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Saridaki, Maria

DOI (link to publication from Publisher):
10.54337/aau510570539

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

TOWARDS NEW CALCULATIVE PRACTICES ON LIFE-CYCLE COSTING

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DISSERTATION SUBMITTED 2022

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DENMARK

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by

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Dissertation submitted for the degree of the PhD

September 2022

Dissertation submitted: September 2022

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Department: Department of the Build Environment

ISSN (online): 2446-1636
ISBN (online): 978-87-7573-817-5

Published by:
Aalborg University Press
Kroghstræde 3
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Stibo Complete, 2022

Preface

I first started working with life-cycle costing (LCC) in spring 2017 during the last semester of my master's degree education in industrial and engineering management at the Technical University of Denmark (DTU). That year, I collaborated with the civil engineering department at DTU about the development of methods enabling integration of LCC into a BIM concept. The topic interested me since firstly, I was combining my MEng in Civil Engineering and my MSc in Engineering Management, and secondly it was both challenging and exciting. Challenging, because the industry was quite immature regarding the economic sustainability and, therefore, facing many challenges that hindered the implementation of LCC methodology. Exciting, because it was a trending topic in the Danish AECO industry, it had started receiving increased attention, and there seemed to be numerous opportunities for overcoming the challenges and improving integration of LCC in practice. However, those opportunities were not utilized, and I was eager to contribute to the field.

Throughout the interviews that I conducted to gather the data for my MSc's thesis study, I met my current supervisor of this PhD study, *Kim Haugbølle*. Kim is a specialist on LCC (his name is linked to LCC in the Danish Industry) and one of the developers of the de facto standard in Denmark application for LCC calculations: *LCCbyg*. Through my discussions with Kim, the idea of a PhD was generated since there was an increased interest to further investigate the opportunities of integrating LCC and to contribute to preparing the industry when LCC will eventually be regulated.

Due to my interest and my previous experience with architects, I chose an Industrial PhD program in collaboration with the Danish architecture firm *Vandkunsten Architects*. That was the initiation of this PhD research that started officially in May 2018.

The study started out great, and the first year went as planned, but afterwards I – and the rest of the world – was confronted with a very unexpected event: the Covid-19 pandemic. The pandemic affected me and my research, so the initial plan changed quite significantly. The study was initially designed to follow an action-research approach in *Vandkunsten Architects*. However, due to Covid-19, all employees in the company and I had to work from home for several months and, thereby, the study had to be redefined to have a more analytical approach. Moreover, I had to cancel my study abroad that was planned to take place at the University of Maryland in the USA where I was aiming to explore the LCC application in the US AECO industry and perform a comparative study to European practices, highlighting opportunities for improvements.

However, after some challenges the research is concluded in August 2022, and it is summarized in this dissertation.

External funding

This PhD research was conducted in an Industrial PhD program that is partially funded by the architectural company *Vandkunsten Architects* and the *Innovation Fund Denmark*.

Innovation Fund Denmark (https://innovationsfonden.dk) is a fund under the Danish Ministry of Education and Research that provides funds to entrepreneurs, researchers, and businesses to develop innovative and viable solutions to society's challenges. Among others, Innovation Fund Denmark offers an industrial research program aimed at establishing closer ties between companies and the university while connecting young researchers to the private sector. The industrial research program invests on Industrial PhD and Industrial postdoc projects. The candidate is employed in a private company and enrolled in a public research institute.

Summary

Life-cycle costing (LCC) is gaining increased attention in the architecture, engineering, construction, and operations (AECO) industry as a vital tool for assessing the economic sustainability throughout the lifetime of a building. LCC has recently become part of procurement policies, European directives, certification schemes, and national regulations. Despite the increased attention, the concept faces limited adoption in the design practices due to various challenges of implementation.

The ***aim*** of this Industrial PhD research is to understand and explain the current practices regarding LCC and provide new insights into the challenges and opportunities of integrating LCC in building design. The project is carried out in three interdependent work packages corresponding to the three research questions of this study:

- RQ1: How does the activity system of building design facilitate or obstruct life-cycle cost calculations in design practices?
- RQ2: To what extent do current actions between the activity system of building design and construction and the activity system of building operation support data exchange regarding LCC?
- RQ3: Which novel actions may stimulate integration of LCC in design practices?

The PhD results are summarized in this thesis that consists of seven papers in addition to a synopsis. The ***research design*** of this project comprises a paradigmatic single case study analysis (the case company is the Danish architectural firm *Vandkunsten Architects*) and sub-case projects. The data collection methods include mainly qualitative methods such as interviews, participants and direct observations, analysis of physical artifacts, as well as a quantitative survey.

In addition, various ***theories and tools*** are used throughout the research study to support and improve the analysis. Activity theory is used initially to analyze the practices of building design and identify several built-in contradictions about LCC and later, to analyze the actions and interactions between the activities of building design and building operation in relation to LCC. Moreover, structured analysis is used as methodological tool to map the data flowing between the actions in social housing projects regarding LCC and to identify enablers for LCC implementation. Finally, user-centered design (UCD) and specifically the concept of personas is used as a tool to recognize the diversity of users in the design practices and their characteristics, work processes, and data management approaches improving our understanding of users so designing better tools and processes.

The research ***findings*** indicated that there are several contradictions in the activity system of building design that obstruct the integration of LCC in the design practices. The study confirmed many of the challenges that have already been discussed in the

existing literature, for instance the lack of available and reliable data for LCC calculation. In addition, the research adds new insights into the limited adoption of LCC, highlighting lack of division of work tasks and limited communication between the LCC practitioner and the design teams, as well as the lack of collaboration and work allocation to utilize the benefits of LCC in decision-making as additional hindrances for LCC adoption.

In addition, the research identifies opportunities and enablers for applying LCC in social housing projects. Specifically, the author pinpointed three actions between the activity system of building design and the activity system of building operation that support data utilization and exchange regarding LCC: (1) Introduction of LCC consideration in the tendering process, (2) Consideration of operation and maintenance in early and late design processes, and (3) Provision of operation and maintenance guide and budget along the project handover. Although the actions enable LCC data exchange, the exchanged data is not fully utilized due to misalignments between the elements of the two activity systems. This research suggests that the activity systems should develop a shared objective to enable LCC consideration throughout the lifetime of the building projects and how to improve data utilization.

Finally, the research focuses on discussing how to support LCC integration in the design practices. First, the author develops, and tests two different methods of data integration based on compatibility and interoperability approaches and highlights five lessons learned through the development and application in the case projects. Then, the research focuses on identifying and characterizing different users of technology and their characteristics in regard to data management approaches. The findings pinpoint three user personas: (1) *the clip-boarder* who manually copy and pastes data from one application to the other for performing LCC calculations, (2) *the spreadsheet expert* who prefers to import and export data between spreadsheet-based tools, and (3) *the programmer* who uses programming language to automate data integration between tools. The knowledge about the different user of technologies reveals different approaches on integrating LCC in design practices.

In ***conclusion***, this explanatory study provides new insights into the cost calculation practices by identifying challenges of LCC limited adoption in the activity system of building design and highlighting opportunities for increasing LCC adoption in the AECO industry through the interaction between the activity system of building design and the activity system of building operation. Moreover, the research improves our knowledge about potential LCC users and their characteristics on the use of technology and data management approaches. The findings of this research study 1) contribute to the research community by adding elements to the existing literature and pinpointing relevant research possibilities; 2) can be used by practitioners to transform current design practices and build useful tools; and 3) can be used by policy makers to develop new standards and regulations towards LCC.

Dansk resume (Danish summary)

Livscyklusomkostninger (LCC) får øget opmærksomhed i arkitektur-, ingeniør-, konstruktions- og driftsindustrien (AECO) som et vigtigt værktøj til at vurdere den økonomiske bæredygtighed gennem en bygnings levetid. LCC er for nylig blevet en del af indkøbspolitikker, europæiske direktiver, certificeringsordninger og nationale regler. På trods af den øgede opmærksomhed står konceptet over for begrænset anvendelse i designpraksis på grund af forskellige udfordringer ved implementering.

Målet med denne erhvervs-ph.d.- afhandling er at forstå og forklare den nuværende praksis vedrørende LCC og give ny indsigt i udfordringerne og mulighederne ved at integrere LCC i bygningsdesign. Projektet udføres i tre indbyrdes afhængige arbejdspakker svarende til de tre forskningsspørgsmål i denne undersøgelse:

- RQ1: Hvordan letter eller hindrer aktivitetssystemet for bygningsdesign beregninger af livscyklusomkostninger i designpraksis?
- RQ2: I hvilket omfang understøtter nuværende handlinger mellem aktivitetssystemet for bygningsdesign og -konstruktion og aktivitetssystemet for bygningsdrift dataudveksling vedrørende LCC?
- RQ3: Hvilke nye handlinger kan stimulere integration af LCC i designpraksis?

Ph.d.-resultaterne er sammenfattet i denne afhandling, der består af syv artikler udover en synopsis. Forskningsdesignet i dette projekt omfatter en paradigmatisk enkelt-case-analyse (case-virksomheden er det danske arkitektfirma Vandkunsten Architects) og del-case-projekter. Dataindsamlingsmetoden omfatter hovedsageligt kvalitative metoder som interviews, deltagere og direkte observationer, analyse af fysiske artefakter samt en kvantitativ undersøgelse.

Derudover anvendes forskellige teorier og værktøjer gennem forskningsstudiet for at understøtte og forbedre analysen. Aktivitetsteori bruges indledningsvis til at analysere praksisser for bygningsdesign, identificere flere indbyggede modsætninger om LCC og senere til at analysere handlinger og interaktioner mellem aktiviteterne inden for bygningsdesign og bygningsdrift i forhold til LCC. Desuden bruges struktureret analyse som metodisk værktøj til at kortlægge datastrømmene mellem aktionerne i sociale boligprojekter vedrørende LCC og til at identificere katalysatorer for LCC-implementering. Endelig bruges brugercentreret design og specifikt begrebet personas som et værktøj til at genkende brugernes mangfoldighed i designpraksis og deres karakteristika, arbejdsprocesser og datahåndteringstilgange, der forbedrer vores forståelse af brugere, så vi kan designe bedre værktøjer og processer.

Forskningsresultaterne pegede på, at der er flere modsætninger i aktivitetssystemet for bygningsdesign, der hindrer integrationen af LCC i designpraksis. Undersøgelsen bekræftede mange af de udfordringer, der allerede er blevet diskuteret i den eksisterende litteratur, for eksempel manglen på tilgængelige og pålidelige data til LCC-beregning. Derudover tilføjer forskningen ny indsigt i den begrænsede

anvendelse af LCC, der fremhæver manglende fordeling af arbejdsopgaver og begrænset kommunikation mellem LCC-praktikeren og designteamene, samt manglen på samarbejde og arbejdsfordeling for at udnytte fordelene ved LCC i beslutningstagning som yderligere hindringer for LCC-vedtagelse.

Derudover identificerer forskningen muligheder og katalysatorer for at anvende LCC i sociale boligprojekter. Konkret pegede forfatteren på tre handlinger mellem aktivitetssystemet for bygningsdesign og aktivitetssystemet for bygningsdrift, der understøtter dataudnyttelse og udveksling vedrørende LCC: (1) Indførelse af LCC-hensyn i udbudsprocessen, (2) Overvejelse af drift og vedligeholdelse i tidlige og sene designprocesser og (3) Levering af drifts- og vedligeholdelsesvejledning og budget langs projektoverdragelsen. Selvom handlingerne muliggør LCC-dataudveksling, udnyttes de udvekslede data ikke fuldt ud på grund af fejljusteringer mellem elementerne i de to aktivitetssystemer. Denne forskning foreslår hvordan man kan forbedre dataudnyttelsen, og hvordan aktivitetssystemerne bør udvikle et fælles mål for at muliggøre LCC-overvejelse gennem hele byggeprojektets levetid.

Endelig fokuserer forskningen på at diskutere hvordan man understøtter LCC-integration i designpraksis. For det første udvikler og tester forfatteren to forskellige metoder til dataintegration baseret på kompatibilitets og interoperabilitets stilgange og fremhæver fem erfaringer fra udviklingen og anvendelsen af case-projekterne. Derefter fokuserer forskningen på at identificere og karakterisere forskellige brugere af teknologi og deres karakteristika i forhold til datahåndteringstilgange. Resultaterne peger på tre brugere: (1) udklipsholderen, der manuelt kopierer og indsætter data fra den ene applikation til den anden for at udføre LCC-beregninger, (2) regnearkseksperten, der foretrækker at importere og eksportere data mellem regnearksbaserede værktøjer og (3) programmøren, der bruger programmeringssprog til at automatisere dataintegration mellem værktøjer. Viden om de forskellige brugere af teknologier afslører forskellige tilgange til at integrere LCC i designpraksis.

Som konklusion giver denne forklarende undersøgelse ny indsigt i omkostningsberegningspraksis ved at identificere udfordringerne ved den LCC begrænset indførsel i aktivitetssystemet for bygningsdesign og fremhæve muligheder for at øge LCC-indførslen i AECO-industrien gennem samspillet mellem aktivitetssystemet for bygningsdesign og bygningsdriftens aktivitetssystem. Desuden forbedrer forskningen vores viden om potentielle LCC-brugere og deres karakteristika om brugen af teknologi og datahåndteringstilgange. Resultaterne af denne forskningsundersøgelse bidrager til forskersamfundet ved at tilføje elementer til den eksisterende litteratur og udpege relevante forskningsmuligheder, og kan bruges af praktikere til at transformere nuværende designpraksis og bygge nyttige værktøjer samt kan bruges af politiske beslutningstagere til at udvikle nye standarder og regler for LCC.

Acknowledgement

First of all, I would like to express my deepest appreciation to all my three supervisors: Kim Haugbølle, Søren Nielsen, and Jan Schipull Kauschen. Each one has significantly contributed to successfully completing this PhD study.

I am grateful to Kim for the time he spent on our countless meetings, his continued support, and his advice throughout those four years. Thank you, Kim, for being there any time I needed your assistance and for all the guidance, the effort, and motivation you offered me when I was stuck. Thank you for reviewing and critically commenting all my research papers. Thank you for all the opportunities that you gave me and helped me to become a better student, researcher, and person.

I am thankful to Søren for the intriguing discussions on my research topic and its relevance for Vandkunsten Architects. Thank you, Søren, for expressing your interest and excellent thoughts on my PhD projects, and for motivating me by showing me that my research is very useful and relevant to Vandkunsten Architects, when I was in doubt. I am grateful for all the advice that you gave me and for being there when I needed help.

I am grateful to Jan for the interesting and long discussions around sustainability in architecture and his innovative ideas around LCC and its application. Thank you, Jan, for your enthusiasm and positive attitude throughout my research study, and for always being willing to help me overcome any possible obstacle. Thank you for giving me constructive feedback and guidance whenever I needed it.

This endeavor would not have been possible without the active participation of the employees in Vandkunsten Architects. I would like to thank each one of you for your engagement as well as your openness and willingness to participate in interviews, surveys, and workshops. I very much appreciate the time you have spent sharing your knowledge and experience about the design practices and Vandkunsten projects. Your contribution was essential for completing this research.

I am also grateful to the researchers at the Department of the Built Environment at Aalborg University who spent time discussing and giving feedback to my research project. Thanks to all of you that you offered me your professional or moral support so I could undertake and finalize my study.

Moreover, I would like to acknowledge all reviewers of my published papers and the researchers that I met in conferences who all contributed on improving my research papers by giving me constructive feedback. Thank you for your interest in my research study and for contributing to publishing my work.

Finally, I would like to thank my family and friends, who supported and motivated me to complete this PhD study. I am especially thankful to my father Manos for his great belief in me and his passion for my success and the completion of my PhD –

he believed that more than me. I am also very grateful to my husband Theodoros, who continuously encouraged me to study harder and helped me keep my spirits and motivation high so I could complete this work. Thank you, Theo, for supporting all my choices in my research study and for standing tall for all my achievements.

List of papers

This PhD thesis is based on seven research papers that are listed below in chronological order according to their publication dates. Three of them, listed as Paper A, F and G, have been published in or submitted to journals, while four of them, listed as Paper B, C, D and E, have been published in conference proceedings.

Paper A

Saridaki, M., Psarra, M. and Haugbølle, K. (2019) "Implementing life-cycle costing: data integration between design models and cost calculations". *Journal of Information Technology in Construction (ITcon)*, Vol. 24, pg. 14-32, http://www.itcon.org/2019/2

Paper B

Saridaki, M. and Haugbølle, K. (2019). "Identifying Contradictions of Integrating Life-Cycle Costing in Design Practices", *In: Lill, I. and Witt, E. (Eds.), "10th Nordic Conference on Construction Economics and Organization",* 7-8 May 2019, University of Tallinn, Estonia. Emerald Reach Proceedings Series, Vol. 2, 33–9.

Paper C

Saridaki, M. and Haugbølle, K. (2019) "Identifying LCC user types using the concept of Personas", *In: CIB WBC 2019: "Constructing Smart Cities", 17-21 June 2019, The Hong Kong Polytechnic University, Hong Kong, China.* CIB Proceedings pp. 4202 – 4212.

Paper D

Saridaki, M. and Haugbølle, K. (2020) "Towards sustainable design: Integrating data from operation of buildings in design practices". *In Conference Proceedings:* World Sustainable Built Environment online conference BEYOND 2020: 2- 4 November 2020. Wallbaum, H., Hollberg, A., Thuvander, L., Fermenias, P., Kurkowska, I., Mjörnell, K. & Fudge, C. (red.). IOP Publishing, 4 s. 052051.

Paper E

Saridaki, M. and Haugbølle, K. (2020) "Informing early-stage design through LCC data". *In Proceedings of the 36th Annual ARCOM Conference. Scott, L. & Neilson, C. J. (red.). Association of Researchers in Construction Management, s. 655-664.*

Paper F

Saridaki, M. and Haugbølle, K. (2022) "Recognizing the diversity of users of life cycle costing through personas". *Journal of Information Technology in Construction (ITcon)*, Vol. XX, pp. xx-xx (submitted for publication).

