranking ensured a thorough investigation of each scenario and that the final design solution was based on both quantified data and qualitative data.

Observation. The project leader brought the outputs from Figure 4 to a pre-meeting with the clients. The clients stated that they were impressed by the thorough investigation and by the very clear visualized outputs. The analysis convinced the client to follow the architect's advice to demolish the existing buildings and build new ones due to poor existing quality and the high cost of renovation.

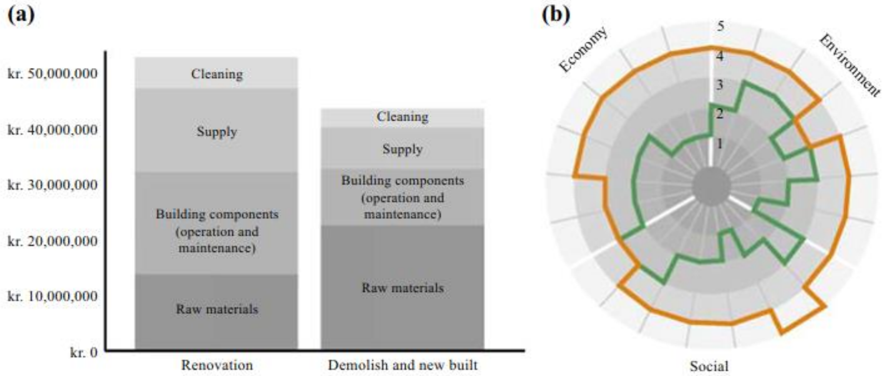
Reflection. As it was a public building with a limited economy, cost was the deciding factor and this was the most crucial aspect for the architects to document in the initial design phase.

3.3 Case 3 – depicting the design process as visuals

Planning and action. The output of the daylight simulations is shown in Figure 5, with the limits of the 2 percent daylight factor marked on the floorplan of the room, for easier communication between design team and client.

Observation. The design loops and design decision parameters were collected in the matrix for each case study. The design team tried to design for the highest possible number of work places in the room, with no additional solar shading needed on the balconies. This was demonstrated to be possible by means of the daylight simulations, but only with a white plane surface as the ceiling. The design team accepted this and included the output from the daylight simulations in the design process to ensure the best possible lighting conditions in the final design.

Reflections. Each iteration of design alternatives was followed by a daylight study to inform the design decisions. Aesthetic considerations guided most of the decisions, but where the daylight simulations could quantify the maximum number of workplaces possible, this was the design decision factor.



Notes: The orange represents the new building and the green represents the renovated building

Figure 4. (a) The column diagram shows the costs for each process for the two scenarios from the LCCByg report; (b) the circle diagram illustrates the social, economic and environmental ratings as outputs from the MBA

4. Discussion

The need for more sustainable design and the increased use of interdisciplinary design teams led both engineers and architects to alter their means of communication. In the engineering consultancy in Case 1, the engineers focused on simpler and more visual communication strategies that could address typical challenges by influencing how the architects organized the building masses during the early design phases. The architects in Case 2 and 3, in turn, aimed to quantify their design approaches so they could influence decisions that would otherwise be determined by the engineers and by financial considerations. This study illustrates how important it is that each discipline's individual methods should be supplemented by the methods used in the other discipline, as this promoted knowledge-based design. This was not just a change in methods but an innovative combination of two methods, one that could achieve more than either of them would have done had they been used in isolation.

In Case 1, the engineers succeeded in incorporating their technical knowledge right from the initial design phase with visual communication. One architect commented that the visuals felt restrictive, however, the simplicity of the visualizations actually ensured that all participants had the same interpretation of the topic, so that a dialogue of solutions could start on equal terms. By visualizing a general issue, the technical knowledge shifted from being quantitative values in a report to being qualitative descriptions of design principles.

By being prepared to make quantified design decisions, the architects were able to emphasize their concept and visions and to ensure an open range of solutions, as illustrated by Case 3. This made the design process receptive to engineering knowledge in the early design phases.

These three case studies illustrate how visualizing technical knowledge can facilitate communication between professions and ensure that design decisions are knowledge based in practice. The case studies also show technical knowledge can be visualized and integrated in the design phase whether it is at an overall and general level, such as Case 1, or deals with specific design matters, such as in Case 2 and 3. Additionally, qualitative descriptions of technical design decisions and the quantification of architectural design decisions both lead to more informed design decisions.

The case studies expanded the range of available communication methods and made it easier to achieve the ultimate goal of sustainable buildings with low emissions. A generic space of solutions defined solely in terms of qualitative or quantitative information risks being perceived as restricting in the design process, while a contextual space of solutions with information that has been configured to inform specific design decisions is more likely to be perceived as an enrichment.

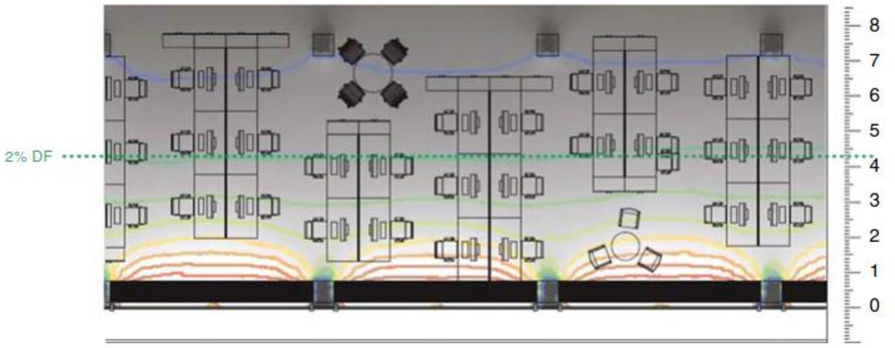


Figure 5. The figure shows the daylight simulation of the room, having the green line as the 2 percent daylight factor limit in the room

Notes: On the right a scale showing the depth of the room in meters from the façade

5. Conclusions

The paper addresses the goal of the building industry to communicate across disciplines to be able to solve the complex matter of sustainable building design.

From this case study research, it can be concluded that simple visuals have great potential as the medium for communicating technical engineering knowledge to architects. Visuals are commonly used by architects as drivers or "tools" in the design process and by adapting the architects' own tools there is a higher potential for understanding and achieving implementation of technical scientific information in the actual design decisions. Informing early design decisions such as geometry, window/facade ratio, orientation, etc., which are typically in the hands of architects, with technical scientific information is a necessity and a common goal for the interdisciplinary design team. However, the timing and the inclusion of only design decision relevant information is essential, as information overload can delay the design process unless the information is fully integrated into the process itself.

For the architects to underline the value of their design, the case studies indicate the potential of quantification of architectural choices to communicate with engineers. Engineers commonly use quantification and it is possible for architectural offices to use simple digital engineering tools to ensure good communication. The quantification of architectural decisions improved the engineers' understanding and their acceptance of the work of the architect.

There is potential for further research in the topic by addressing visuals and quantifications as the medium of communication between architects and engineers in a larger range of case studies.

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APPENDIX I

CASE 04

CASE 06

CASE 07

CASE 08

CASE 10

CASE 14

CASE 19

CASE 21

CASE 04

This case study consists of a new building to a university, as a part of a larger development of the university campus in southern Denmark. There is a big focus upon keeping the existing atmosphere as the rest of the campus with green landscape and red bricks.

PROJECT INFORMATION

The new building has to fulfil the needs for current teaching environments and be flexible to accommodate future changes within teaching environments and usage of the buildings.

DESIGN TEAM

Engineers within HVAC and structure.

From JJW:

- Architect 1: Project leader, specialised in the initial design phases and architectural competitions
- Architect 2: Specialised in the initial design phases and experience with teaching environments
- Sustainability expert: DGNB auditor
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

- Sustainability screening of project brief

TECHNICAL INPUTS

- Sustainability section

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops are mapped and illustrated in the following Figure 1. Here the dark blue arrow illustrates in which design phase of which the project is at the time of the case study at JJW. The dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

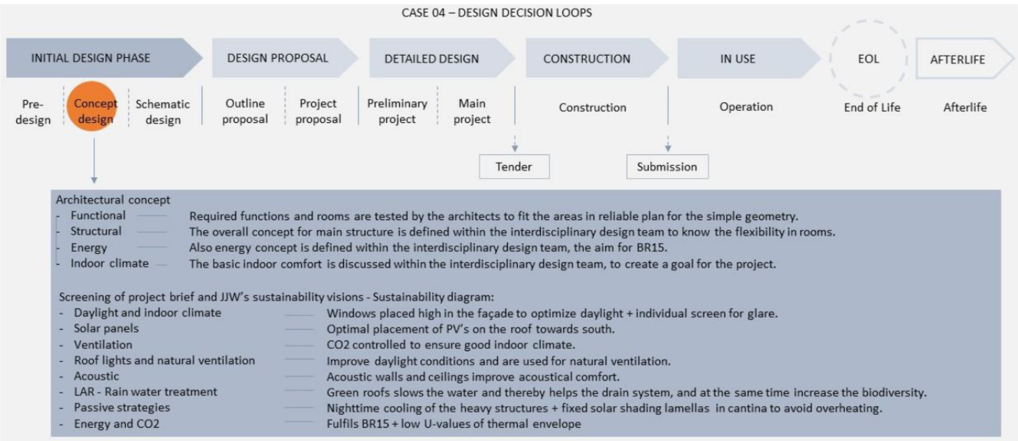


Figure 1 - Case 04 design decision loops, the dark blue arrow illustrates the design phase of which the project is at the time for case study at JJW, the dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

The mapping of IED and DGNB are solely related to the JJW tasks in a holistic perspective, and not the entire project setup.