Paper G

Saridaki, M. and Haugbølle, K. (2022) "Transforming the activity systems involved in building design to include LCC". *Construction Management and Economics*, Vol. XX (X), pp. xx-xx. (Submitted for publication).

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List of Abbreviations

AECO	Architecture, Engineering, Construction and Operation
AT	Activity Theory
BIM	Building Information Modelling
LBF	"Landsbyggefonden", in English: National Building Foundation
LCC	Life-cycle Costing
SA	Structured analysis
RQ	Research Question
UCD	User-centered design
WLC	Whole life-cycle cost
WP	Work Package

1. Introduction

1.1 Introduction to the topic

The new sustainable building class in the Building Regulations 2020 is an important driver in achieving the 17 sustainability goals of the United Nations (UN). Sustainable design considers environmental, economic, and social assessments of buildings throughout their lifetime. Life-cycle costing (LCC) is a methodology that promotes life-cycle perspective on buildings, and it is used in the Architecture, Engineering, Construction and Operation (AECO) industry as a decision-making tool that enables comparison between alternative solutions that have different cash flows over time. LCC is guided by the international standards CEN (CEN, 2012) and ISO (ISO, 2017), many industrial guidelines (e.g., Caplehorn, 2012; Dhillon, 2010; Farr, 2011), and several tools (Sørensen *et al.*, 2016) (Saridaki *et al.*, 2019). However, the concept faces weak adoption in the AECO industry due to several challenges regarding data accuracy and the current design practices (e.g., Bird, 1987; Cole and Sterner, 2000; Fu et al., 2007; Gluch and Baumann, 2004; Marshall, 1987; Ruparathna and Hewage, 2015) (Saridaki *et al.*, 2019).

In recent years, notable new trends have greatly revitalized the focus on LCC in AECO industry. First, the increased interest on sustainability and sustainable constructions has fostered the focus on LCC. LCC is part of various certification schemes, like LEED and DGNB. To support integration of LCC in sustainable practices, new integrated methodologies of LCC have been developed (Du, 2015; Hoogmartens *et al.*, 2014). LCC is becoming an integral part of assessing new façade materials (Samani *et al.*, 2018), new technologies like heat pump concepts (Paiho *et al.*, 2017) and new sustainable design principles (Wei *et al.*, 2016), and optimizing energy retrofit of existing buildings (Copiello *et al.*, 2017). Moreover, procurements policies and regulations are pushing for an increased use of LCC through the European Procurement Directive from 2014 (European Commission, 2014), national regulation for using LCC in public constructions (Bygningsstyrelsen, 2017), the new sustainable building class in the Danish Building Regulations 2020 (Mortensen *et al.*, 2018), and the upcoming Danish Building Regulations of 2023 (Bolig- og Planstyrelsen, 2021) (Saridaki *et al.*, 2019). Research has provided a centralized source of reference for the calculation assumptions concerning key input parameters (Goh and Sun, 2016) and identified factors causing uncertainties during the building' s operation (Arja *et al.*, 2009). Furthermore, studies have examined the potential of using standards in green public procurement to drive innovation (Rainville, 2017) and have developed models to support decision making including LCC for energy-efficient improvements of entire buildings (Junghans, 2013).

Despite this revitalized focus on LCC, its integration into design practices continues to be a significant challenge for firms like Vandkunsten Architects. This PhD study will provide new insights on the challenges and opportunities of applying LCC in design practices. This will be achieved by: (1) mapping the facilitating and hindering factors of LCC in current design work processes, (2) exploring actions and interactions between building design and operation towards LCC, and (3) discussing how to stimulate integration of LCC in design practices.

1.2 Project description and research questions

The PhD project applies an understanding and explanatory approach reflected in three work packages aimed at understanding the current design practices, identifying interaction between design and operation, and discussing possible actions to support integration of LCC in design practices. This project was carried out in three interdependent work packages (WP1-3) corresponding to the main objectives of the study:

- Work Package 1: Understanding factors and conditions facilitating or obstructing life-cycle costing in current design practices.
- Work Package 2: Identifying interaction between building design and building operation.
- Work Package 3: Discussing how to support the integration of LCC in design practices.

In the following sections, the three work packages are described along with their research questions, objectives, methodology, and results.

WP 1: Understanding factors and conditions facilitating or obstructing life-cycle costing in current design practices

Research Question: How does the activity system of building design facilitate or obstruct life-cycle cost calculations in design practices?

Objectives: WP1 focuses on understanding the current design practices of the Vandkunsten Architects and identifying factors that facilitate or obstruct the implementation of life-cycle cost calculations. Hence, the objectives of this study are as follows:

- To improve our understanding of current cost calculation in design practices,
- To identify challenges in the work processes and data management approaches that obstruct the LCC integration in the AECO, and
- To recognize opportunities for transferring information and data with regard to LCC between Vandkunsten Architects and particular building clients.

Methodology: WP1 follows two different approaches for analyzing the current practices and meet the research objectives. It starts by drawing on social-constructivist work on calculative practices and uses activity theory as the theoretical framework for mapping and understanding the cost calculation practices in

Vandkunsten Architects as part of the activity system of building design and for identifying contradictions between its elements. The study relies on qualitative analysis of data from documents, observations, and interviews in Vandkunsten Architects (Kvale and Brinkmann, 2009). Then, structured analysis is used as an information analysis methodology for analyzing the activities of social housing projects, which are a particular interest of Vandkunsten Architects, in a physical and logical way (Congram and Epelman, 1995). To model the system of social housing projects, data was gathered through observations, qualitative research interviews, and analysis of documents and physical artefacts.

Results: The outcome of WP1 includes the identification of challenges in the current work practices and provides the foundation for WP2 that focuses on enablers of LCC in the design practices. The results of WP1 include:

- **Paper B:** Saridaki, M and Haugbølle, K (2019) "Identifying Contradictions of Integrating Life-Cycle Costing in Design Practices", *In: Lill, I. and Witt, E. (Eds.), "10th Nordic Conference on Construction Economics and Organization",* 7-8 May 2019, University of Tallinn, Estonia. Emerald Reach Proceedings Series, Vol. 2, 33–9.
- **Paper D:** Saridaki, M and Haugbølle, K (2020) "Towards sustainable design: Integrating data from operation of buildings in design practices". *In Conference Proceedings:* World Sustainable Built Environment online conference BEYOND 2020: 2- 4 November 2020. Wallbaum, H., Hollberg, A., Thuvander, L., Fermenias, P., Kurkowska, I., Mjörnell, K. & Fudge, C. (red.). IOP Publishing, 4 s. 052051.

WP 2: Identifying interaction between building design and building operation

Research Question: To what extent do current actions between the activity system of building design and construction and the activity system of building operation support data exchange regarding LCC?

Objectives: WP2 focuses on identifying actions through the interaction between building design and operation that enable LCC consideration throughout the building project lifetime. The objectives of WP2 are as follows:

- To identify actions and interaction that enable data utilization and exchange with regards to LCC throughout the lifetime of a building project, and
- To reflect on the need of possible change in the activities of building design and building operation to ensure integration of LCC.

Methodology: Similar to WP1, WP2 follows an exploratory and explanatory approach for identifying actions and understanding why and how those actions can further support LCC integration. Thus, structured analysis is used as an information analysis methodology to further explore the processes of a particular type of project of Vandkunsten Architects and to identify LCC cost-related data flowing between the design processes. Furthermore, activity theory is used as theoretically grounding, but this time the focus is on the interaction between two activity systems: the activity system of building design and construction and the activity system of building operation. The research methodology includes a case study analysis with two embedded case studies of Vandkunsten Architects and the data collected through interviews, direct and participant observations, and analysis of physical artefacts.

Results: The outcome of WP2 will provide the foundation for improving LCC integration in the design practices of Vandkunsten Architects. The results of WP2 include:

- **Paper E:** Saridaki, M and Haugbølle, K (2020) "Informing early-stage design through LCC data". *In Proceedings of the 36th Annual ARCOM Conference. Scott, L. & Neilson, C. J. (red.). Association of Researchers in Construction Management, s. 655-664.*
- **Paper G:** Saridaki, M. and Haugbølle, K. (2022) "Transforming the activity systems involved in building design to include LCC". *Construction Management and Economics*, Vol. XX (X), pp. xx-xx. (Submitted for publication).

WP 3: Discussing how to support the integration of LCC in design practices

Research Question: Which novel actions may stimulate integration of LCC in design practices?

Objectives: WP3 focusing on supporting the design of actions towards LCC consideration by focusing on understanding the characteristics of current and potential LCC users in Vandkunsten Architects and data management approaches. The objectives of WP3 are as follows:

- To develop, test, and summarize lessons learned from different methods of data integration based on compatibility and interoperability approaches, and
- To identify and characterize different users of technology and their characteristic, work processes, and data management approaches.

Methodology: While WP1 and WP2 focus on contradictions and opportunities in the activities of building design and operation, WP3 focuses on the technical aspect of data integration and on people as current or potential LCC users. When developing methods of data integration, the research approach includes a literature review, a few interviews, and three case projects for testing the developed methods. When focusing on people, the user-center design (UCD) method is used to characterize different user types and identify their characteristics in work practices and data management approaches. Data was collected through observations, interviews, and a quantitative survey.

Results: The outcome of WP3 sets the knowledge about users and data management approaches that can be used for creating more relevant tools and processes towards LCC in the AECO. The results of WP2 include:

- **Paper A:** Saridaki, M., Psarra, M. and Haugbølle, K. (2019) "Implementing life-cycle costing: data integration between design models and cost calculations". *Journal of Information Technology in Construction (ITcon)*, Vol. 24, pg. 14-32, http://www.itcon.org/2019/2
- **Paper C:** Saridaki, M and Haugbølle, K (2019) "Identifying LCC user types using the concept of Personas", In: CIB WBC 2019: "Constructing Smart Cities", 17-21 June 2019, The Hong Kong Polytechnic University, Hong Kong, China. CIB Proceedings pp. 4202 – 4212.
- **Paper F:** Saridaki, M. and Haugbølle, K. (2022) "Recognizing the diversity of users of life cycle costing through personas". *Journal of Information Technology in Construction (ITcon)*, Vol. XX, pp. xx-xx (submitted for publication).

The following table (Table 1) provides an overview of the research papers that predominately focus on answering the RQs under the three work packages. However, others among the seven papers may have also contributed on answering each of the three RQs. For instance, Paper A (Saridaki *et al.*, 2019) is aimed at answering RQ3; however, the findings reveal some input that also contributes to answering RQ1.

Table 1. Overview of the papers includes in the thesis and the work-packages that are related to.

WP/ RQ	Paper	Short Citation	Research-aim of the paper
1	B	Saridaki, M and Haugbølle, K (2019) "Identifying Contradictions of Integrating Life-Cycle Costing in Design Practices"	To improve the understanding of the cost calculations in the design practices as an activity system with several built-in contradictions.
	D	Saridaki, M and Haugbølle, K (2020) "Towards sustainable design: Integrating data from operation of buildings in design practices"	To explore the collaboration between architects and building clients and explain how it supports or inhibits LCC calculations.

2	E	Saridaki, M and Haugbølle, K (2020) “Informing early-stage design through LCC data”.	To investigate how O&M data from existing projects can be used to inform the design of new projects.
	G	Saridaki, M. and Haugbølle, K. (2022) “Transforming the activity systems involved in building design to include LCC”	To identify actions of data utilization and exchange towards LCC between the activities of building design and building operation.
3	A	Saridaki, M., Psarra, M. and Haugbølle, K. (2019) “Implementing life-cycle costing: data integration between design models and cost calculations”	To develop and test two different methods of data integration between design models and cost calculation tools for implementing LCC calculation.
	C	Saridaki, M and Haugbølle, K (2019) “Identifying LCC user types using the concept of Personas”	To recognize current and potential LCC users and their characteristics in work processes, aspiration, and needs.
	F	Saridaki, M. and Haugbølle, K. (2022) “Understanding the diversity of users of life cycle costing through personas”	To improve the understanding on diversity of users of technology and their different approaches on data integration.

1.3 Research scope and limitations

The scope of this research study is to improve the understanding of and to get new insights about the status of LCC in the AECO industry by identifying challenges and opportunities for LCC implementation as well as discussing how to further support LCC integration. Thus, this research is explanatory and focuses on explaining the causes and consequences of a well-defined problem, the limited LCC adoption in the AECO industry. Specifically, in WP1 & the research focuses on improving our understanding of why a particular phenomenon occurs, and in WP3 on discussing how knowledge about users and data management can be used for future improvements.

Before starting this PhD research, the author performed an analysis on the different stakeholders of LCC tools, and identified three main stakeholders: tool providers, users, and clients (Saridaki and Haugbølle, 2022a). The three main stakeholders are assessed based on the influence and impact on LCC implementation. The assessment indicated that LCC users have both high interest and influence on LCC adoption in the AECO industry, while tool providers high interest but low influence, and clients low interest and high influence. Therefore, the author decided to focus on LCC users, and specifically architects and building designer of Vandkunsten Architects.

The research study uses Vandkunsten Architects as the main case study under examination with several embedded sub-case projects that are Vandkunsten' s internal projects. Thus, the author approaches the research mainly from the design perspective since the employees in Vandkunsten Architects are architects and building designers.

Although the researcher uses Vandkunsten Architects as the center of the research and focuses on LCC integration in the design practices, the study is not limited to design when it comes to social housing projects and the research under WP2. To answer RQ2, the author examines not only the design but also the operation practices, since it is proved to have significant influence on LCC adoption. Specifically, the collaboration between design and operation and the exchange of LCC related data may contribute on increase LCC implementation (this topic is further analyzed and discussed in Papers D, E and F (Saridaki and Haugbølle, 2020a, 2020b, 2022a)). Therefore, the analysis of social housing projects was supported by data that are collected from the building client and facility manager of the project under examination.

Moreover, as it is stated above, the research does not focus on tool providers. However, LCC integration in the design practices is also affected by the tools and methods that are used in the AECO industry. In WP3, the author focuses on different data management approaches and on understanding the characteristics of users and their tool requirements. Thus, the discussion on RQ3 is relevant for LCC tool providers since it reveals insights about current or potential LCC users that can be used for developing useful and effective tools and methods.

1.4 Structure of the thesis

This paper-based thesis consists of seven papers and a synopsis that are all linked together in order to achieve the research aim of investigating new calculation practices for life-cycle costing. The synopsis is structured in six chapters as follows:

Chapter 1: Introduction
The first chapter introduces the reader to the concept of life-cycle costing and to the status of LCC in the Danish AEC industry along with the opportunities and challenges for its adoption in practices. Moreover, the PhD project is described in this chapter, along with the objectives of the study and the research questions. The scope of the research is also discussed.

Chapter 2: Theoretical background

This chapter provides a theoretical background on LCC methodology presenting the different purposes of LCC analysis and the requirement of data. In addition, the current application of LCC is presented.

Chapter 3: Methodology
This chapter outlines the methodology used in this research project. First, the theories and tools used to support the research are presented. Then, the research design is described as well as the research methods and data collection are presented. At the end of this chapter, the quality of the research is assessed with regards to the four types of validity.

Chapter 4: Findings
This chapter presents a summary of the seven papers. Each paper is presented based on the following four elements: the purpose of the research, the methodology, the findings, and the conclusion.

Chapter 5: Discussion
This chapter discusses the findings of the papers and part of the research that it is done but not published. Moreover, it discusses on how the results are linked to each other and answers the research questions.

Chapter 6: Conclusion and contribution
The final chapter concludes the thesis by answering the main research questions of this study. It also outlines the contribution of this study to the literature and consequences or practices. At the end of the chapter, future research is proposed.

2. Theoretical background – state of the art

2.1 Life-cycle costing

There are different terms that are used in both the literature and the industry for describing the economic consideration in the long term, such as the total cost of ownership (TCO), cost in use, life-cycle cost (LCC), whole life-cycle cost (WLC), and whole life appraisal (WLA), where the last three are the most common in use today (Flanagan *et al.*, 1989).

The ISO 15686-5 Service Life Planning, Part 5: Life-cycle costing (ISO, 2017) differentiates the terms WLC and LCC as described in Figure 1. LCC covers “a defined list of costs over the physical, technical economic or functional life of a constructed asset, over a defined period of analysis” (ISO, 2017, pg. 6) including also environmental costs that may have an either negative or positive effect, for instance cost of taxes or income from renewable energy generation, respectively. WLC covers LCC, non-construction costs, as well as wider occupancy costs and local, national, or international policies, allowance, taxes etc.

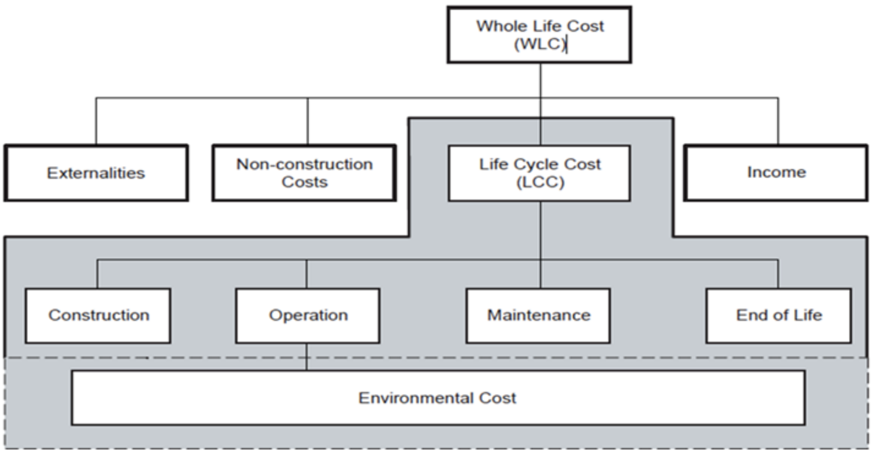

Figure 1. WLC and LCC elements (adopted after ISO, 2008)

Life-cycle costing (LCC) is a methodology of systematically assessing life-cycle costs over a period of analysis that is defined as “an economic assessment considering all agreed projected significant and relevant cost flows over a period of analysis expressed in monetary value. The projected costs are those needed to achieve defined levels of performance, including reliability, safety, and availability” (ISO, 2017). LCC is a valuable decision-making tool since it can be used to compare alternative design solutions that have different cost effect over time based on several key factors such as cost, quality, and comfort (Collier, 2009; Dell'Isola and Kirk, 2003; Flanagan *et al.*, 1989; Norman, 1990).