MAPPING IED

XXX	**High focus**
XX	Middle focus
X	General focus

IED-PROCESS	IED-CRITERIA	CASE 04
Reduce	Context	XXX
	Orientation/placement	XX
	Geometry	XXX
	Daylight	XX
	Facade design	XX
	Zone/ programming	XXX
	Structural concept	XX
	Energy concept	XX
	Use of roof area	XXX
Optimize	Windows	
	Lighting	
	Ventilation	X
	Cooling/heating system	X
	Automation/ controlling	
Produce	Renewable energy	X
	Passive cooling	XX

MAPPING DGNB

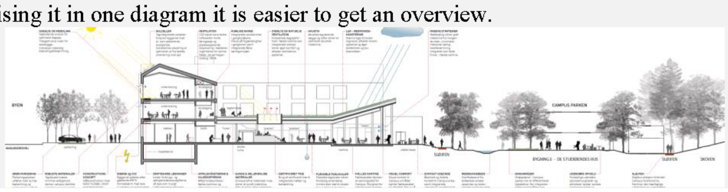
DGNB criteria	Criteria description	Case 04	
		Directly affected	Indirectly affected
	Environment Impact		
ENV 1.2	Local Environment Impact - High-risk materials and substances for environment and health	X	
ENV 1.3	Responsible Procurement - certified timber and natural stone	X	
	Economic guaranteed future		
ECO 2.1	Flexibility and adaptability	X	
ECO 2.2	Robustness	X	
	Health, comfort of user satisfaction		
SOC 1.1	Thermal Comfort	X	X
SOC 1.2	Indoor Air Quality		X
SOC 1.3	Acoustic Comfort	X	
SOC 1.4	Visual Comfort	X	X
SOC 1.6	Quality of outdoor spaces	X	X
	Aesthetics		
SOC 3.1	Design and Urban Quality	X	
SOC 3.3	Plan layout and disposal	X	
	Technical completion		
TEC 1.1	Fire Safety		X
TEC 1.5	Cleaning and Maintenance		X

KNOWLEDGE BASED DESIGN

- Use of roof lights to night cooling and natural ventilation, based on close collaboration with engineers.

REFLECTIONS

- Development of sustainability section to communicate the sustainability concepts for the client. By visualising it in one diagram it is easier to get an overview.



Case 06

The project is a different typology; hence the site is a new development to be built as an island in the harbour of Copenhagen. The site has to include a new residential area with landscape and residential buildings included.

PROJECT INFORMATION

- Development of new area with residential buildings.

DESIGN TEAM

The design team consisted of JJW and another architectural office collaborating together at JJWs office and engineers not working in same office.

From JJW:

- Architect 1: Project leader, specialised in the initial design phases and architectural competitions
- Architect 2: Specialised in the initial design phases
- Sustainability expert: DGNB auditor
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

- Good living conditions and comfortable indoor climate.
- Attractive urban landscape surrounding the new residential buildings.

TECHNICAL INPUTS

- Solar shading studies to support design process of geometry and orientation of buildings on site.
- Wind studies of the buildings on site to investigate the wind conditions in the area.

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops are mapped and illustrated in the following Figure 2. Here the dark blue arrow illustrates in which design phase of which the project is at the time of the case study at JJW. The dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

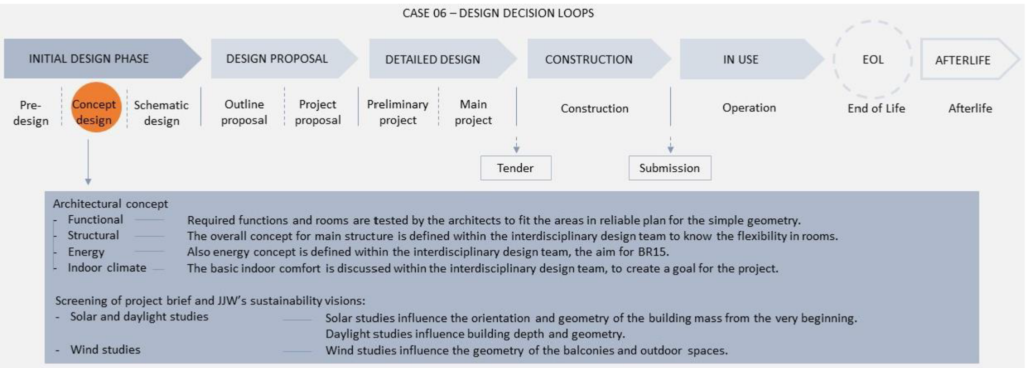


Figure 2 - Case 06 design decision loops, the dark blue arrow illustrates the design phase of which the project is at the time for case study at JJW, the dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

MAPPING IED

XXX	**High focus**
XX	Middle focus
X	General focus

IED-PROCESS	IED-CRITERIA	CASE 06
Reduce	Context	XXX
	Orientation/placement	XXX
	Geometry	XXX
	Daylight	XX
	Facade design	X
	Zone/ programming	X
	Structural concept	
	Energy concept	
	Use of roof area	
Optimize	Windows	
	Lighting	
	Ventilation	
	Cooling/heating system	
	Automation/ controlling	
Produce	Renewable energy	
	Passive cooling	

MAPPING DGNB

DGNB criteria	Criteria description	Case 06	
		Directly affected	Indirectly affected
	Global and local environment		
ENV 2.6	Water Circulation Systems	X	
	Health, comfort of user satisfaction		
SOC 3.3	Development Layout and Flexible Use	X	
SOC 4.1	Urban Integration	X	
	Technical completion		
TEC 3.4	Quality of Bicycle Infrastructure	X	
TEC 3.5	Quality of Pedestrian Infrastructure	X	

The mapping of IED and DGNB are solely related to the JJW tasks in a holistic perspective, and not the entire project setup.

KNOWLEDGE BASED DESIGN

- The modelling of building geometry and orientation is influenced by inputs of studies based on technical knowledge.
    - Solar shading studies, influence geometry and orientation of buildings on site.
    - Daylight studies, influence geometry and building depth.
    - Wind studies influence placement of buildings on site.

REFLECTIONS

- The technical inputs can ensure knowledge-based design decisions from the very beginning of modelling the building masses.

Case 07

This project has a different setup from other JJW cases, by being a parallel process with other competing design teams. The client has contact to all teams through the process to guide them individually. The project is a new building located central at Frederiksberg, Copenhagen.

PROJECT INFORMATION

- The new building has to contain different functions. However, all have to include the public into some degree. The location is above a new Metro station, which sets requirements to the architectural quality.

DESIGN TEAM

The design team consists of HVAC and structural engineers and JJW team. The collaboration is mainly through weekly meetings. The communication with the sustainability expert and PhD researcher is solely start-up meeting and a final meeting just before submission, thereby not integrated design.

From JJW:

- Architect 1: Project leader, specialised in the initial design phases and architectural competitions
- Architect 2: Specialised in the initial design phases
- Sustainability expert: DGNB auditor
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

- Social sustainability – emphasising social interaction and spontaneous meetings among people.

TECHNICAL INPUTS

- No technical inputs, only sustainability screening

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops are mapped and illustrated in the following Figure 3. Here the dark blue arrow illustrates in which design phase of which the project is at the time of the case study at JJW. The dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

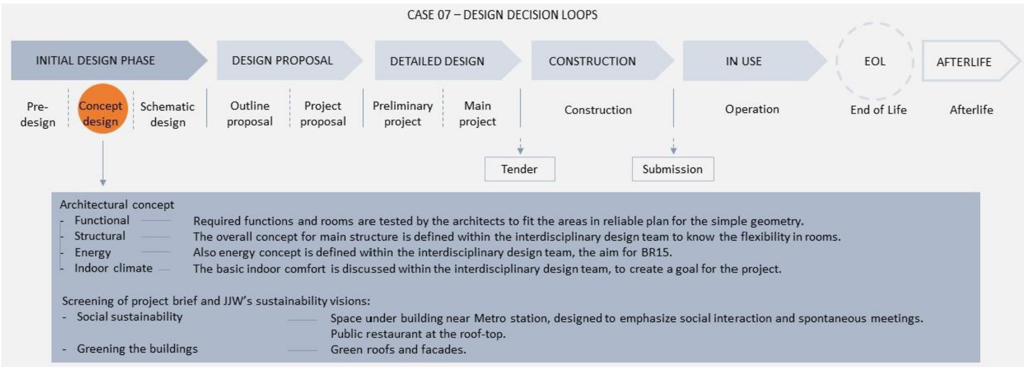
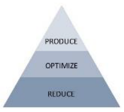


Figure 3 - Case 07 design decision loops, the dark blue arrow illustrates the design phase of which the project is at the time for case study at JJW, the dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

MAPPING IED



XXX	**High focus**
XX	Middle focus
X	General focus

IED-PROCESS	IED-CRITERIA	CASE 07
Reduce	Context	XXX
	Orientation/placement	XXX
	Geometry	XXX
	Daylight	XX
	Facade design	XXX
	Zone/ programming	XXX
	Structural concept	XX
	Energy concept	XX
	Use of roof area	XXX
Optimize	Windows	
	Lighting	
	Ventilation	X
	Cooling/heating system	
	Automation/ controlling	
Produce	Renewable energy	
	Passive cooling	