LCC has been used to serve different purposes, including the following:

- For assessing different investment scenarios, including deciding between renovating an existing building or investing in a new construction,
- For evaluating different design alternatives for either the entire building or main building components,
- For selecting between different design materials that have different maintenance specifications and lifetime,
- For confirming or benchmarking previous decisions in design or choice of materials and
- For estimating future costs for planning and budgeting.

Thus, there are several benefits of applying LCC in all different stages of a building project lifetime: idea and planning, design and construction, operation, and end of life (ISO, 2017). Some of the key benefits of LCC implementation includes the contribution of improving risk management and decision-making processes since it offers a systematic and measurable analysis of comparing and selecting between competitive alternatives (Lansink, 2013) as well as cost reduction in the long term (Norman, 1990).

2.2 Life-cycle costing application in practices – limitations & barriers

Although there are increased benefits of LCC application, the literature has identified several challenges of LCC adoption in practices. The main challenges are discussed below and summarized in Table 2.

Although buildings are long-term investments, usually building clients are focused on short-term costs (Higham *et al.*, 2015), and they do not recognize the benefits of applying LCC in order to assess investment scenarios (Gluch and Baumann, 2004). In addition, many the stakeholders in the AECO industry show little awareness of sustainability and sustainable design (Chiurugwi *et al.*, 2015; Olsson *et al.*, 2015; Olubodun *et al.*, 2010).

Moreover, many practitioners lack of understanding of LCC definition and concept (Gluch and Baumann, 2004), while others pinpoint that there is high complexity in performing LCC calculations, and considering the level of uncertainty, they prefer to rely on empirical judgment (Lansink, 2013).

Although there is a variety of tools for LCC (Sørensen *et al.*, 2016), the available tools are not usable (Goh and Sun, 2016; Olubodun *et al.*, 2010) and they lack automated procedures for calculations (Saridaki *et al.*, 2019). Therefore, LCC implementation becomes a time-consuming task that is prone to human errors (Fu *et al.*, 2004;

Hunter *et al.*, 2005). Also, there are limited standards and formal guidelines indicating how and when to perform LCC analysis (Goh and Sun, 2016; Kehily and Underwood, 2017; Olubodun *et al.*, 2010). Besides, LCC tools require several data from different stakeholders (Saridaki *et al.*, 2019), and there is not any standardized methodology on how to exchange life-cycle data (Chiurugwi *et al.*, 2015; Monteiro and Martins, 2013; Saridaki *et al.*, 2019).

Furthermore, one of the main challenges of LCC limited adoption is related to the lack of available and reliable data (Fu *et al.*, 2004; Gluch and Baumann, 2004; Oduyemi *et al.*, 2014; Salvado *et al.*, 2018). The issue of data availability is even more critical in early design phases of building projects where the decision-making process has more significant impact (Dhillon, 2010). According to Lansink (2013), when LCC is implemented in early phases, the calculations are based on assumptions that may lead to inaccurate results. Inaccurate results may also be related to the limited collaboration between LCC practitioner and the design team in building practices (Plume and Mitchell, 2007; Saridaki and Haugbølle, 2019a).

Lastly, although the opportunities offered by BIM for increasing data management and automation (Chiurugwi *et al.*, 2015), BIM is not fully adopted in the building design, and in cases where it is used the design models are not robust and reliable and thereby, automation of LCC calculations is challenging (Edirisinghe *et al.*, 2017; Saridaki *et al.*, 2019; Saridaki and Haugbølle, 2019a).

Table 2. Main challenges of LCC limited adoption in the AECO industry as identified in the literature.

Challenges of LCC limited adoption in building design practices	**References**
Lack of understanding of LCC definition and concept	(Cole and Sterner, 2000) (Gluch and Baumann, 2004)
Lack of reliable/accurate cost data	(Gluch and Baumann, 2004) (Fu *et al.*, 2004) (Oduyemi *et al.*, 2014) (Salvado *et al.*, 2018)
Little awareness on sustainability	(Olubodun *et al.*, 2010) (Chiurugwi *et al.*, 2010) (Olsson *et al.*, 2015)
Limited understanding of the benefits of LCC	(Gluch and Baumann, 2004)
Consideration of short-term horizon of building investments	(Higham *et al.*, 2015)
Lack of usable tools	(Goh and Sun, 2016) (Olubodun *et al.*, 2010)
Lack of automate procedures for calculation	(Saridaki *et al.*, 2019)

Complex / Time-consuming task/ Prone to human error	(Fu *et al.*, 2004) (Hunter *et al.*, 2005) (Lansink, 2013)
Lack of standards and formal guidelines	(Olubodun *et al.*, 2010) (Goh and Sun, 2016) (Kehily and Underwood, 2017)
Lack of standardized methodology for exchanging life-cycle data	(Monteiro and Martins, 2013) (Chiurugwi *et al.*, 2015) (Saridaki *et al.*, 2019)
Challenges on establish robust and reliable models for automating the LCC calculations	(Edirisinghe *et al.*, 2017) (Saridaki *et al.*, 2019) (Saridaki and Haugbølle, 2019a)
Lack of collaboration between LCC practitioner and design team	(Plume and Mitchell, 2007) (Saridaki and Haugbølle, 2019a)
Limited communication in decision-making process	(Saridaki and Haugbølle, 2019a)
Limited use of BIM in building design	(Saridaki and Haugbølle, 2019a)

2.3 Application of LCC in Denmark

There are several tools that are used for calculating LCC of entire buildings or building components in the AECO industry (Sørensen *et al.*, 2016). Most of the tools have a spreadsheet format since it is user-friendly and easy to operate; however, there are also stand-alone applications and web-based tools (Sørensen *et al.*, 2016). In Denmark, LCC practitioners use different tools that serve different purposes.

In order to comply with certifications and perform calculations, Danish practitioners are extensively using the LCCbyg application. LCCbyg is developed by the former the Danish Building Research Institute at Aalborg University (AAU) on behalf of the Danish Transport, Construction and Housing Agency (LCCbyg, 2022). It is a tool used to calculate and assess the life-cycle cost of either an entire building or individual building components, and it also supports DGNB certification in Denmark. The tool calculated the net present value of the different alternative solutions as well as the different cost groups or income types. LCCbyg has a user-friendly interface and includes various default values as well as various groups for building types and building elements, while it offers flexibility to customized calculation. Moreover, the results can be summarized in a report that can include various illustration, figures, and tables and can be exported in different formats.

In addition, it is mandatory for all social housing and public buildings in the Danish AECO industry to perform LCC calculations for both renovation and new construction (Bygningsstyrelsen, 2017). Therefore, Danish practitioners use the web-based tool (https://totaloekonomi.lbf.dk/), that is developed by the national building foundation (in Danish: Landsbyggefonden, abbreviated LBF). The LCC tool is used to perform economic assessment and calculate the net-present value (NPV) of three main building components (windows, façade, and roofs) since those components constitute the majority of costs in both construction and operation. The data required to perform an LCC assessment is the construction cost, the maintenance activities, and intervals, along with maintenance cost as a percentage of the construction cost and the lifetime of the components/materials under examination. The tool includes default values for various components under those three categories; however, there is a possibility to change the values if it is required. Practitioners should use the tool to assess at least two different alternatives for each of the building components.

In the following, Table 3 will present a comparison between the LCCbyg and LBF tool.

Table 3. Comparison of commonly used tools in the Danish AECO: LCCbyg and LBF tool,

LCCbyg	**LBF tool**
Stand-alone application	Web-based tool
LCC calculation of all components	LCC calculation of specific components
Include default values	Include default values
Compare alternative design solutions for both the entire building and individual building components	Compare different alternatives of the same components
Graphical representation of the results (figures, illustrations, tables)	Numerical results are summarized in a table
Results can be exported in various forms (pdf, spreadsheet, cvs file)	Results are exported in pdf file
Comply with DGNB certification	-

3. Methodology

This chapter outlines the theoretical and research methodologies used during the three years of the research study. Specifically, the author starts by presenting the theories and tools applied throughout the three work packages and reflects on their benefits and relevance. Then, it is followed by a discussion on the research approach and methods, including data collection and analysis applied in this study to answer the research questions.

3.1 Theories and tools

Throughout the study, different theories and tools were used to meet the objectives of the three work packages and answer the research questions: activity theory, structured analysis, and user-centered (UCD) design methods (Table 4).

Table 4. Overview of the theories and tools used in each research paper and work package.

WP1	Paper B	Activity theory
	Paper D	Structured analysis
WP2	Paper E	Structured analysis
	Paper G	Activity theory
WP3	Paper A	-
	Paper C	UCD, Personas
	Paper F	UCD, Personas

Activity theory was used in WP1 and WP2 as a methodology for describing and explaining the activities of building design and building operation in the case projects under examination. Structured analysis was also used in both WP1 and WP2 as an information analysis tool to describe the processes of social housing projects and map the data flowing through them. UCD and particularly the methodology of constructing personas that is proposed by Cooper (Cooper *et al.*, 2014) was used in WP3 to develop different LCC user types in Vandkunsten Architects.

Usually, theory is integral to research and research is integral to theory. It is important to mention that the theories and tools that were used did not guide this research, since this research is based on practices. However, the theories and tools were used as methodologies and contributed on structuring and presenting the research analysis in a more consistent and systematic way.

The following sub-sections present the three above-mentioned theories.

3.1.1 Activity theory

Activity theory (AT) is used in this study both as a theoretical framework for understanding the current LCC calculation in design practices in the case study under examination, contributing on answering RQ1 but also as an analytical tool for underpinning the interaction of actions towards LCC between the activity systems that interact throughout the lifetime of building projects, contributing to answering RQ2.

AT, also known as cultural historical activity theory (CHAT) was introduced by two Russia phycologists, Lev Vygotsky (Vygotsky, 1978) and Alexei Leont'ev (1978) in the early 1920s and further developed by Engestrom (Engeström, 1987) some decades later. AT empathizes the important of focusing on human activities rather than individual actions when analyzing organization settings (Boer *et al.*, 2002), and provides a theoretical framework for describing the structure, the content, and the development of a human activity (Bertelsen and Bødker, 2003).

AT was originally designed for human-computer interaction analysis, but today is used as a broaden cross-disciplinary analytical framework for different forms of human practices (Kuutti, 1996). It has been proven beneficial for project-based organizations. In construction industry, AT has been used for describing and analyzing the interaction and complexity of actions in projects and for development of tools and applications (Lu *et al.*, 2018).

According to the initial model, an activity is described through the interaction between an individual or organization (Subject) and a row material or problem space (Object) mediated by tools and signs (Tools) (Engeström, 1987). By emphasizing the collective nature of human activity, Engeström (1987) expanded the original model by introducing three additional elements, namely Rules, Community, and Division of Labor, that frame the analysis of human behavior in a more consistent and systematic way. Figure 2 presents the triangle of an activity system along with its elements.

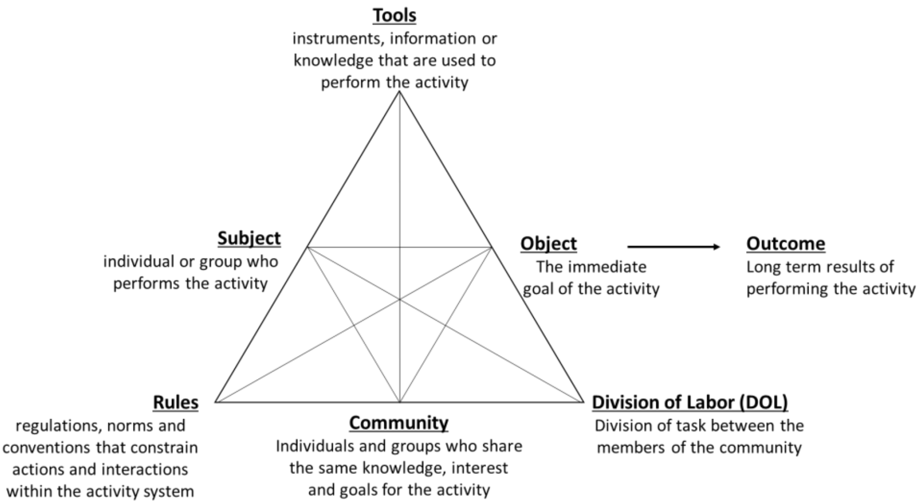

Figure 2. Model of an activity system (adopted after Engeström, 1989).

In a building design activity, the elements of the activity systems can be described as following (further explained in Paper G, (Saridaki and Haugbølle, 2022, submitted for publication)):

- **Subject**: Group of architects and engineers, including LCC practitioners as part of the group
- **Object**: Sustainable building design
- Outcome: Building construction that meets the requirements of clients/users
- **Tools**: Modeling and design tools (e.g., Revit, Sketch up), calculation tools (e.g., Sigma Estimates, LCCbyg, LCAbyg), spreadsheets, etc.
- Community: AEC industry, building clients, engineers, consultants, etc.
- **Rules**: Building regulations, ISO standards, procurement policies, certification schemes, guidelines and manuals, etc.
- **Division of Labor (DOL)**: Horizontal division of tasks internally between the subjects and externally between the subjects and the community and vertically between the subjects and the community

There are five basic principles that are used to help analyzing an activity system: 1) Object- orientedness, 2) Hierarchical structure of activities, 3) Mediation, 4) Internalization & externalization, and 5) Historical development (Kaptelinin and Nardi, 2006).

Based on those principles, an activity can further be analyzed by the following key terms, as discussed in Paper G (Saridaki and Haugbølle, 2022a, submitted for publication):

- Interaction
- Mediation
- Disturbances
- Contradictions
- Evolution

In this research, the above-mentioned principles are used for describing and analyzing the activity systems of the case projects under examination.

Reflection on the theory

In this research, AT is used mainly as framework for mapping the current activities of building design (In Papers B and G (Saridaki and Haugbølle, 2019a, 2022b)) and the activity system of building operation (In Paper G (Saridaki and Haugbølle, 2022b)) in a structured and methodological approach. Kaptelinin (2014) stated that AT is very useful to orientate researchers in complex problems of real-life and help them identified key issues that need to deal with and thereby, direct them on searching relevant evidence and suitable solutions. Indeed, the key benefit of AT in this research was to help the author to ask right questions when analyzing the activity system and seeking for explanations.

At first place, the AT model (presented in Figure 2) guided the author on searching and collecting relevant data to map the activity systems in the case studies under examination. It also contributes to setting a clear perspective on the activity under examination when selecting the *Subject* of the activity system.

Moreover, the use of principles and key terms mentioned in the section above supported the analysis and the data interpretation. For instance, the concept of *contradictions* in Paper B (Saridaki and Haugbølle, 2019a) contributed to analyzing the activity system and identifying links between the collected data and thus, understanding the core challenges of LCC implementation in building design.

Barnard (2010) highlights the threat of external validity when AT is applied in a single organization. However, in this research study, the author used AT to explore the content and interaction of constructs to explain and improve an identified topic and therefore, external validity and generalization are not critical.

3.1.2 User-Centered design and Personas

User-centered design (UCD) methods and specifically the concept of personas is used in this research study as a methodology for constructing LCC user personas and recognize their characteristics in work practices, contributing on answering RQ3.

UCD is a modern human-computer interaction design philosophy (LeRouge *et al.*, 2013) that focuses on end-users' requirements instead of technical requirements when developing systems (Junior and Filgueiras, 2005). UCD approaches involve the users actively in the design processes and thus, enable usable and useful products

(Ji-Ye Mao *et al.*, 2005). There are various methods used in UCD, including the concept of personas (Pruitt and Grudin, 2003).

Personas were introduced in 1999 by Alan Cooper (1999) and since then, the concept has been increasingly used in software design, product development, and marketing. There are several examples of using personas in research and practices that are summarized in Paper F (Saridaki and Haugbølle, 2022b, submitted for publication). In addition, Paper F presents many studies in which the concept of personas had been applied in the practices of the AECO industry as a tool for understanding the users and to identify potential areas for optimizations or improvements as well as designing or evaluating tools.

Personas are hypothetical archetypes that represent a group of people sharing the same characteristics, motivation, and needs (Pruitt and Adlin, 2006; Turner and Turner, 2011). Thus, personas are a representation of target users (Pruitt and Adlin, 2006) for whom designers are willing to design (Floyd *et al.*, 2008). A literature review about personas and their characteristics is presented in the study of Floyd et al. (2008) as well as in Papers C and F (Saridaki and Haugbølle, 2019b, 2022a).

There are many benefits of using personas when developing tools and processes (summarized by Chapman and Milham, 2006; Miaskiewicz and Kozar, 2011 and Paper F (Saridaki and Haugbølle, 2022b)).

In this research, the author followed the eight-principle steps of constructing personas proposed by Alan Cooper and presented below (Cooper et al., 2014, p. 82):

1. Group interview subject by role,
2. Identify behavioral variables,
3. Map subjects against behavioral variables,
4. Identify significant behavior patterns,
5. Synthesize characteristics and define goals,
6. Check for redundancy and completeness,
7. Designate persona types, and
8. Expand description of attributes and behaviors.

A further description of each of the eight steps can be found in Paper C (for steps from 1 to 4) (Saridaki and Haugbølle, 2019b) and in Paper F (all steps) (Saridaki and Haugbølle, 2022a).

Reflection on the theory

The application of LCC in the AECO industry is highly dependent on the adoption of tools and processes by the users, and therefore, it is important to ensure their active participation when developing interventions. Therefore, to answer RQ3, the study applies UCD and specifically the concept of personas to involve practitioner in the research processes. However, this study adopts an analytical approach, and by constructing personas, it aims to improve our understanding on the different users of technology instead of designing an LCC tool.