MAPPING DGNB

DGNB criteria	Criteria description	Case 07	
		Directly affected	Indirectly affected
	Economic guaranteed future		
ECO 2.1	Flexibility and adaptability	X	
ECO 2.2	Robustness	X	
	Health, comfort of user satisfaction		
SOC 1.1	Thermal Comfort		X
SOC 1.2	Indoor Air Quality		X
SOC 1.4	Visual Comfort	X	
SOC 1.6	Quality of outdoor spaces	X	
	Functionality		
SOC 2.1	Design for All / Accessibility	X	
SOC 2.2	Public Access	X	
	Aesthetics		
SOC 3.1	Design and Urban Quality	X	
SOC 3.2	Integrated Public Art		X

The mapping of IED and DGNB are solely related to the JJW tasks in a holistic perspective, and not the entire project setup.

REFLECTIONS

- The collaboration between architects and sustainability expert was limited. This resulted in limited influence regarding sustainability in the design proposal.

Case 08

This project has been through a long process before the inclusion of the PhD researcher and the case study process. The basis for this case study is that the engineers in the design team went bankrupt and thereby a lot of knowledge and technical information were lost. The project manager approached the PhD researcher to assist with some technical inputs to turn the situation to a positive scenario.

PROJECT INFORMATION

The project is a public-school project in Copenhagen.

DESIGN TEAM

The design team consists of architects from JJW and new engineering team, HVAC and structural.
From JJW:

- Architect 1: Project leader, specialised in new buildings and refurbishment projects.
- Sustainability expert: DGNB auditor
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

- Reaching BR15
- Investigations of using the 'ventilation window' instead of regular windows and expanded ventilation system.

TECHNICAL INPUTS

- Energy frame calculations for the project, to reach BR15
- Simple calculations of ventilation rates for the 'Ventilation window' as alternative to expanded mechanical ventilation ducts.

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops are mapped and illustrated in the following Figure 4. Here the dark blue arrow illustrates in which design phase of which the project is at the time of the case study at JJW. The dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

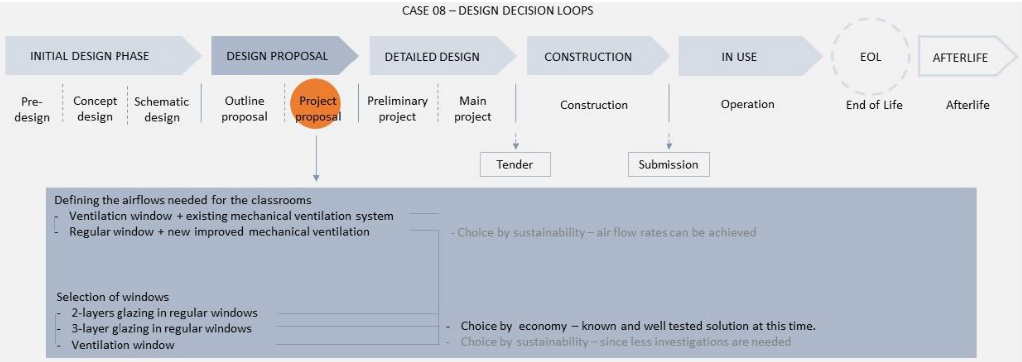
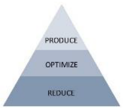


Figure 4 - Case 08 design decision loops, the dark blue arrow illustrates the design phase of which the project is at the time for case study at JJW, the dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

MAPPING IED



XXX	**High focus**
XX	Middle focus
X	General focus

IED-PROCESS	IED-CRITERIA	CASE 08
Reduce	Context	
	Orientation/placement	
	Geometry	
	Daylight	
	Facade design	
	Zone/ programming	X
	Structural concept	
	Energy concept	XX
	Use of roof area	
Optimize	Windows	XXX
	Lighting	
	Ventilation	XXX
	Cooling/heating system	XXX
	Automation/ controlling	XX
Produce	Renewable energy	
	Passive cooling	XXX

MAPPING DGNB

DGNB criteria	Criteria description	Case 08	
		Directly affected	Indirectly affected
	Total life cycle costs		
ECO 1.1	Life Cycle Cost (LCC)	X	
	Economic guaranteed future		
ECO 2.1	Flexibility and adaptability	X	
ECO 2.2	Robustness	X	
	Health, comfort of user satisfaction		
SOC 1.1	Thermal Comfort	X	
SOC 1.2	Indoor Air Quality	X	
SOC 1.3	Acoustic Comfort		X
SOC 1.4	Visual Comfort	X	
SOC 1.5	User Control		X
	Technical completion		
TEC 1.2	Sound Insulation		X
TEC 1.4	Adaptability of Technical Systems		X
TEC 1.5	Cleaning and Maintenance		X

The mapping of IED and DGNB are solely related to the JJW tasks in a holistic perspective, and not the entire project setup.

KNOWLEDGE BASED DESIGN

- Technical investigations inform the process of selection of windows and ventilation system.
    - Known technology is chosen, since limited documentation of the new types of windows are available at the time for decision.

KNOWLEDGE DEVELOPMENT

- The Ventilation window is investigated and might be feasible to use in a future project.

REFLECTIONS

- Implementing a new product is a time consuming and complex affair, due to the need for new knowledge in the design team. The gained knowledge in this project might help for other projects to use this product.

Case 10

This project is a new public building, with limited costs available.

PROJECT INFORMATION

The main focus of this project is based upon a request for LCC calculations on various materials and components in relation to the MBA from Copenhagen Municipality.

DESIGN TEAM

Architects and engineers consulting through meetings when appropriate.

From JJW:

- Architect 1: Project leader, specialised in complex buildings and sustainability
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

- LCC to support design decisions when selecting materials for the building.

TECHNICAL INPUTS

- LCCByg calculations upon different scenarios related to the different materials for the building.

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops are mapped and illustrated in the following Figure 5. Here the dark blue arrow illustrates in which design phase of which the project is at the time of the case study at JJW. The dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

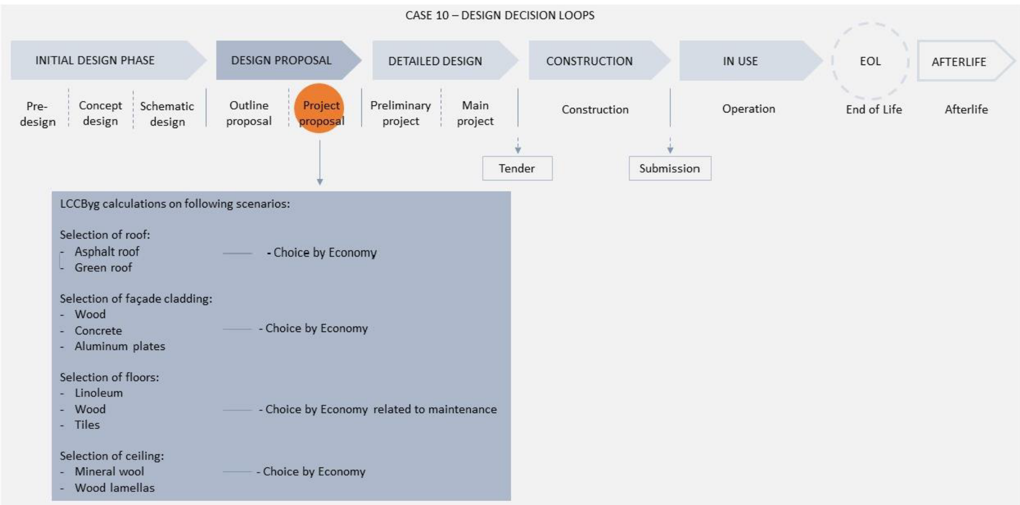


Figure 5 - Case 10 design decision loops, the dark blue arrow illustrates the design phase of which the project is at the time for case study at JJW, the dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

MAPPING IED

No IED Mapping was possible.

MAPPING DGNB

DGNB criteria	Criteria description	Case 10 Directly affected	Indirectly affected
	Global and local environment		
ENV 1.1	Life Cycle Impact Assessment (LCA) - Environmental impacts		x
	Total life cycle costs		
ECO 1.1	Life Cycle Cost (LCC)	x	

The mapping of IED and DGNB are solely related to the JJW tasks in a holistic perspective, and not the entire project setup.

KNOWLEDGE BASED DESIGN

- Recommendations for the client of materials. Based on LCCByg calculations.

REFLECTIONS

- During the process it occurred that the listed life times on the materials were not the same in the SIGMA books as in LCAByg. This project used the SIGMA books to ensure comparability to pervious calculations.

Case 14

This project was a won written architectural competition. The project is concerning a new residential building for students in a new development area 'Carlsbergbyen' in Copenhagen.

PROJECT INFORMATION

The project started with an internal meeting (not a pixie meeting), where a sustainability screening was conducted in plenum.

DESIGN TEAM

Engineers and architects do not work together, consultancy through meetings.

From JJW:

- Architect 1: Project leader, specialised in the initial design phases and architectural competitions
- Sustainability expert: DGNB auditor
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

- Maintenance and cleaning
- Robust materials
- Number of residential units and limited hallway area.