In this analytical context, the benefits of using UCD and personas are recognized in this study, since it provided valuable information on the characteristics, motivation, needs, and work processes of different type of users. The construction of personas contributed also to an understanding of how people would like to work with LCC and revealed insights into current and potential LCC users. In addition, the use of the eight steps proposed by Alan Cooper (Cooper *et al.*, 2014) as a methodological tool was quite helpful since it guided the processes of collecting as well as analyzing and synthesizing data in order to construct the personas.

The main shortcoming of applying the eight-principle steps in this study is related to the designation between the constructed personas that is suggested in step 7 of the methodology. The prioritization between persona is especially useful in design-oriented studies that aim to define the design target. However, this study aims to uncover the different users instead of narrowing the research focus to one dominant persona.

3.1.3 Structured analysis

Structure analysis (SA) is used in this research as a methodological tool to map the data flowing between the activities in social housing projects. It contributes to answering RQ1 & RQ2, by mapping the data flow and identifying actions that support collaboration and data exchange between the activities of design and operation as well as highlight data flowing between the activities of social housing projects. It should be mentioned that the use of structure analysis in this research does not have an explanatory approach; however, it used as a tool for visualizing the activities along with their actors and their control mechanisms.

SA was initiated in late 1960s as a methodology for describing complex IT systems (Ross, 1977) and it was defined as a "graphic language for blueprinting systems" with roots in "'cell modelling' of human-directed activities" (Ross, 1977, p. xii). SA became popular in the 1980s and since then it has been used to various projects in diverse industries (Congram and Epelman, 1995) aimed at analyzing systems and business requirements by viewing the activity systems from the perspective of the data flowing through them (Saridaki and Haugbølle, 2020c). According to Congram and Epelman (1995), SA is highly effective for describing services because: firstly, it focuses on activities ("building block of services") and secondly, it is the only methodology that structurally describes who or what performs the activity ("mechanisms") and what guides or limits the activity ("controls").

One of the most used tools in SA for modeling and analyzing systems is the data flow diagrams (DFDs). A set of interrelated DFDs can be used to describe a system (Wang. Lian and Raz, 1991). DFDs are arranged hierarchically and are decomposed with a top-down approach, where the top diagram summarizes the diagram below, and so, in each level the diagrams become increasingly more detailed. DFDs map the relationship between activities and data by using the following components (DeMarco, 2002) that are further described in Paper E (Saridaki and Haugbølle, 2020b):

- External elements that are represented by a rectangle.
- Processes or activities that are represented by a cycle or an oval.
- Flow of data that is represented by an arrow.
- Registers or datastores that are represented with two parallel horizontal lines.

Reflection on the tool

In this research, SA is used as a method to describe the system of social housing projects and its activities in a logical way, without providing any explanatory insights. However, the use of DFDs proved to be extremely useful for mapping the system of social housing projects and highlighting evidence that there is LCC related data flowing between the activities. Therefore, the findings in Papers D and E (Saridaki and Haugbølle, 2020c, 2020b) include DFDs that form a valuable starting point for discussing the collaboration between the actors involved in design and operation and the opportunities of developing cost driver to support early-stage design towards LCC, respectively.

3.2 Research design

The research design of this study compromises a single case study analysis. The case company under examination is the Danish architectural firm, Vandkunsten Architects. It should be mentioned that the PhD student was employed by Vandkunsten Architects during the period of the PhD project. The reason for this employment was the increased interest of the company to obtain research in the field of LCC that will be used for better integration of the concept in their practices.

However, before the beginning of the PhD project, the author conducted a preliminary analysis through which she recognized and grouped the different stakeholders of LCC and their roles. Part of the analysis is presented in Paper C (Saridaki and Haugbølle, 2019b). The analysis showed that LCC users have high interest and high influence on the adoption of LCC in the industry, and therefore it was decided that the research should focus on current and potential LCC users such as the employees in Vandkunsten Architects.

After a series of meetings and seminars, Vandkunsten Architects was selected as the case study in this project, for two main reasons. Firstly, the company consists mainly of architects and designers that are current or potentials LCC users, and therefore, they have high interest and influence on the integration of LCC in the Danish industry. Secondly, the company was really interested in this project since the results are expected to contribute to both the company's business and its earnings. Specifically, the PhD project is linked directly to Vandkunsten' s overall strategy of staying an independent business - in a business environment presently undergoing rapid and radical disruption through mergers or acquisitions for example by engineering companies - and making Vandkunsten Architects the leading practitioner of LCC calculations. Moreover, by winning architectural competitions Vandkunsten Architects generates more than 50% of the turnover. Vandkunsten Architects is willing to increase the success rate in competitions by enhancing company's sustainable profile and affecting the general mindset of the designer and producing more competitive and attractive design projects. The other half of Vandkunsten turn-overs stem from direct sales to clients. It is estimated that more clients will procure sustainable buildings due to the new voluntary sustainable building class in the upcoming building regulation. And finally, the results of the project will increase the earning of the company since the project target a field of particular interest to professional clients.

Vandkunsten Architects came to be a paradigmatic case study for investigating the LCC adoption in the Danish design practice, since (Saridaki and Haugbølle, 2019a):

(i) the type and size of Vandkunsten Architects is typical,
(ii) the process applies a range of elements that are typical of cost calculations during design, and
(iii) the firm and its projects reveal contradictions caused by LCC when applied in design.

The collaboration with Vandkunsten Architects and the execution of the PhD project took place for three years and three months, from May 2018 to August 2021.

3.2.1 The case

Vandkunsten Architects is a Danish company founded in 1970 by five young and passionate architects. Today, the highly innovative company consists of five partners and employs some 70 highly skilled and dedicated employees. Vandkunsten Architects is located in a converted workshop building in Copenhagen (https://vandkunsten.com).

The leading position of Vandkunsten Architects kicked off from the very start by winning the national competition for low-rise/high-density residential architecture (in Danish: "*tæt/lav*"). Only a few years later, the popular and iconic non-profit housing experiment Tinggården was built, which has served as both a national and international exemplar of low-rise/high-density housing. Since the establishment, Vandkunsten Architects has successfully won a substantial number of architectural competitions and have produced a number of significant projects with respect for sustainability.

By focusing on people and being committed to their own beliefs that good architecture have the ability to make society livable, Vandkunsten Architects work within the full range of architectural practices. The company handles diverse projects of landscape and city planning, new buildings, and urban renewals and renovation of both residential and commercial buildings. The activities expand outside of Denmark to the nearest markets of Scandinavia and northern Europe.

Some of their dominant projects include the urban transformation of iconic Christiania, the multi-purpose building Hamar Cultural Centre in Norway, the eco-label houses with façades of recycled brick on the Harbour Cove project, Circle House (upcycling) and an experimental house built of seaweed. Throughout the almost 50 years of experience, Vandkunsten Architects have achieved plentiful national awards like *RENOVERprisen* for best refurbishment project, Nykredit' s Sustainability Prize, the *Eckersberg* Medal and the *Nykredit* Prize. Moreover, they have gained international recognitions such as the *Kasper Salin Prize*, *Fritz Schumacher Medal*, *Sveriges Arkitekters Bostadspris* and the *Alvar Aalto Medal*. In addition, the firm has been nominated five times for the prestigious *Mies van der Rohe Award* (https://vandkunsten.com/en/approach).

3.3 Research methods and data collection

Throughout the research study, different methods are used to answer the research questions. Specifically, the authored followed different research methods for collecting the data required to answer the research questions, including subject focused literature review (I), multiple sub-case analysis (I & II), a multiple test case approach, and main case study analysis. All those steps are continuously supported by literature review II, for instance regarding the theories and tools that are used. Table 5 presents an overview of the research methods under each work package and research paper.

Table 5. Overview of the research methods used in each research paper and work package.

WP/RQ	Paper	Research methods	
1	B	Literature review I & Multiple sub-case analysis I	Literature review II
	D	Multiple sub-cases analysis II	
2	E	Multiple sub-cases analysis II	
	G	Multiple sub-cases analysis II	
3	A	Multiple test-case analysis	
	C	Single main case study analysis	
	F	Single main case study analysis	

In order to gather data throughout the different research items, the author used different methods. Specifically, the most used sources for data gathering in case studies analysis as presented by Yin (Yin, 2018) are used in this study, and this includes direct observations, participant observations, interviews, documents, and physical artefacts. In addition, a survey was used under the single main study analysis. Table 6 summarizes all the different data collection sources throughout the different research methods in the study. Although the survey indicates a quantitative approach of gathering data, this is not mix-method research (mix-method characterizes research that use both qualitative and quantitative approaches (Bowers *et al.*, 2013). According to Creswell (Creswell, 2014), qualitative and quantitative approaches should not interpreted as two distinctive categories and "a study tends to be more qualitative or vice versa. Mixed-method research resides in the middle of this continuum because it incorporates elements of both qualitative and quantitative approaches". Therefore, since this research study mainly relies on a qualitative approach, it is considered as qualitative. However, when answering RQ3, the qualitative research is supplemented with a quantitative method of data gathering to meet the research objectives.

Table 6. Data collection sources on the different research methods in the research study

WP	Paper	Research method	Data collection sources
1	B	Multiple sub-case analysis I	Direct observations Interviews Documents
1& 2	D, E & G	Multiple sub-cases analysis II	Direct observations Participant observations Interviews Documents Physical artefacts
3	A	Multiple test-cases analysis	Interviews Physical artefacts
3	C & F	Single main case study analysis	Direct observations Interviews Survey

In the following, the author analyzes the different research methods as well as the data collection approach under each of them.

Literature review, parts I and II

The first literature review, indicated as ***literature review I*** in Table 5, was performed early in this PhD project as part of the WP1 and contributed to answering the RQ1. The aim of *literature review I* was to encounter relevant studies that contribute to identifying the challenges of LCC application and reasons of its limited adoption in the AEC industry.

Therefore, during autumn 2018, the author performed a systematic literature review by following the step-by-step methodology suggested by Okoli (Okoli, 2015). The research was accomplished by using mainly Google scholar and several online databases accessible from Aalborg University facilities on high reputation journals (like: Building Research and information, Construction Innovation, Building Environment and Project Management).

The research subject was contained four aspects: (1) Life-cycle costing, (2) AEC industry, (3) barriers, and (4) adoption. Therefore, the search words for each one of the abovementioned aspects, considering synonyms, scientific terms, etc., are as follows:

- Aspect 1: life-cycle costing; life-cycle costing; life-cycle cost; life-cycle cost; LCC; Whole life-cycle costing; WLCC; life-cycle cost analysis; LCCA
- Aspect 2: Architecture, Engineering, Construction & Operation; AECO; construction industry; construction sector; building sector
- Aspect 3: Barriers; challenges; issues; obstacles; hindrances
- Aspect 4: adoption; implementation; application

The research resulted on twenty-eight (28) studies in English that are read and evaluated as relevant or irrelevant to the subject of the analysis. In the end, fifteen (15) studies were assessed as relevant since they contribute to answering the RQ1 and to writing Paper B (Saridaki and Haugbølle, 2019a).

The second method step of the literature review, indicated as ***literature review II***, was a continues process that took place throughout the three years of the PhD study and had a more broaden approach since contributed in different part of the research.

For instance, a literature review was performed to support the development of data integration methods in Paper A (Saridaki *et al.*, 2019). The review was based on existing reviews of Thurairajah & Boyd (2017) in relation to BIM, Toth et al. (2012) and Negendahl (2015) in relation to data management approached and Haugbølle & Raffnsøe (2019) in relation to LCC, as well as it supplemented with additional research in Google Scholar.

Another example is the literature review on transferring knowledge between design and operation that contributed to Papers D, E and G (Saridaki and Haugbølle, 2020c, 2020b, 2022b), which were based on existing reviews of Rasmussen at al. (2017) as well as Jensen (2009, 2012), supplemented with research in Google scholar.

A third example that indicates the literature in tools is given by the literature review that was performed on the different methods in UCD, and on the application and benefits of personas in practices for Papers C and F (Saridaki and Haugbølle, 2019b, 2022a).

Multiple sub-case analysis I

A multiple sub-case analysis that is numbered *I* in Table 5 is performed under WP1, aimed at understanding the current cost calculation practices internally in Vandkunsten Architects and contributing to answering RQ1 and writing Paper B

(Saridaki and Haugbølle, 2019a). The elements of analysis were ***three case projects*** of Vandkunsten Architects selected based on their performance regarding LCC calculations:

- *Project 1:* A remarkable case since high-level (in volume and level of detail) LCC calculation have been performed successfully.
- *Project 2:* A typical project in terms of LCC application, including typical calculation methods.
- *Project 3:* A project without any LCC calculation.

All projects are high quality residential buildings.

The author's engagement with the three projects took place from August to October 2018. During that period, the author gathered qualitative data from documents, direct observations, and interviews in Vandkunsten Architects.

Specifically, the author gathered ***documents*** related to the LCC calculation processes in the three projects under examination, including calculation tools and spreadsheets, calculation reports, relevant databases, etc. The analysis of the documents gave me a first overview on the calculation principles, methods, and tools used in Vandkunsten Architects. The analysis of the documents was used also later in the process of gathering data, to support observation outcomes as well as to prompt participants to engage in conversation during the interviews.

In addition, ***observational data*** was gathered through files note, based on daily observations of the work and calculation process along that period. The observations emphasized on understanding the data flow on work processes and the collaboration of the architects internally in the company as well as their collaboration with clients and external stakeholders (e.g., engineers).

Furthermore, to complete the analysis, seven ***semi-structured interviews*** were conducted during October 2018. The interviewees were selected by using role-based sampling (Dennehy and Conboy, 2017; Ikonen *et al.*, 2010) including both the project manager and all cost calculation practitioners of each of the three projects under examination. In total, there were three interviewees related to the first case under analysis, two interviewees related to the second case, and two interviewees related to the third case. The interview questions were open-ended, and interviewees were free to elaborate on their experiences in relation to the case projects and the LCC calculation process. Each interview lasted between 40 to 60 min and was recorded. Each recording was transcribed the day after the completion of each interview.

Multiple sub-case analysis II

A multiple sub-case analysis that is numbered *II* in Table 5 is performed at the end of WP1 and mainly in WP2, aimed at understanding the collaboration and reveal new insights regarding LCC between design and operation. Therefore, the research focused on analyzing a paradigmatic project of a particular building clients, social housing organization, and contributed to RQ1 and RQ2 as well as used as case studies in Papers D, E and G (Saridaki and Haugbølle, 2020c, 2020b, 2022b).

The need to focus on social housing projects emerged due to two different reasons. Firstly, a high percentage (about 50%) of Vandkunsten Architects projects are residential building projects for social housing organization, and therefore, there was a particular interest to explore how the work processes in social housing projects enable the implementation of LCC calculations. Secondly, it was already identified in the research that LCC practitioners face challenges on gathering data for applying LCC in early design stages. Social housing organizations seemed to be suitable actors for eliminating this challenge, since they have extended experience and data from owning and managing building projects that can transfer into the design of new projects.

Before selecting the case projects, research on different social housing projects from the portfolio of Vandkunsten Architects was performed. It was observed that Vandkunsten Architects has close collaboration with a particular building client over the past ten years, having been involved in a series of projects offered by that client. This client is one of the bigger social housing organizations in Denmark, managing more than 60.000 units in the capital region of Copenhagen. It was also noticed that the processes of planning and conducting building projects with this client were informally standardized.

Therefore, for this research study two projects were selected as sub-cases for examination:

- *Project 1:* A typical new social housing project that is the last project of a series of projects with that client, completed in January 2012.
- *Project 2:* A social housing building project that is under renovation.

This decision for using *Project 1* was rational, since it was a typical project that follows the same processes as all previous projects of that series, and since it was recently completed, it was easier to collect data for the analysis. Regarding *Project 2*, the need for investigating a renovation building project arose after analyzing *Project 1*, to validate some of the findings in a project that is under operation and has available O&M related data for examination.

In ***Project 1***, the analysis began with understanding the processes of collaboration between architects and the social housing organization and observing LCC related data flow between the processes. Throughout the analysis, the opportunity of using available data to inform the design processes was recognized, and therefore, the case project was also used for proposing a method on how architects can identify cost-drivers in social housing projects and how to use them to improve their decision-making process. The research data in this case project was collected through observations, analysis of documents, analysis of physical artefact, and semi-structured interviews.

During autumn 2019, ***observation*** on the case participants and ***several interviews*** were performed. This time, the interviewees were selected by using snowball sampling technique (Bryman and Bell, 2007; Saunders *et al.*, 2016). The first interviewee was the project manager of the case project, who also suggested other people with whom it would be relevant to interview. In total five semi-structured interviews were conducted during November and December 2019. Three of the interviewees were architects in Vandkunsten Architects that are involved in the case project, while two of the interviewees were employees of the social housing organization that owns the case project. Each interview lasted about an hour. All three internal interviews were recorded, while during the interviews with the client organization, the interviewer took notes.

To further support the analysis, ***documents*** and ***physical artefacts*** of the project under examination were gathered and analyzed. Some of the documents had exceptional impact on this case analysis and contributed on designing proposals that are presented in the discussion of Paper E (Saridaki and Haugbølle, 2020b).

Later, before the selection of the case ***project 2***, the author conducted interviews with representatives of social housing organizations and analyzed documents from several social housing projects gathered in the database of the national building foundation institute (*https://lbf.dk/).* However, in order to be able to make a complete analysis, there was a need to access detailed data from operating existing buildings of a social housing organization that are not available in the database. However, this task was challenging for both confidentiality issues and Covid-19.

Fortunately, while the author was struggling to identify relevant data for the analysis, Vandkunsten Architects started working on a renovation project of a social housing organization (Project 2 under examination). That was a significant opportunity, since the author has the possibility to be involved in the processes and interview people from the client organization to gather the data that was required for the analysis. Therefore, the case selection was an incidental choice; however, the client organization is the same as in the Project 1. However, it is hard to declare that this is a paradigmatic case, since smaller social housing organizations may have a totally different structure of gathering O&M data and using that data to inform their decisions for future maintenance plan.