TECHNICAL INPUTS

- Sustainability screening
    - One-page-strategy to set clear goals for the projects
    - The DGNB wheel to assist the description

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops are mapped and illustrated in the following Figure 6. Here the dark blue arrow illustrates in which design phase of which the project is at the time of the case study at JJW. The dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

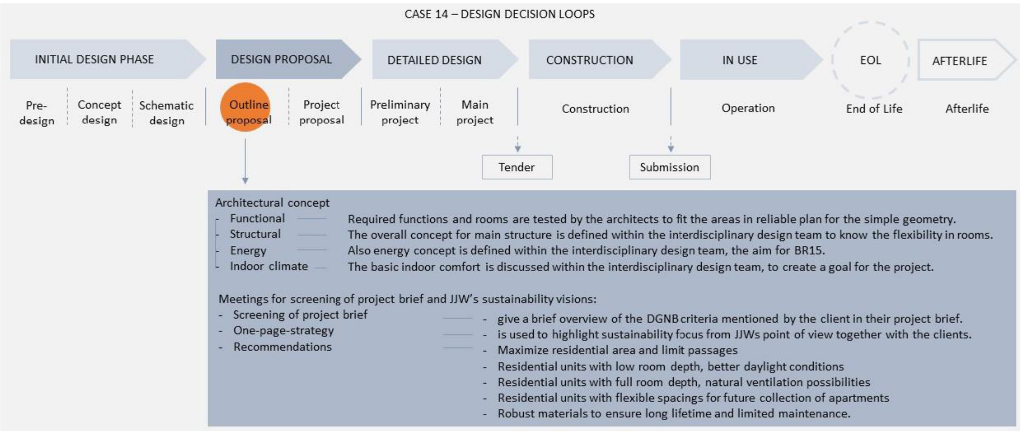


Figure 6 - Case 14 design decision loops, the dark blue arrow illustrates the design phase of which the project is at the time for case study at JJW, the dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

MAPPING IED

XXX	**High focus**
XX	Middle focus
X	General focus

IED-PROCESS	IED-CRITERIA	CASE 14
Reduce	Context	XXX
	Orientation/placement	XXX
	Geometry	XXX
	Daylight	XX
	Facade design	X
	Zone/ programming	XXX
	Structural concept	X
	Energy concept	X
	Use of roof area	
Optimize	Windows	
	Lighting	
	Ventilation	
	Cooling/heating system	
	Automation/ controlling	
Produce	Renewable energy	
	Passive cooling	

MAPPING DGNB

DGNB CRITERIA	CRITERIA DESCRIPTION	CASE 14	
		Directly affected	Indirectly affected
	Life cycle cost		
ECO 1.1	Life cycle cost (LCC)		X
	Economic guaranteed future		
ECO 2.1	Flexibility and adaptability	X	
ECO 2.2	Robustness	X	
	Health, comfort and user satisfaction		
SOC 1.4	Visual Comfort		X
	Technical completion		
TEC 1.5	Maintenance and cleaning	X	

The mapping of IED and DGNB are solely related to the JJW tasks in a holistic perspective, and not the entire project setup.

REFLECTIONS

- Development of knowledge about One-page-strategy as tool in a design process.

Case 19

This project consists of three smaller individual projects. All buildings have the function as public child care facility related to the public schools. The budget is tight because it is public buildings.

PROJECT INFORMATION

The design team consider using CLT as structural materials for all buildings. The development of knowledge related to the material is conducted simultaneously with Case 12. However, these buildings are not as far in the process as Case 12, so there might be increased possibility to use the material.

DESIGN TEAM

Engineers specialised in structure and architects from JJW.

From JJW:

- Architect 1: Project leader, specialised in projects through all design phases and teaching environments.
- Architect 2: Student assistant with knowledge within competition architecture
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

- Alternative structural material CLT instead of concrete.
    - o Simple structure with no surface treatment for healthy indoor climate
    - o Less environmental emissions related to production compared to concrete

TECHNICAL INPUTS

- Literature study from online sources, to gain knowledge about the topic.

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops are mapped and illustrated in the following Figure 7. Here the dark blue arrow illustrates in which design phase of which the project is at the time of the case study at JJW. The dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

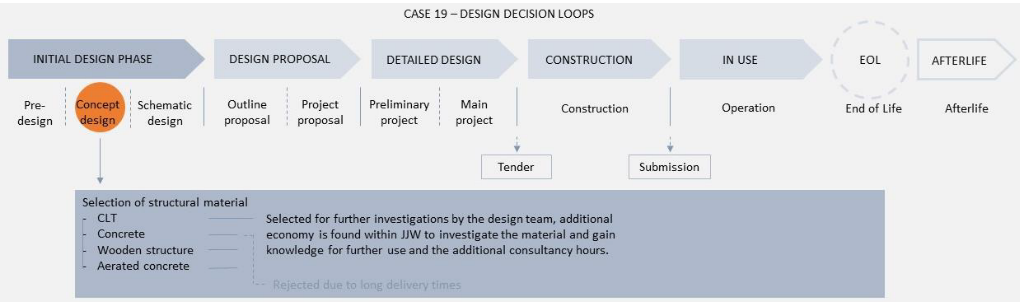


Figure 7 - Case 19 design decision loops, the dark blue arrow illustrates the design phase of which the project is at the time for case study at JJW, the dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