The case under examination was used to explore the way of data gathering in existing social housing projects and understanding how future maintenance activities are scheduled. The analysis gave valuable insights on operation of social housing project, contributing to answering RQ2 and writing Paper G (Saridaki and Haugbølle, 2022b).

In Project 2, data for the case project analysis was gathered through participant observations, interviews, and analysis of documents and physical artefacts.

Specifically, the author ***actively participated*** in this project and performed calculations regarding LCC as well as was involved in the decisions for the project renovation. In addition, she performed ***informal interviews*** with the architects involved in the project, the engineers as the main consultants of this project, and two social housing representatives. The aim of the interviews was to understand the processes in social housing organizations regarding O&M activities and how they plan them for the future, and if and how data from operating existing buildings is used to inform the future O&M plans. The interviews were the starting point to request and gather documents and artifacts including among else, past and current O&M plans (including activities and expenses). The **documents and artifacts** were analyzed, contributing to understanding the structure of different accounts and the way of calculating budgets for future O&M activities.

Multiple test cases analysis

A multiple cases analysis that indicated as multiple test case analysis in Table 5 is performed at the end of WP3 aiming to develop and test two different methods of LCC calculations based on two different approaches on data integration to contribute to answering RQ3 and Paper A (Saridaki *et al.*, 2019).

Before starting the development of the model, the author conducted three ***interviews*** in LCC practitioners to understand the implementation of LCC and the available tools and processes in the Danish AECO Industry. The interviewees were a consultant of a leading engineering company, a practitioner on sustainability group of the same company, and a senior researcher at the Department of the Built Environment of Aalborg University (formerly the Danish Building Research Institute) and developer of the LCCbyg application, Kim Haugbølle. The first two interviews focused on clarifying the current work processes for LCC, the different tools used in the industry, the data gathering requirements for LCC implementation, and the challenges of using the available tools in projects. The last interview focused on the application of LCCbyg in the Danish AECO industry, the benefits and limitations of the tool and potential areas of improvements. The data collection through the literature and the interviews contributed to recognizing the LCC implementation in the current practices and its limitation and needs and therefore, to the development of the two different methods.

However, to support the development as well as to test the two approaches, three case were used. Those cases are the ***physical artefacts*** of the research analysis:

- Case 1: A simplified building model developed by the authors of Paper A (Saridaki *et al.*, 2019)and consists of five basic components. This model was easy to handle as well as suitable for testing the models, and therefore, it was useful during the development of the models.

- Case 2: A university building model used to test and validate the two methods in a large scale as well as for optimizing the processes of the methods application.
- Case 3: An office building model, that is an on-going project of the leading engineering company, with a high complexity. The project is used to apply the developed models and produce results.

The application of the developed methods in the three above-mentioned cases, and especially in case 3, and contributed on identifying several lessons-learned regarding data management and LCC calculations.

Single main case study analysis

A single case study analysis that is indicated in Table 5 is performed under WP3 to support the discussion on supporting integration of LCC in design practices. The case study under examination is the main case company of this research, Vandkunsten Architects, and the analysis focuses on the people and their work processes and not on projects. The aim of this analysis is to understand and provide insights into the current and potential LCC users and their characteristics. This will contribute to developing useful and effective interventions towards LCC implementation. This research method contributed to answering RQ3 and in Papers C and F (Saridaki and Haugbølle, 2019b, 2022a).

The study uses Vandkunsten Architects as the case study for performing this analysis, since the author is interested in improving the integration of LCC in the company and therefore, the knowledge about current and potential users will contribute on developing tools and processes. However, as discussed in the introduction of section 3.2, Vandkunsten Architects is a paradigmatic case in the Danish AECO industry and thus, the results are relevant in general.

The engagement with this research that focuses on practitioners was performed during 2018 to 2020. There were two main reasons that this study took so long. First, the research subjects were the employees in Vandkunsten Architects, and to obtain a holistic understanding of their characteristics in work processes and their goals and challenges, the author wanted to observe them participating in different projects, doing different tasks, and having different roles. Secondly, the theoretical methodology that was followed had several steps, and to assess the results after each step, additional observations and informal discussion were performed internally in the company.

Although direct observations were the source in this research, different data collection methods were used, including semi-structured and unstructured interviews and a survey. The use of mix-methods was critical for the triangulation of the understanding about the subjects.

Specifically, ***direct observations*** were continuously conducted through the entire period of this research study. The intention behind the observations, however, varied from time to time. For instance, at some point the intention was to observe the tools that the subjects were using, while in other steps, the intention was to observe how the subjects use the tools, or what the challenges were by using that tool.

In addition, several ***interviews*** both unstructured and semi-structured were conducted throughout the process. The interviewees were employees of Vandkunsten Architects. At this step, the reason for an interview was more to validate or supplement an observation or a research result and less to reveal a new insight into the research. Thereby, most of the interviews were unstructured and in a form of discussion rather than in a form of a formal interview.

A ***survey*** was also performed as part of this study aimed at gathering additional information about the subjects and their characteristics. The survey was performed by using Google Forms and included 20 questions. The questions multiple choice or in linear scale and few of them required a short answer. The survey was sent to 60 subjects during November 2018, and throughout a 15-day period, 48 responses were collected. During the analysis of the survey, the responses were evaluated based on qualitative data gathered in previous steps and supplemented with additional observations in order to limit the objectiveness of the responses as much as possible.

The data collection methods are also summarized in Table 1 of Paper F (Saridaki and Haugbølle, 2022a).

3.4 Assessing the quality of the research design

In case study analysis, it is important to assess the quality of the empirical research (Yin, 2018). There are four elements that are commonly used for assessing the quality of case studies: construct validity, internal validity, external validity, and reliability (Wohlin *et al.*, 2012). In the following, it is discussed what actions were taken to ensure the quality of the research towards those four elements.

Construct validity

Construct validity refers to what extent correct operational measures have been used to sufficiently measure the construct (Dennehy and Conboy, 2017; Wohlin *et al.*, 2012).

Construct validity is tackled in this research by gathering multiple sources of evidence in all different steps of the research, as it is proposed by Yin, (Yin, 2018). Specifically, the author used different theories, tools, and research methods to answer the research questions of this study. Moreover, the data collected by using different methods including interviews, participant, and direct observations and analysis of physical artefacts, ensuring data triangulation, and reducing researcher’s influence on the outcome of the study.

Internal validity

Internal validity refers to the awareness of considering all causal relationships between the examined variables (Kitchenham *et al.*, 2002; Runeson and Höst, 2009; Wohlin *et al.*, 2012). It also reflects on the trustworthiness of cause-and-effect relations between variables and results and thereby, the elimination of alternative explanations of a finding.

In order to ensure internal validity, the author continuously discussed the research finding and got feedback from researchers and practitioners in the AECO industry. Specifically, the research findings were continuously reviewed and discussed with the employees in Vandkunsten Architects and the supervisors of this project to ensure that there were no missing or misunderstood elements. In addition, the research findings were presented and discussed in four international conferences, various seminars, and workshops.

External validity

External validity refers to the extent the research results can be generalized (Kitchenham *et al.*, 2002; Runeson and Höst, 2009; Wohlin *et al.*, 2012). Generalization of case studies has been criticized in different research (Gibbert *et al.*, 2008; Yin, 2018). However, Flyvbjerg (2006) argues that even single case studies are usually both appropriate and valuable to be generalized if the cases are strategically selected.

In this research, the case study is strategically selected, since Vandkunsten Architects represents a paradigmatic case in the Danish AECO industry. In addition, the case projects are typical architectural projects where each one was strategically selected to serve the scope of the corresponding work package. For instance, to ensure that the findings are not case specific in RQ1, three different case study were selected with different characteristics regarding the LCC application: one without LCC calculation, one with typical LCC consideration, and one with outstanding LCC application (In Paper B (Saridaki and Haugbølle, 2019a)).

Moreover, the study has been presented in international conferences, reviewed by external researchers, and published in both journal and conference proceedings, indicating that the research findings are of interest to a broader audience in the AECO industry.

Reliability

Reliability in research is a measure of the stability or consistency of the results, indicating to which extent the results can be reproduced when the research is repeated under the same conditions (Yin, 2009).

When it comes to quantitative research, statical methods can be applied for establishing reliability of the research findings. However, in qualitative research, reliability of the findings is ensured by designing incorporate methodological strategies.

To ensure reliability and eliminate the dependency on the researcher, the data collected throughout the research was reviewed by the individuals and critical stakeholders involved in the case projects under examination. In addition, the findings of the research were continuously reviewed by the supervisors at both Vandkunsten Architects and Aalborg University as well as the steering committee of this research study.

4. Findings

This section presents the summaries of the Papers A to G written during this research study. Each paper's summary will incorporate the following: a short introduction to the topic, the purpose of the paper, the research approach, the research findings, and the results.

4.1 Paper A

Saridaki, M, Psarra, M and Haugbølle, K (2019) "Implementing life-cycle costing: data integration between design models and cost calculations ". *Journal of Information Technology in Construction (ITcon)*, Vol. 24, pg. 14-32, http://www.itcon.org/2019/2

The ***purpose*** of this study is to develop, test, and summarize lessons learned by using two different methods of data integration that provide direct link between design models and cost databases and that perform LCC calculation for the entire building or individual building components.

The ***research approach*** is a combination of a literature review on LCC, BIM, and data integration methods as well as a few interviews. Specifically, the authors conducted three interviews in order to understand the LCC calculation practices in the AECO industry. The first two interviewees were employees of an engineering consultancy working extensively with LCC, and the interviews were aiming to identify the current work processes when implementing LCC analysis including the different tools that practitioners use for LCC calculation, the data gathering processes, the challenges of performing LCC, and the possibilities for improvement. The third interviewee was a senior researcher specialized in LCC and the developer of the LCCbyg application that is extensively used in the Danish AECO industry for performing LCC calculation among else for the DGNB certification. The interview was aiming to identify the benefits and shortcomings of using LCCbyg application as well as possibilities for improvement.

The developed methods were tested in three different cases: 1) a simplified building model with five basic components (walls, windows, door, roof, floor, and floor covering) for easy validation of the results since it was possible to create manual results and compare, 2) a university building models for testing in large scale and validate the methods, and 3) an office building model that is provided by the engineering consultancy for producing results.

The ***findings*** include the development of two different methods for performing LCC calculations by linking design models and cost databases based on the compatibility and interoperability approaches.

In both methods the results are generated through the 5D cost estimation software Sigma Estimates (Sigma Estimates, 2003) that provides an establish connection with Revit Autodesk (design tool) (Autodesk Revit, 2018) and Molio price database (cost database) (Molio Prisdata, 2018). Through its plug-in function to Revit Autodesk, Sigma Estimates can extract pre-selected data (elements and their quantities) from the design model and import them in a "Sigma Project". Then the "Sigma Project" can be linked to a "Sigma Library" that includes unit costs of all elements and thus, it can calculate the total cost of a project. However, Sigma Estimates cannot generate life-cycle costs since it does not consider inflation. Therefore, the two methods that are developed in this research transform cost values into LCC results.

Before starting the development of the two methods, the authors created in Sigma Estimates a "Sigma library" that is structured in three levels (Fig. 4 in Appendix A, Paper A):

- Level 1: Element type (e.g., wall, window)
    - Level 2: Life-cycle stage (e.g., construction, maintenance)
        - Level 3: Specific activity

The *first method* is a **spreadsheet tool** that is developed based on the principles of compatibility between Sigma Estimates and MS Excel and on the possibility to export/import from Sigma Estimates in an Excel format. Specifically, in this approach, an MS Excel tool is developed to transform the cost of the activities in Sigma Library to life-cycle costs, by using Visual Basic for Application to script the equation that transforms costs to life-cycle costs. In the MS Excel tool, the user should enter some basic information about the project (e.g., lifetime, inflation rate, etc.), and then the tool will convert the costs into life-cycle costs.

Method A can be described in six steps (Fig. 5 in Appendix A, Paper A):

1. Building the Revit model
2. Generation of a Sigma project by exporting elements from Revit Model to Sigma Estimates through the plug-in function
3. Developing a Sigma Library
4. Extracting Sigma Library in an Excel format and calculating LCC
5. Importing the Excel calculation results to Sigma Estimates by creating a new Library
6. Connecting the Sigma Project of step 2 and the Sigma Library of step 5 and create final LCC results.

The connection between Sigma Project and Sigma Library in step 6 is facilitated through a coding system that is developed in this research and it is based on the international classification system BIM7AA. The codes are assigned to the elements in both the Revit Model and the Sigma Library to enable the connection.

The *second method* is a **dynamic model based on visual programming language**, where a Dynamo model is developed for performing the LCC analysis based on the principles of interoperability. The Dynamo model includes some pre-set functions and calculates an LCC parameter by having the LCC equation encrypted in Python.

The model collects the elements of the Revit Model grouping them by code and structures all required information for each element by also attaching LCC parameters. By running the model, it exports all information into a Sigma Project.

Method B can be described in five steps (Fig. 8 in Appendix A, Paper A):

1. Building the Revit Model
2. Developing a Sigma Library
3. Using the dynamic model as a mediator between Revit model and Sigma Estimates for making modifications and preparing the LCC calculations
4. Generation of Sigma project automatically by running the dynamo model
5. Creating LCC results by connecting the Sigma Library of step 2 and the Sigma project of step 4.

In this method, the connection between Sigma Library and Sigma Project is also facilitated by a coding system. However, the coding system here is different since it does not refer to the building elements as in Method A, but to the activities of each of the elements.

Through the developments and testing of the two methods, the authors identified five issues of integrating data and performing LCC calculations:

- Non-conformity of unit values between design models and cost databases.
- Lack of commonly used classification system in the AECO industry.
- Extensive manual work requirement for performing LCC calculation since existing tools lack automate procedures.
- Poor design of models lacking distinctive types of elements leading to difficulties on extracting quantities and implementing the analysis.
- Insufficient methodology for exchanging life-cycle data between engineers, manufactures, and facility managers.

In ***conclusion,*** this study developed and tested two methods for performing LCC calculations of integrating data between different types of autonomous software based on compatibility and interoperability principles. In both methods, the developed tools are mediators between the Revit Model and the cost calculation software, Sigma Estimates, and covert activity costs to life-cycle costs. Method A is developed based on an MS Excel tool while method B a dynamic model by using visual programming language. The MS Excel tool in method A can be easily applied by a broader audience since it offers a familiar graphical user interface. The Dynamic model offers a permanent link with the design model that enables visibility of the direct effect of any design changes on LCC results. Although the successful generation of results in the test cases, both methods faced numerous issues with data integration across the different software and the generation of LCC results.

4.2 Paper B

Saridaki, M and Haugbølle, K (2019) "Identifying Contradictions of Integrating Life-Cycle Costing in Design Practices", *In: Lill, I. and Witt, E. (Eds.), "10th Nordic Conference on Construction Economics and Organization",* 7-8 May 2019, University of Tallinn, Estonia. Emerald Reach Proceedings Series, Vol. 2, 33–9.

In recent years, there has been an increased interest on sustainable design and constructions with focus not only on the environmental performance of buildings but also on the economic quality in a long-term perspective. Life-cycle costing (LCC) is widely used by the AEC industry as a decision-making methodology to evaluate the economic effect of alternative design solutions over time. Despite the increased interest in LCC, the concept faces limited adoption in design practices due to several challenges with its application.

The ***purpose*** of this paper is to understand the current application of cost calculations in design practices and to investigate the challenges of LCC limited adoption. By using activity theory in a Danish architectural firm, the authors aim to understand the activity system of building design and identify built- in contradictions that hamper the integration of LCC in the design practices.

The ***research approach*** in this research includes a literature review and analysis of three case projects. In the literature review, several studies on LCC application in the industry with focus on challenges of limited adoption were gathered and analyzed. For the case study analysis, a mid-size Danish architectural firm that it is a frontrunner for sustainable design and development was selected. Three paradigmatic projects of the case company were chosen for the analysis: Project A, an extraordinary case with successful and detailed LCC calculations; Project B, a typical case, using standard calculation methods; and Project C, no LCC calculations. The research data from the three case projects was collected through documents, observations, interviews and physical artefacts. The data from both the case study analysis and the literature review was used to develop the activity system of building design with regard to LCC implementation.

The ***findings*** reveal contradictions in all levels of the activity system.

Primary contradictions, within the following elements:

- *Subject*: By reviewing the literature, it was pointed out that architects and engineers of the AECO industry struggle for understanding of the LCC definition and methods. This was also observed through the case study analysis, since only few of the case subjects had the knowledge to perform an LCC analysis.
- *Tools:* In both literature and the case projects analysis, it was identified that the industry lacks available and reliable data for performing LCC calculations. An additional observation in the case study analysis was the

deficiency of available tools for early design stages calculations where the decision-making is more critical.

- *Community*: In both literature and case projects analysis, it was obsered that the stakeholders in the AECO industry have limited awareness of sustainability and limited understanding of the benefits of LCC. For instance, the building clients of the case projects are not considering the long-term benefits of LCC in investment decisions.

Secondary contradictions between the following elements:

- *Subject vs tools*: In both literature and the case study, it was determined that although the availability of various LCC tools, LCC practitioners are missing usable tools that can be effectively used in their practices. Available tools lack automate procedures and thereby, LCC becomes a complex and time-consuming task, while the results are prone to human errors.
- *Subject vs DoL*: The case study analysis pinpointed that during the calculation process there was insufficient collaboration between the LCC practitioner and the design team. Consequently, there was an increased risk of misunderstanding and miscalculations due to unreliable or continuously changing design models. Moreover, the LCC calculation results were not communicated to the design teams and therefore, were not used in the decision-making process.
- *Subject vs Community*: In both literature review and case study analysis, it was determined that there was not any standardized methodology or guidelines for gathering, managing, and exchanging life-cycle data between the stakeholders of a building project.

Tertiary contradictions between the following activity models:

- *Traditional design processes vs new processes that include BIM*: Although the advanced opportunities offered by BIM, it was observed in both literature and the case study analysis, that there are still challenges in establishing robust and reliable models, since building designers lack collaboration interchange on mind. In project B, for example, the models were missing information on elements' materials, while in projects A & C, many of the stakeholders were reluctant of using BIM models.

Quaternary contradictions between the following central and the co-existing activities:

- *Central activity of LCC implementation vs activities of project design*: Although the design practices in projects A & B have been improved in terms of BIM in order to support LCC calculations, the work distribution as well as work and data management processes of co-existing activities do not support the decision-making process.

In ***conclusion***, this research confirms as well as adds new insights in the literature of LCC limited adoption. The additions are observed in the secondary and quaternary level of contradictions. In secondary level, contradictions were identified between the subject and DoL, highlighting that the limited collaboration between LCC practitioner and the design team as well as the unstructured division of tasks are hindrances of LCC implementation. Similar observations were identified on quaternary level indicating that the current way of collaboration and work allocation do not support implementation of LCC in design practices and do not consider LCC results in decision-making to improve the quality of building projects.

4.3 Paper C

Saridaki, M and Haugbølle, K (2019) "Identifying LCC user types using the concept of Personas", *In: CIB WBC 2019: "Constructing Smart Cities", 17-21 June 2019, The Hong Kong Polytechnic University, Hong Kong, China.* CIB Proceedings pp. 4202 – 4212.

Several studies have been performed in order to identify the reasons of LCC limited adoption in the AEC industry. In addition, there is scarcity of studies about how LCC practitioners apply the concept in practices.

The ***purpose*** of this study is to recognize current and potential LCC users and understand their characteristics and their work practices. In order to meet the research aim, the study applies user centered design methods. Specifically, the concept of personas is used to construct users' personas and recognize how building designers work with LCC in regard to data integration.

The ***research approach*** that is followed for constructing personas is a single case study analysis. The case study is a Danish architectural firm that consists of architects and engineers for whom the author is willing to design. Through the case study, data was collected through both qualitative and quantitative methods, including direct observations, interviews, and a survey.

Moreover, the author followed the following eight principle' steps for constructing personas as proposed by Cooper et al. (2007, pg. 82) and presented in section 3.1.2 in this thesis.

However, this paper presents the initial part of the research study and focuses on steps 1 to 4 of the process: 1) Group interview subject by role, 2) Identify behavioral variables, 3) Map subjects to behavioral variables, and 4) Identify significant behavior patterns.

The ***findings*** of each step are briefly presented below.

Step 1: Grouping interview subject by role

By conducting preliminary research, the author identified the different stakeholders of LCC in the AEC industry and analyzed their role in terms of interest and impact on LCC. The analysis indicated LCC users as important stakeholders for LCC integration, and so the author decided to focus on current and potential LCC users as the subjects of this analysis.

Step 2: Identify behavioral variables

In this step, the analysis resulted in identification of twenty-two behavioral variables that are presented under seven main categories. The seven categories along with the behavioral variable under each category are listed below:

A. *Demographic* indicates what a person looks like;

1. Gender
2. Age

B. *Aptitude* indicates the users' level of knowledge and ability to learn;

3. Education
4. Role in the company
5. Years of experience

C. *Personality* indicates the subjects' curiosity on learning and developing skills;

6. Introvert vs Extrovert
7. Judging vs Perceiving
8. Feeling vs Thinking
9. Resistance vs Adaptive

D. *Skills* indicate user skills and familiarity with commonly used software;

10. Familiarity with technology and programs
11. Programming skills
12. Familiarity with Microsoft Excel
13. Familiarity with graphical applications
14. Familiarity with CAD applications

E. *Activities* indicate users' activities in frequency and volume;

15. Use of software in general
16. Use of software in work practices
17. Frequency of using software

F. *Attitude* indicates users' perspective on usability of software;

18. Evaluation of software in terms of usability
19. Challenges of using those software

G. *Motivation* indicates users' expectations and goals;

20. Expectation of improvement in software
21. Need of additional features or software
22. Goals by using different software

Step 3: Map subjects to behavioral variables

In order to map the case subjects against the identified behavioral variable, an online survey was sent to the case company. The results of the survey were supported by additional observations and interviews in order to eliminate bias of case subjects.

The results of mapping the case subjects against the behavioral variables are presented in detail in the corresponding paper. It is not considered critical to present the results here, since the results themselves are not important to the research. However, the results of this step are important inputs to the following step of identifying significant behavioral patterns.

Step 4: Identify significant behavior patterns

In this step, the author analyzed the correlation of the results of the third step and identified three significant patterns.

Pattern 1 indicates architect at the age 41-50, who are less thinking and more feeling, have low programming skills and they use Microsoft Office and CAD applications. Their main challenge is the high volume of manual work, and they would like to save time and reduce effort when working with different tools.

Pattern 2 indicates architects at the age 31-40, who are introvert, and they work with BIM and Microsoft Office applications. They also work with spreadsheets and their frustration is the lack of compatibility between tools. They would like to ease procedures in use of software and minimize errors in spreadsheets.

Pattern 3 indicates architects that have an engineering background at the age 31-40. They judge the tools and processes; however, they are easily adaptive in new technologies. They have programming skills and work with BIM. Their goal is to increase software interoperability and be able to automate procedure and reduce time spent on tasks.

In ***conclusion***, this study uses the concept of personas in a Danish architectural firm, in order to recognize different LCC user types and their characteristics in work practices. The four first steps of the framework for constructing personas are followed. The fourth step resulted in the identification of three significant behavioral patterns, indicating that there are three different user types in the case study under examination. In following research, those patterns are synthesized with characteristics from users following the next fourth steps of the process for designing personas.

4.4 Paper D

Saridaki, M and Haugbølle, K (2020) "Towards sustainable design: Integrating data from operation of buildings in design practices". *In Conference Proceedings:* World Sustainable Built Environment online conference BEYOND 2020: 2- 4 November 2020. Wallbaum, H., Hollberg, A., Thuvander, L., Fermenias, P., Kurkowska, I., Mjörnell, K. & Fudge, C. (red.). IOP Publishing, 4 s. 052051.

One of the main challenges of LCC adoption in the AEC industry is related to the lack of available data in early design stages of building projects, when LCC is considered more valuable for making decisions. In order to overcome this challenge, researchers have suggested taking knowledge from existing buildings and using it to the design of new buildings.

The author observed opportunities for using knowledge from operation to design in social housing projects. Social housing organizations are both building clients and facility managers of several buildings, and they have access to operational data which can be transfer to new projects.

The ***purpose*** of this study is to explore the collaboration between architects and particular building clients of social housing organizations and to observe how this collaboration supports transferring LCC-related knowledge and data from operation to design.

The ***research approach*** includes a case study analysis in a Danish architectural firm working extensively on social housing projects. Specifically, a paradigmatic social housing project was selected for the analysis and data was collected through direct observations, participant observations, and interviews.

In order to map the processes of the selected project and understand the data flow between those processes, structured analysis (SA) is used. By using SA, the author identified how the collaboration between architects and building clients guides or limits LCC activities.

The ***findings*** indicated the processes and data flow in the selected case project. In Figure 3, the processes that describe the activities in a social housing project are illustrated along with the actors that are involved and the outcome of each activity.

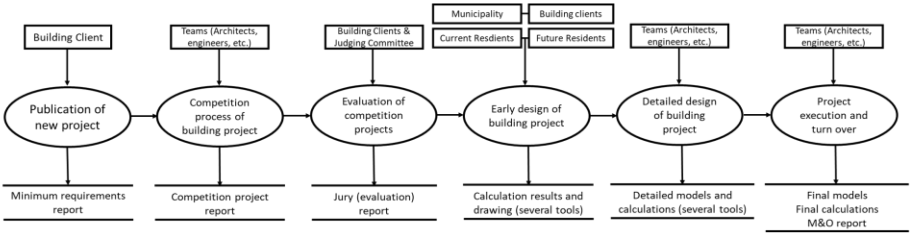

Figure 3. Data flow diagram of social housing project under examination (adopted after Saridaki & Haugbølle, 2020).

Through the analysis, it is observed that the collaboration between architects and building clients in social housing projects enables LCC-related data and information flowing in two processes of the SA system. Specifically, there is a data and information transfer from operation of existing building to the design of new projects through the following activities:

a) Through the availability of the minimum requirements' report as an outcome of the process of publication of a new project. The minimum requirements' report includes among others, a 30-years maintenance schedule of expected expenditures. This schedule is calculated by the building clients based on data from existing buildings and provides information about the maintenance frequency and cost of various building elements that can be used to inform the new building project.
b) Through the activities in the process of early design of building projects, where the design team meets the residents of existing social housing buildings and share information in relation to the performance of the building and unexpected maintenance and operational issues. This information can also be used by the design team to improve the design of the new building projects.

Although the opportunities of data and information transfer from existing building to the design team in the above-mentioned activities, the analysis pinpointed that there is limited attempt to perform LCC in current practices, since the rest of the activities do not support LCC implementation.

In ***conclusion***, this research used SA in order to map the process of a social housing project and to explore how the collaboration between architects and building clients of social housing organizations supports the information transfer from existing buildings to new building projects in regard to LCC. The results indicated that some activities support data and information transfer from building operation to design; however, several actions should be taken from both sides in order to exploit the opportunities and inform the design of new building.

4.5 Paper E

Saridaki, M and Haugbølle, K (2020) "Informing early-stage design through LCC data". *In Proceedings of the 36th Annual ARCOM Conference. Scott, L. & Neilson, C. J. (red.). Association of Researchers in Construction Management, s. 655-664.*

Despite the increased awareness in the AEC industry on the importance of LCC application in design practices in order to ensure economic sustainability of building projects, LCC methodology has limited adoption in the practices. One of the main challenges of the LCC limited adoption is poor availability of cost data. This challenge is even more critical in early design stages when the use of LCC is more valuable.

The ***purpose*** of this research is to analyse the process of building projects and investigate if there is any LCC related data or knowledge from operating existing buildings floating between the processes that can be used in early design stages to inform the design process of new projects. The study focuses on the social housing sector in Denmark, since social housing organizations owns and manage a significant number of buildings and thus, are considered "banks" of operational and maintenance data.

The ***research approach*** includes a case study analysis, where the case company is a Danish architectural firm with a reputation of designing social housing projects. The case project under analysis is a recently completed social housing project. The data for the case project analysis is collected through five semi-structured interviews with both the architects and the clients of the project as well as the collection of physical artefacts.

In order to analyze the case project, the authors used Structured Analysis (SA). Specifically, data flow diagrams (DFDs) (a tool in SA method) are used to analyze the processes of the case project and identify LCC related data flowing through them.

The ***findings*** reveal the design of two data flow diagrams, the Level 0 and Level 1.

The data flow diagram in Level 0 indicates the repetition of three main processes through the buildings' lifetime: planning, conducting, operating of building projects (Fig. 2, Appendix E, Paper E).

In the data flow diagram of Level 1, the author focuses on the end of planning and beginning of conducting process, since it is interested in the early design stages of building projects. The data flow diagram of Level 1 is illustrated in Figure 4.

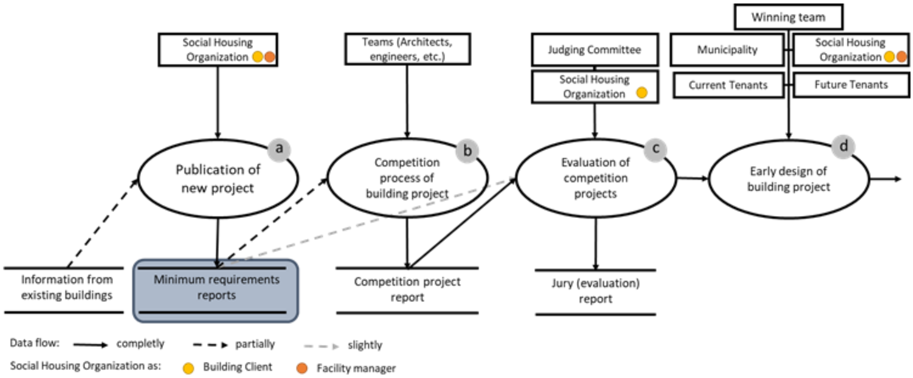

Figure 4. Data Flow diagram of the case project in level 1 (adopted after (Saridaki and Haugbølle, 2020b)*)*

As illustrated in Figure 4, the social housing organization uses some information from existing buildings to form the publication of a new project (process a). The outcome of the publication includes two reports with requirements to the new project. The reports include among others both qualitative and quantitative requirements in relation to LCC. For instance, qualitative requirements include increase lifetime performance as well as low maintainability and operation costs of building components while quantitative requirements include a maintenance schedule with some activities and expected expenditures for the first 30 years of operating the building. In process B, pre-prequalified teams compete for winning the project. The competition projects include project' s analysis, proposed drawings, and several calculation results. In process c, a judging committee together with the social housing organization evaluate the competition projects submitted by different teams. The award criterion in this case study was the most economically advantageous tender. The case project won the competition and continued to the next process of designing the building project (process c). Already in early-stage design, the design team collaborated with many stakeholders that provided useful inputs to building design. For instance, the social housing organization provided information about the economic performance of other similar projects and tenants of existing buildings discussed with the design team issues of maintaining and operating the building

The analysis shows that there are some processes in which LCC related data is transferred to the design team. In this research, the authors are focusing on the quantitative schedule of maintenance activities and expenses for the first 30 years of operating the building, which is part of the minimum requirement report in process a. Since the social housing organization provides this maintenance schedule to the design team, architects should use the information and the data to drive the design of new building. The data from the provided schedule can inform the design of a new project by:

- Proposing alternative design solutions that at the very least, comply with the given maintenance schedule.
- Pinpointing the most critical the maintenance activities that have the higher total life-cycle cost and proposing alternative solution to eliminate the cost.

In ***conclusion***, for informing the design of new buildings, cost data from operation of existing buildings can be used by the design team. In social housing projects, there are existing forms of cost related data that can be used to inform design. One source of cost related data is the 30-year maintenance expenditure schedule, which is part of the minimum requirements report. By analyzing the schedule, the design team can identify useful information and recognize cost-drivers in regard to LCC.

4.6 Paper F

Saridaki, M. and Haugbølle, K. (2022) "Recognizing the diversity of users of life cycle costing through personas". *Journal of Information Technology in Construction (ITcon)*, Vol. XX, pp. xx-xx (submitted for publication).

This paper builds upon Paper C (Saridaki and Haugbølle, 2019b) and brings the process for constructing LCC user personas to completion, by following the eight principle steps as suggested by Cooper et al (Presented in the above paper). While Paper C presents the four first step of the process, this paper revisits those steps and continues the process, presenting the findings in all eight steps.

Therefore, the ***purpose*** of this research is to improve our understanding about the diversity of current and potential LCC users and their characteristics, work processes, and data management approaches.

The ***research approach*** is a single case study analysis. The case company is an architectural firm located in Copenhagen, Denmark and data was collected through observations, interviews and a survey.

The ***findings*** reveal the identification of three users' personas. In the following paragraph, steps 5, 6, 7 & 8 are briefly presented.

Step 5: Synthesize characteristics and define goals

In this step, each of the three patterns that were identified in step 4, is synthesized with behavioral characteristics of users in relation to data processing in work practices, their frustration, and goals. In addition, fictional details are added in order to make personas more realistic.

Persona 1 is a traditional male character who performs tasks by manually copying and pasting data from one source to another. His main frustration is the uncertainty about correct data input, and his goal is to finish tasks on time.

Persona 2 is a female character who uses spreadsheets for calculations because she feels restricted by the default setting of different tools. Her frustration is that she ends up with manual work to structure data in spreadsheets, and her goal is to improve the workflow.

Persona 3 is a technophile male who uses programming in order to minimize manual work. He is frustrated about the unstructured data, and his goals is to automate processes and reduce time spent on tasks.

Step 6: Check for redundancy and completeness

In this step, the findings were checked for redundancy and completeness. Through revision of the collected data and additional observations, the author identified missing information and filled in gaps in order to complete personas' profile.

Step 7: Designate persona's types

The aim of this step is to prioritize personas and select a design target. In this research, this step was not followed, since all three identified personas are equally important for the research.

Step 8: Expand description of attributes and behaviors

In this step, the three profiles are completed by adding personas' narratives and photos. The constructed personas are characterized as "The clip-boarder", "The spreadsheet expert" and "The programmer" and are presented in figures 4,5 and 6 of the corresponding paper.

As discussed in this paper, the construction of the three personas highlights the diversity of user types as users of technology, in regard to their data processing approach, data integration method and tools requirements. Specifically, the results reflect on three different approaches to data processing that should be taken into consideration when developing tools and processes. Although the findings refer to the use of technology in general, they can be used to guide the LCC application processes and provide useful insights on the requirements of the users towards LCC tools.

In ***conclusion***, by applying the concept of personas in a Danish architectural firm, this research revealed three different user types in regard to work practices and data integration approaches: "The clip-boarder" who copies and pastes from one position to another manually; "The spreadsheet expert" who imports and exports data in spreadsheets; and "The programmer" who uses programming language to transfer data and wants to automate processes. The findings contribute to understanding how people work with technology in practices and reveal the diversity of users, by pinpointing three approaches of data integration. In regard to LCC, the construction of personas provides valuable information that can be used for designing novel LCC tools and processes and for increasing LCC adoption in design practices.

4.7 Paper G

Saridaki, M. and Haugbølle, K. (2022) "Transforming the activity systems involved in building design to include LCC". *Construction Management and Economics*, Vol. XX (X), pp. xx-xx. (Submitted for publication).

The ***purpose*** of this study is to examine the collaboration and data exchange between design and operation regarding LCC in social housing projects. Specifically, by using activity theory, the research focuses on characterizing the interaction between the activity system of building design and construction and the activity system of building operation and focuses on identifying actions that support data utilization and exchange in regard to LCC. Then, there is a discussion of how the activity system should be transformed to ensure LCC application throughout lifetime of the project.