MAPPING IED

XXX	**High focus**
XX	Middle focus
X	General focus

IED-PROCESS	IED-CRITERIA	CASE 19
Reduce	Context	
	Orientation/placement	
	Geometry	
	Daylight	
	Facade design	X
	Zone/ programming	
	Structural concept	XXX
	Energy concept	
	Use of roof area	
Optimize	Windows	
	Lighting	
	Ventilation	
	Cooling/heating system	
	Automation/ controlling	
Produce	Renewable energy	
	Passive cooling	

MAPPING DGNB

DGNB CRITERIA	CRITERIA DESCRIPTION	CASE 19	
		Directly affected	Indirectly affected
	Life cycle cost		
ECO 1.1	Life cycle cost (LCC)	X	
	Economic guaranteed future		
ECO 2.1	Flexibility and adaptability	X	
ECO 2.2	Robustness	X	
	Technical completion		
TEC 1.5	Maintenance and cleaning	X	

The mapping of IED and DGNB are solely related to the JJW tasks in a holistic perspective, and not the entire project setup.

KNOWLEDGE DEVELOPMENT AND REFLECTIONS

- Within this case study the focus was solely upon expanding the common knowledge about CLT as material.
    - Through common meetings with engineers and specialists in CLT.
    - Focussing upon economy for the product and the additional consultancy hours for implementing new details in project.
    - The environmental benefits over other materials

Case 21

This project is a DGNB certification of a new residential building. The building is designed, and construction is about to begin, this is therefore solely a DGNB certification.

PROJECT INFORMATION

The PhD researcher was assigned the project for supervision of the LCAByg tool to the project leader. The project leader is about to become DGNB auditor by leading this project.

DESIGN TEAM

There is a close collaboration between engineer and architect.

From JJW:

- Architect 1: Project leader, DGNB consultant
- PhD: MSc Architectural Engineering in Energy Design, DGNB consultant

SUSTAINABILITY FOCUS

- DGNB certification for new residential buildings
    - LCAByg

TECHNICAL INPUTS

There is a division of the DGNB topics between architect and engineer.

- The engineer conducts the LCCByg calculations.
- The architect conducts the LCAByg calculations.

DESIGN DECISION LOOPS

Based upon the Description of Service the design decision loops are mapped and illustrated in the following Figure 8. Here the dark blue arrow illustrates in which design phase of which the project is at the time of the case study at JJW. The dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

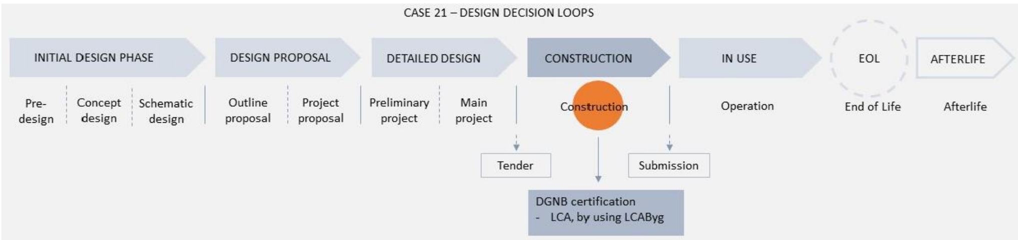
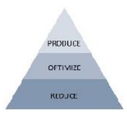


Figure 8 - Case 21 design decision loops, the dark blue arrow illustrates the design phase of which the project is at the time for case study at JJW, the dark blue box contains the design decision loops and the orange dot indicate the phase for interaction with the PhD researcher and the technical inputs.

MAPPING IED



NO IED mapping for this case study.

XXX	**High focus**
XX	Middle focus
X	General focus

MAPPING DGNB

DGNB CRITERIA	CRITERIA DESCRIPTION	CASE 21	
		Directly affected	Indirectly affected
	Global and local environment		
ENV 1.1	Life Cycle Impact Assessment (LCA) - Environmental impacts	X	

The mapping of DGNB is solely related to the JJW tasks in a holistic perspective, and not the entire project setup.

KNOWLEDGE DEVELOPMENT AND REFLECTIONS

- This project develops internal knowledge at JJW about LCAByg as a tool in a DGNB certification process.
- Useful for future projects at JJW.

APPENDIX Y

Additional data from questionnaires and interviews are due to confidentiality not included in the thesis. However, the data are available for the PhD committee.

In recent decades the main focus has been on reducing the energy required to operate buildings. This has recently changed to a focus on sustainability in a broader sense. The present PhD research developed a method for Integrated Sustainable Design (ISD), in which sustainability is addressed by including technical inputs in every phase of the design process at architectural offices, challenging the classical approach. The ISD method was derived from case studies at a large architectural office and combines the Integrated Energy Design method, the Danish Description of Service and DGNB.

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