The ***research approach*** is a case study analysis with two embedded case studies of a new building project and a renovation building project, both typical social housing projects. The new building project is in the design phase while the renovation project is in operation. The data collection was performed over a 9-month period and included nine semi-structured interviews, participant and direct observations of the stakeholders involved in the case projects, and an analysis of physical artefacts like tender and project documents, reports, financial documents, and databases. Moreover, to analyze the case project, the author used activity theory as theoretical grounding, also using the activity theory's key terms of interaction, mediation, disturbances, contradictions, and evolution.

The ***findings*** pinpointed that there are two activity systems that interact throughout a building project life-cycle: the activity system of building operation and the activity system of building design and construction. The elements of the two activity systems are summarized in Table 7.

Table 7. Description of the elements of the activity system of building design & construction and building operation

	AT of building operation	**AT of building design & construction**
Subject	Social housing organization, tenants, tenants' democracy	Team of architects and engineers
Community	Government, local municipality, National building Fund (LBF)	Social housing organization, central government, local municipality, National Building Fund (LBF), tenants
Tools	Reporting tools and spreadsheets, IT tools (LBF), Expert knowledge	Modelling tools, simulation & calculation tools, Materials' knowledge

Rules	Law on renting social housing, general social housing law, LBF guidelines	National Building Regulations, law on renting social housing, general social housing law
DoL	Internally between the departments of social housing organization	Internally between the team members
Objective	O&M of social housing buildings, Renting/ administration, Construction of new projects, renovation of existing buildings	Building design and construction
Outcome	Financially, physically, and socially sustainable and well-functioned dwellings	Sustainable building projects that meet users' needs

The common objective of the two activity systems in the case projects under examination was to design and construct a building to be owned and operated by the social housing organization. Thereby, the two activity systems interact throughout the project lifetime to achieve their common objective. Through the analysis, it is observed that this interaction includes among else LCC related data exchange. Specifically, the findings reveal three actions that mediate the adoption of LCC in building design project indicating the attempt of the activity systems by creating a shared objective towards LCC.

The *first action* includes the introduction of a novel maintenance plan in project competitions. The model maintenance plan is introduced by the activity system of building operation as part of the tendering documents in competition phase and includes 18 maintenance activities (both exterior and interior maintenance) along with their expected expenditures expressed in monetary value for the first thirty years of the operation of a building.

This action indicates an attempt of the social housing organization as the subject activity system of building operation to initiate the LCC consideration already in the project competition phase by providing LCC related data. However, the analysis showed that those data are not utilized by the activity system of building design and construction since the competition projects are focusing on the award criterion that is the most economically advantageous tender in regard to initial cost.

The *second action* that is observed includes the consideration of O&M in the early and late design processes by the activity system of building design and construction. In early design, the two activity systems interact through regular meetings and information and knowledge regarding building operation and performance is transferred to the activity system of building design. However, the authors did not observe any structured action for utilization of that knowledge in building design. In late design, however, the activity system of building design performed an LCC assessment by using a web-based tool that is offered by the National Building Funding since this is a mandatory requirement for all new and renovation projects of social housing. It is observed however, that the LCC assessment was only used as reporting document and not as decision-making tool in the building design.

The *third action* includes planning for long-term operation and maintenance, and it is observed during the project handover where the activity system of building design prepares an operation and maintenance guide and budget report that is handed over to the activity system of building operation. The O&M guide and budget include information about the building components like lifetime data, O&M requirements and intervals, instructions of use, product data sheets, and guarantees. Although, the O&M guide and budget can be used by the building operation to optimize the O&M plan of the building, it is pinpointed that the activities of building operation are planning based on their own experience instead of utilizing the provided information. The analysis indicated two main reasons for this: first, the O&M guide and budget only address a limited part of the activities taking place in the activities of building operation and second, due to the different classification systems that it is used by building design and the building operation.

The identification of the above-mentioned actions challenges the hypothesis of the AECO industry lacking available data, indicating that in social housing projects there is a variety of LCC related data exchanged between the activity system of building design and construction and building operation. However, the exchanged data is not fully utilized due to misalignments between the elements of the activity systems, and specifically between the tools because of using different classification systems, between the DoL because of limited communication during design processes, and between rules because the lack of commonly defined rules.

To enable the creation of a shared objective towards LCC, the elements of both the activity systems should be transformed. Regarding the element of tools, it is highlighted that there should be an alignment in the classification systems used by the activity system of building operation and the activity systems of building design. In addition, to improve data reliability, the activity system of building operation may improve the way of processing data and create a more precise and project-specific model maintenance plan, while the activity system of building design and construction may improve the data utilization from the model maintenance plan and use LCC calculation for O&M planning. Regarding the division of labor, the two activity systems may improve the collaboration throughout the project lifetime. That includes active interaction and increasing responsibilities to ensure the information is well communicated and utilized. Regarding the rules, it is important that the two activity systems follow commonly defined rules and standardize processes for data management, processing, and exchange as well as adopt mechanisms to ensure that the processes are followed, and the exchanged information is utilized.

In ***conclusion***, this study pinpointed three actions where LCC related data is transferred between the activity system of design and construction and the activity system of building operation in social housing projects. Although those actions create disturbances on the activities, instead of attempts of creating a shared objective towards LCC. The study indicated some misalignments between the elements of the two activity systems that obstruct the collaboration and utilization of data. Thereby, it is suggested that the activity systems should be transformed to resolve misalignments and to create a shared objective towards LCC.

5. Discussion

The general aim of this PhD project is to contribute to the integration of LCC in the AECO industry. As described in section 1.2, the study is performed with three work packages aimed at understanding the current calculation practices, analyzing potential interventions for improving the use of LCC, and discussing the challenges and dilemmas of integration of LCC in the design practices.

The findings of the research study are summarized in seven research papers that all together contribute to answering the research questions in the different work packages.

Specifically, as seen in Table 1, RQ1 (WP1) is mainly addressed in Papers B and D (Saridaki and Haugbølle, 2019a, 2020a); however, other research papers have contributed to it. RQ2 (WP2) is addressed in Papers E and G (Saridaki and Haugbølle, 2020b, 2022b), while RQ3 is addressed in Papers A, C and F (Saridaki *et al.*, 2019; Saridaki and Haugbølle, 2019b, 2022a).

In the following sections, the findings of this research study are tied together to provide the answers to the three research questions under the work packages.

5.1 Answering research question 1

The first research question is about understanding the current cost calculations in design practices and identifying factors and conditions facilitating or obstructing life-cycle costing in current design practices. Hence the research question is the following:

RQ1: How does the activity system of building design facilitate or obstruct life-cycle cost calculations in design practices?

Although the support of facilitating LCC in building design practices, LCC faces limited adoption due to several challenges that have been identified in the literature and confirmed and supplemented in this research study.

By analyzing the activity system of building design in the case study under examination, this study identified several contradictions that obstruct the integration of life-cycle costing in the design practices. The findings of Paper B (Saridaki and Haugbølle, 2019a) summarize contradiction of the activity system of building design in several levels that are identified in both literature and the case study under examination.

The literature pinpoints the lack of awareness of economic sustainability and the benefits of LCC as an important barrier of LCC adoption in the AECO (Gluch and Baumann, 2004; Olsson *et al.*, 2015). This is *confirmed* in this study as it is observed that many of the stakeholders in building design, especially building clients, are not aware of the LCC concept and its benefits in investment decisions in the long term. Thus, building clients of the case projects under examination are not asking for LCC and are focusing on minimizing short-term cost of the building projects.

The literature also states that many building designers have limited understanding on LCC definition and methods (Gluch and Baumann, 2004). This is also observed in this research study. When the project started in 2018, almost half of the building designers in the case study under examination did not know what LCC stood for and the majority did not have the knowledge to perform an LCC analysis (in a survey contacted in early 2019, 36% stated that they know how to perform an LCC analysis).

Regarding LCC tools, although a high availability of tools (Sørensen *et al.*, 2016), their usability has been questioned (Goh and Sun, 2016; Olubodun *et al.*, 2010) due to the lack of automation, complexity of calculation, and time requirements (Fu *et al.*, 2004, 2007; Hunter *et al.*, 2005). Those limitations have been also identified in the case study under examination. As an example, in one of the multi case project analysis I, the LCC practitioner did not find any existing application useful for performing LCC calculation in early design phases and thereby, the LCC practitioner used a spreadsheet and several other applications and spent approximately 40 hours on the calculations. Through the interviews, the LCC practitioner stated that the calculation requires a lot of manual work, and it was very hard to control the calculations for potential errors.

In literature it is also highlighted that the industry lacks standardized methodology for managing and exchanging life-cycle data between the different stakeholders involved in the LCC processes, including engineers, manufactures, and facility managers (Chiurugwi *et al.*, 2015; Monteiro and Martins, 2013). This is also observed in different case studies under examination. The LCC practitioners faced difficulties on finding guidelines for maintenance from the manufactures, while he observed difference on cost related data between cost databases and manufactures. The lack of guidelines and standardized methodology for life-cycle data (like EPDs or COBie) was also observed when developing different methods of data integration in Paper A (Saridaki *et al.*, 2019). In that case, the authors conducted interviews with manufacturers to gather cost related and life-cycle data since the EPDs showed significant discrepancies especially regarding the frequency, volume, and cost of maintenance activities throughout the lifetime.

Moreover, the literature recognizes the opportunities offered by BIM regarding automation in calculations and advanced life-cycle management(Xu *et al.*, 2014). Although the benefits offered by BIM integration in the AECO industry, there are still challenges with establishing robust and reliable design models (Edirisinghe *et al.*, 2017) since building designers do not consider collaboration and interchange while designing (Plume and Mitchell, 2007). This is also confirmed in the case study under examination, since the BIM models that the LCC practitioner used for performing the calculations were missing appropriate information, e.g., about the materials of different elements. As a result, there were errors in the LCC calculation that required increased effort and attention to avoid. Moreover, in the case study, the building designers do not use BIM in all cases, since there are projects that require highly detailed design that is difficult to be captured in 3D modelling and thus, they are designed in 2D tools.

Through this research, *additional* challenges were identified in relation to the collaboration between the LCC practitioner and the design team in the current building design practices that obstruct the LCC implementation. Firstly, there was limited and unstructured collaboration between the building design team and the LCC practitioners involved in project 2 of the multiple sub-case analysis I. The LCC practitioner took the BIM model at a point when the building design was not finalized. Because of the lack of communication, the LCC practitioner relied on the unfinalized models for the calculations, without being aware of any changes in the building design. As a result, the LCC calculations was unreliable and did not represent the final building model. Secondly, there were two LCC practitioners involved in the calculation process that did not have clearly divided tasks and consequently, some tasks were performed twice. Thirdly, there was limited communication in the decision-making process; the process that is one of the main benefits of LCC.

Besides the identification of several challenges, the author also identified opportunities of LCC implementation when analyzing a social housing project of Vandkunsten Architects, indicated as project 1 in the multiple sub-case analysis II. The findings highlight attempts of collaboration between building designers and building clients as well as actions towards LCC information sharing between building design and building operation.

In conclusion, RQ1 discusses several challenges of LCC limited adoption in the design practices; however, it pinpoints that there are opportunities of overcoming some of the existing challenges through the collaboration between design and operation. Therefore, RQ2 focuses on analyzing the actions between the activity system of building design and building operation and exploring to what extent those actions support LCC implementation.

5.2 Answering research question 2

While the RQ1 deals with understanding the current calculation practices and identifying contradictions that facilitate or obstruct LCC integration in the activity system of building design, RQ2 focuses on the actions between the activity system of building design and activity system of building operation and on identifying how those actions support LCC-related data exchange and utilization and contribute on creating of a shared-objective towards LCC. The second research question is formulated as follows:

RQ2: To what extent do current actions between the activity system of building design and construction and the activity system of building operation support data exchange regarding LCC?

To overcome the challenge of poor data availability in building design, researchers and practitioners have suggested transferring knowledge from operation to design. In literature review of Rasmussen et al (2017), the author explored different methods for transferring knowledge from operation to design. Among others, LCC application is pinpointed as one of the practical recommendations for optimizing transfer of knowledge (Chew *et al.*, 2017; Jensen, 2012, 2019; Meng, 2013a; Rasmussen *et al.*, 2017).

In the research by Jensen (2009, 2012), the author presented four mechanisms of transferring knowledge throughout the life-cycle of projects, including (1) codification of knowledge from building operation to increase awareness among designers, (2) regulations to ensure that codifying knowledge is used by the design teams, (3) continuous briefing between facility managers and building users during the design process, and (4) project reviews to ensure that designers are taking consideration of building operation. To implement those transfer mechanisms several stakeholders should be involved: building users to share their experiences from building operation (Chandra and Loosemore, 2011), facility managers to provide knowledge and insights of operating buildings (Jensen, 2009, 2012; Meng, 2013b) and building clients to assure that operational knowledge in considered in building design (Jensen, 2009, 2012).

While literature presents LCC as a method for transferring knowledge from operation to design, this research not only *confirms* that LCC is a significant tool for transferring knowledge throughout the life-cycle of the building projects, but also pinpoint that transferring LCC related data from operating existing buildings to the design of new building can contribute on improving LCC integration throughout the lifetime of the project.

In this research, through the case study analysis, the author identified opportunities of transferring knowledge regarding LCC in some projects of the case study under examination. Specifically, potentials of applying LCC and overcoming many of the challenges that were analyzed answering RQ1 were identified in social housing projects. Social housing organizations are the building project client/owner. Facility managers of many social housing buildings in operation and administrative offices have close communication with the tenants. Social housing organizations as the facility managers possess several data from maintaining and operating building and have knowledge of operational aspirations and concerns. due to the close collaboration with building users. As building client, social housing organizations can transfer this knowledge from operation to design as well as have the power to ensure that the operational knowledge is considered in the building design.

The analysis of current practices on social housing projects confirms that there are opportunities for transferring knowledge between building operation and building design that can contribute to overcoming the challenge of data availability and improve LCC integration. However, besides the opportunities and the LCC related data flowing between the activities of design, construction, and operation, the analysis indicated that there are still challenges that hinder the collaboration and data utilization and thus, obstruct the creation of a shared objective towards LCC.

Specifically, the author identified three actions of exchanging LCC related data:

- Action 1: Introduction of a novel Model Maintenance Plan in project competitions
- Action 2: Designing for operation and maintenance
- Action 3: Planning for long-term operation and maintenance

The contribution of each action towards LCC as well as the challenges of utilizing the exchanged data and knowledge is discussed in the following sections.

Action 1: Introduction of a novel Model Maintenance Plan in project competitions

Through the introduction of the maintenance plan by the activity system of building operation to the activity system of building design in the tendering processes, the social housing organization transfers LCC related data from operation of existing building to the designers. Specifically, the model maintenance plan contains codified knowledge (a few maintenance activities along with their expected expenditures for the first thirty years of the operation of a building) from building operation that may contribute to increasing awareness among building designers. This codified knowledge can be effectively used in early designing of building projects, overcoming the challenge of availability and reliability of LCC related data in early design processes. As an example, the design team can use the data to perform LCC calculations in the early design stage and propose alternative design solutions for different building elements that their maintenance costs comply with or they are even more efficient than the given maintenance schedule.

Besides the initial attempt of the activity system of building operation to increase the consideration of LCC in building design by providing tools, in the case study this tool is not utilized by the design team when submitting their proposals. The analysis indicated that the design team focused on initial construction costs instead of LCC since this is the most significant award criterion while there is not any criterion that assesses the consideration of LCC. According to Jensen (2012) theory, the processes are missing appropriate regulations to ensure that the design team uses the codifying knowledge.

Action 2: Designing for operation and maintenance

The second attempt of transferring knowledge is observed through continuous communication and regular meetings between the activity system of design & construction and the activity system of building operation as well as the performance of LCC calculations during the design processes of the social housing building projects.

The regular meeting presents a continuous briefing action between the design team, the facility manager (social housing organization), and the building users during the design process (Paper E (Saridaki and Haugbølle, 2020b)). However, the analysis of the case project pinpointed that there is no structure action by the designers that indicates the exploitation of that information. Moreover, it is observed that the activities of the building design towards LCC are missing structured project reviews. The adoption of project reviews could contribute to ensuring that designers consider the knowledge from building operation (Jensen, 2012).

In the later design stage, the building designers perform an LCC assessment since it is mandatory for all social housing projects. By the regulations of social housing, the tool is encouraged to be used as an opportunity for discussion between the design teams and the building clients for the choice of different materials through the early design process. However, in the case project the tool was used merely as a reporting tool in late design stage to comply to the regulations rather that an opportunity to contribute to the decision-making process.

Action 3: Planning for long-term operation and maintenance

The third action for transferring knowledge - this time from the activity system of building design to the activity system of building operation - is observed at the end of design process when the design team (subject) hands over an operation and maintenance guide and budget report (tools) to the social housing organization.

The analysis indicated that the O&M guide is a tool that initiates the optimization and planning of O&M activities for the years of building operation. However, it is observed that the social housing organization is planning the building O&M based on experience without utilizing the information provided by the building designers. In addition, the budget is performed by consultants.

In the activities of building operation in the case study under examination, the operation and maintenance guide and budget address only a small percentage of the activities occur in operation. Therefore, instead of using the tool, the subject interacts with the elements to plan and perform the O&M activities. In addition, this research study pinpoints that a reason of limited exploitation of this tool is related to the different classification systems used by the two activity systems. The activity system of building design and construction uses a classification that is precisely used by designer and contractors (e.g., SfB, BIM7AA). However, the activity system of building operation uses a different classification system, called DFK, that is more precise and relevant for facility management.

In conclusion, there are some attempts by the activity system of building operation to transfer knowledge to design and initiate action for increasing the LCC consideration in the design processes. However, those attempts seem to be insufficient and only partially work since the knowledge and data transferred from operation to design are not fully utilized due to several misalignments between tools, regulations, and the collaboration of the two activity systems. The author pinpoints that the elements of the two activity systems should be transformed to enable the creation of a shared objective towards LCC.

In the following research question, the author focuses again on the design practices and explores actions that will simulate the integration of LCC. The research perceives LCC users as important actors in LCC integration and thus, focuses on understanding the characteristics of current and potential LCC users and their approaches to data management. Moreover, it investigates how technological opportunities and BIM can support LCC application.

5.3 Answering research question 3

While RQ2 identified several actions between the activity system of building design and building operation towards LCC and opportunities of LCC-related data exchange, there are still challenges and contradictions that obstruct the LCC integration. In RQ3, the research returns on the design practices and actions that may support LCC integration. The study deploys the technological opportunities offered by BIM and develops and tests two models using different data management approaches (Paper A (Saridaki *et al.*, 2019)). Moreover, the author focuses on the LCC users, as critical actors of LCC integration, and aims at improving our understanding about the diversity of users and their characteristics in work processes and data management (Paper F (Saridaki and Haugbølle, 2022a)). The third and last question of this research study is the following:

RQ3: Which novel actions may stimulate integration of LCC in design practices?

The literature provokes several attempts of integrating LCC in design practices; however, the concept is not yet fully adopted. Despite the initiatives towards LCC, data management continues to be a significant challenge for firms like Vandkunsten Architects. BIM promises significant opportunities for automation and data management; however, real-world problems persist (Chiurugwi *et al.*, 2015; Edirisinghe *et al.*, 2017; Owen *et al.*, 2010).

To support the integration of LCC in the Danish design practices and answer RQ3, the author tests two different data management approaches by developing two different methods of data integration between design models and cost databases based on compatibility and interoperability (Paper A (Saridaki *et al.*, 2019)). In both cases, the developed models are integrated into the cost calculation tool, Sigma Estimates, that is linked to the Danish cost data base, Molio Price database, and has an established connection with the design software, Revit. Model A is based on the principle of compatibility and the LCC calculation is performed on MS Excel. Model B is based on the principle of interoperability, and it uses visual programming language (VPL) for LCC calculations. While Model A can be easily applied due to a user-friendly interface, model B offers a permanent link between the design model and cost calculation tool, and therefore, users can directly see how a change in the model affects the LCC results.

Through the application of the two models in three test cases, the author identified several limitations relevant to data integration approaches (discussed in Paper A (Saridaki *et al.*, 2019)):

- non-conformity of unit values,
- lack of commonly used classification systems,
- extensive manual work requirements,
- poor design of models, and
- insufficient methodology for exchanging life-cycle data.

The identification of those issues pinpoints that there are challenges in relation to data management that the industry needs to overcome to deploy the technological opportunities offered by BIM.

Through this research, the author observed that the effectiveness of any tool or process towards LCC is very much rely on the practitioners. Therefore, the author focuses on the designers as current or potential LCC users and aims at understanding their characteristics and exploring how they work with tools and processing data. The findings show a diversity of users by identifying three different user personas: the clip boarder persona, the spreadsheet expert persona, and the programmer persona. A significant difference between the identified personas is how they work with technology and processing data, demonstrating three different methods of data integration:

The ***clip-boarder persona*** processes data by manually selecting, coping, and pasting data from one application/ position to another. They prefer to work with independent and stand-alone tools that are simple and easy to use while including default values, in order to reduce manual work and minimize uncertainty about data.

The ***spreadsheet expert persona*** processes data by exporting and importing data from an application to another in csv file/ spreadsheet. They like to set up pipelines between tools and use spreadsheets as the mediator of calculations. They prefer tools in a spreadsheet format, where data can be imported and exported easily.

The ***programmer persona*** processes data by using programming and thus, exchanging data between applications automatically. They follow interoperability methods to link individual tools through file transformation. Thus, they prefer an open tool that supports interoperability.

The identification of personas increases our awareness that there are at least three different approaches regarding tools, data management approaches and processes that should be considered when developing new interventions towards LCC.

Instead of simplifying and focusing on dividing practitioners into being either LCC user or not LCC user, those findings provide a more reflective approach with a stronger awareness of users' diversity and emphasis on the need for understanding the different users and their different requirements before designing tailor-made solutions. Increased awareness about the difference and the diversity of users encourages a more pluralistic approach towards developing tools, practices, and data that may in turn increase the chances of implementing LCC in the AECO industry and ultimately improve the economic sustainability of buildings and constructions.

6. Conclusion

This research study aims to contribute on improving the LCC integration in the design practices of AECO industry by answering three research questions:

- RQ1: How does the activity system of building design facilitate or obstruct life-cycle cost calculations in design practices?
- RQ2: To what extent does current actions between the activity system of building design and construction and the activity system of building operation support data exchange regarding LCC?
- RQ3: Which novel actions may stimulate integration of LCC in design practices?

The research questions were answered through the publication of seven papers (Papers A-G). The following sections summarize how the findings of this research study contribute to research, practitioners, and policy makers.

6.1 Contribution to researchers

This explanatory research aims to increase integration of LCC in design practices by identifying and explaining the reasons of LCC limited adoption as well as pinpointing enablers and opportunities for LCC implementation. Therefore, this research study contributes to the research by confirming existing elements in the literature but also adding new elements and providing new research opportunities. Although the research does not contribute to theory as such, it reveals opportunities of using the theories to analyze, understand, and explain the practices in the AECO industry.

By answering RQ1, the findings contribute to the existing literature regarding the challenges of LCC limited adoption by confirming and adding elements as well as pinpointing opportunities of LCC implementation in social housing project. Throughout the case studies analysis, the author identified many challenges that are already discussed in the existing literature, for instance the lack of reliable cost data for performing LCC calculations that has been already pinpointed in the literature (Fu *et al.*, 2004; Gluch and Baumann, 2004; Oduyemi *et al.*, 2014; Salvado *et al.*, 2018). However, the study also reveals new insight into the existing literature that have not been presented before, for example limited communication regarding the reliability of design models and for decision-making (presented in Paper B (Saridaki and Haugbølle, 2019a)). Regarding the opportunities of LCC integration, the author was inspired by the existing literature regarding the exchange of knowledge between building operation and building design and highlighted possibilities of LCC implementation in social housing projects contributing to the existing literature by revealing a new area for examination (contribution of Paper D (Saridaki and Haugbølle, 2020c)).

By answering RQ2, the findings contribute to the research by providing a better understanding on the actions in social housing projects as well as the form of collaboration and data exchange between design, construction, and operation (Papers E and G (Saridaki and Haugbølle, 2020b, 2022b)). Moreover, the author challenged the hypothesis of poor data availability for LCC calculation (stated by Fu et al., 2004; Gluch and Baumann, 2004; Oduyemi et al., 2014) and pinpointed three actions of data exchange between design and operation that are presented in Paper G (Saridaki and Haugbølle, 2022b, under submission). By identifying those actions, the author discusses the possibilities and challenges of data exchange and utilization and contributes to the research area of transferring knowledge between design and operation as a more fundamental problem than just exchange of data. Moreover, the author highlights the relevance and benefits of using activity theory and structured analysis for analyzing actions and interactions in building projects as well as mapping the data flowing between the activity system of building design and building operation in building projects respectively throughout their lifetime.

By answering RQ3, the research findings contribute to the research regarding the application of different data management approaches by confirming and adding five lessons-learned of developing and testing two different methods in two building projects (in Paper A (Saridaki *et al.*, 2019)). In addition, the research in Paper F(Saridaki and Haugbølle, 2022a) contributes to methodological/theoretical research by highlighting the benefits of applying UCD methods not only as a design-oriented methodology but also as an analytical framework for improving our understanding about the users and for designing new tools and work processes. This study followed the eight steps for constructing personas proposed by Cooper (2014); however, due to the analytical approach of this study, the author did not designate between the three personas (this step is important in design-oriented processes, but a limitation in analytical process), but instead she empathizes the diversity of users and highlights the importance of thinking in diversity. The findings summarized three different user personas and contributes on providing valuable insights on people characteristics and their data management approaches.

6.2 Contribution to practitioners

This research has a strong focus on practices of building project design, and it is built on a case study analysis with several sub-case projects. Thereby, the research findings contribute to the design practices by analysis and explaining the challenges and opportunities regarding LCC as well as providing insights into improving the current practices and developing processes and tools that will enable integration of LCC.

By answering RQ1, the research contributes to the practices since the findings reveal insights into the various contradictions that shape the design processes and data management in architectural offices. The identification of contradictions in Paper B (Saridaki and Haugbølle, 2019a) contributes to understanding the core causes of the challenges of LCC implementation in the AECO industry and encourages AECO practitioners to redefine the design practices by amplifying motivation for change and development towards LCC adoption. In addition, the research findings of Paper D (Saridaki and Haugbølle, 2020a) contribute to the practices by highlighting that there are opportunities for LCC implementation in social housing projects and pinpointing availability of data and information that designers could utilize for performing LCC calculations.

By answering RQ2, the research contributes to practices by pinpointing three actions that support data utilization and exchange regarding LCC in social housing projects. The author provided solid examples on how the data that is provided by the social housing organization to the activity system of building design (for instance through the Model Maintenance Plan in the tendering process) can be utilized by the design team to perform LCC calculation and include LCC consideration in the project design (discussed in Paper E (Saridaki and Haugbølle, 2020b)). Moreover, the research findings of Paper G discussed contradictions between the element of the two activity systems that obstruct the utilization of the exchanged data and provided suggestions on how those elements of the activity systems under examination should be transformed in order to resolve existing misalignments that enable the creation of a shared objective towards LCC in the design practices.

By answering RQ3, the research contributes significantly to design practices and the integration of LCC by improving our understanding on the diversity of users of technology in design practices, pinpointing three different user personas (in Paper F (Saridaki and Haugbølle, 2022a, under submission)). The findings on the three personas provide insights into the characteristics of the designers and the way of working with technology and processing data, reflected in different methods of data integration methods. The research findings increased the awareness that there are at least three different approaches in relation to tools and processes that should be taken into consideration when developing new solutions. Hence, the results provided valuable information that can be used not only for designing novel LCC tools and increasing LCC implementation in the AECO industry but also in digital technologies in general. Furthermore, the findings of Paper A (Saridaki *et al.*, 2019) contribute to the practices by discussing lessons-learned of developing and testing two different approaches of LCC calculations, based on the different data integration approaches in two case projects. The author proposed recommendations to overcome existing obstacles of LCC implementation contributing to enable LCC integration in AECO practices.

6.3 Contribution to policy makers

This PhD study may contribute to policy making on LCC since it provides valuable insights into the challenges and impact of regulations and guidelines on LCC implementation. The findings of this study should be used by policy makers to improve how LCC is regulated through new requirements and regulations and to stimulate the creation of a shared long-term objective towards LCC. Improving the current policies is considered a critical intervention for stimulating the integration of LCC in the AECO industry.

By answering RQ1, the research findings pinpointed that the lack of standardized methodologies for managing and exchanging life-cycle related data between the different stakeholders of the project (Paper B (Saridaki and Haugbølle, 2019a)) was a significant barrier for LCC application, highlighting the need for developing standardized processes throughout the project lifetime and among different building professionals.

By answering RQ2, the research findings reveal that there are regulations that drive the consideration of LCC in social housing projects in both building design, through the mandatory LCC calculation using the LBF tool and building operation by registering O&M data and expenses in yearly basis. However, the findings highlighted misalignments between the elements of the two activity systems, and specifically, the lack of common rules and reviewing mechanisms to regulate and support data exchanging and utilization between design and operation. Therefore, the author pinpointed the need to develop and adopt commonly defined rules in addition to standardize processes of collaboration and data exchange as well as new incentives towards LCC to align the activity systems of building design and construction and building operation towards the creation of a shared objective regarding LCC.

By answering RQ3, the research findings in Paper A (Saridaki *et al.*, 2019) pinpoint that there is a need for creating common classification systems or mapping processes to translate classification systems between design and operation to enable automation in LCC calculations. In addition, the findings of Paper F (Saridaki and Haugbølle, 2022a, under submission) highlight the need for developing different types of tools to enable use of LCC with different groups of people in the AECO industry. Thereby, this encourages policy makers to fund and promote the development of diverse tools and processes.

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Appendices

Appendix 1. Paper A

Appendix 2. Paper B

Appendix 3. Paper C

Appendix 4. Paper D

Appendix 5. Paper E

Appendix 6. Paper F

Appendix 7. Paper G

Appendix 1

Paper A

www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

IMPLEMENTING LIFE-CYCLE COSTING: DATA INTEGRATION BETWEEN DESIGN MODELS AND COST CALCULATIONS

SUBMITTED: November 2018
REVISED: February 2019
PUBLISHED: February 2019 at https://www.itcon.org/2019/2
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SUMMARY: *The objectives of this study were to develop, test and summarise lessons learned using two different methods for data integration between autonomous software packages for design models, cost calculations and cost databases with regard to generating life-cycle costing analysis. The two developed methods followed the principles of compatibility and interoperability and were tested in three test cases: a simplistic design model, a university building model and a private company's office building model. The compatible method entailed an MS Excel tool while the interoperable method followed a more automated procedure through a visual programming environment. Both methods were, however, facing several obstacles with regard to data integration across autonomous software packages and automated procedures for calculation of life-cycle cost which in turn left plenty of manual work and made the results prone to human errors.*

KEYWORDS: *Life-cycle costing (LCC), Building Information Modelling (BIM), data integration, interoperability, compatibility, data management*

REFERENCE: *Maria Saridaki, Magdalini Psarra, Kim Haugbølle (2019). Implementing life-cycle costing: data integration between design models and cost calculations. Journal of Information Technology in Construction (ITcon), Vol. 24, pg. 14-32, http://www.itcon.org/2019/2*

1. INTRODUCTION

In a long-term perspective, the running costs of buildings equal the initial construction costs (Haugbølle and Raffnsøe, 2019; Goh and Sun, 2016). Hence, life-cycle costing (LCC) is a vital methodology for promoting a life-cycle perspective on buildings ensuring a fair comparison of solutions with different cost profiles over time, informing the decision-making process and improving risk management (Hofer *et al*, 2010). LCC has become a mature concept governed by two international standards (CEN, 2012; ISO, 2008), several industry guidelines (e.g. Caplehorn, 2012; Dhillon, 2010, Farr, 2011) and a multitude of tools (Sørensen *et al*, 2016). Still, the uptake has continued over the years to be rather weak due to significant challenges with regard to constraints in data accuracy and in current design practices (e.g. Bird, 1987; Cole and Sterner, 2000; Fu *et al.*, 2007; Gluch and Baumann, 2004; Marshall, 1987; Ruparathna and Hewage, 2015). In recent years, three new trends have strongly revitalised the focus on LCC in the built environment.

Firstly, the challenge of sustainability has fostered a renewed focus on LCC. Various certification schemes like LEED and DGNB require the use of LCC, while new integrated methodologies of life-cycle costing and life-cycle assessment are being developed (Du, 2015; Hoogmartens *et al.*, 2014). In a European context, the Level(s) framework for sustainability assessment of buildings, introduced in 2017 by the Joint Research Institute, entails LCC as one of its core indicators (European Commission, 2017). Secondly, new procurement policies are pushing for an increased use of LCC through the recent European Procurement Directive from 2014 (Directive 2014/24/EU) (European Commision, 2014) and local regulations, like the recent Danish national regulation on LCC in public construction (Bygningsstyrelsen, 2017). In addition, the new Danish Building Regulations 2020 will introduce a new voluntary sustainable building class addressing resource efficiency, hazardous materials, indoor environment and long-term value stability, including LCC (Mortensen et al., 2018). Thirdly, researchers and practitioners have lately shown increasing interest in LCC in relation to the new technological opportunities offered by building information modelling (BIM) (Liu *et al.*, 2015; Lu *et al.*, 2014; Miettinen and Paavola, 2014; Xu *et al.*, 2014).

BIM offers significant benefits of advanced productivity (Azhar *et al.*, 2008; Love *et al.*, 2011) and collaboration as the information can be stored and accessed any time (Meadati, 2009) and shared within the project team (Miettinen and Paavola, 2014; Eastman *et al.*, 2018). Through BIM, project variables such as cost, time and quality can be controlled from an early stage and contribute to more valuable decision-making (Fischer and Kunz, 2004) and thereby increase the information availability (Ahuja *et al.*, 2009; Dainty *et al.*, 2006).

This promising integration of BIM and LCC is pursued through a number of different approaches such as embedding LCC in existing 5D BIM tools (Kehily and Underwood, 2017), developing plug-ins to support the use of BIM for better maintenance accessibility (Liu and Raja, 2014) and developing a unique collaboration tool for asset and maintenance management (Spagnolo, 2018). Other approaches include applying standards like COBie to bridge the differences between BIM design tools and facility management systems (Tu et al., 2016), adding new techniques on multi-criteria decision-making for BIM use (Jalaei et al., 2015) and using semantic web for integration of IFC objects and information on facility management work (Kim et al., 2018).

Despite this revitalised focus on LCC, data management continues to be a significant obstacle for its application. While the use of BIM design tools promises to automate e.g. quantity take-offs, the real-world problems persist with regard to establishing robust and reliable models without flaws in the quantities (Chiurugwi *et al.*, 2015; Edirisinghe *et al.*, 2017; Owen *et al.*, 2010). More importantly, the absence of interoperability between different independent software solutions is a major hindrance to easing design simulations and exploiting data on geometry, quantities and cost flows across tools (HM Government, 2015; Hooper, 2015; Monteiro and Martins, 2013; Tsai *et al.*, 2014).

The same significant obstacles with regard to data management can be observed in the Danish architecture, engineering and construction (AEC) industry. Currently, the Danish AEC industry typically execute an LCC calculation based on a combination of three tools: (1) Sigma Estimates: a 5D BIM cost estimation tool (Sigma Estimates, 2003), (2) LCCbyg: a Danish application for LCC analysis (LCCbyg, 2018) and (3) internally developed spreadsheets. Although Sigma Estimates provides the possibility of a direct link and connection to cost libraries, the present value of future costs cannot be calculated, and the price development rates cannot be inserted. On the other hand, LCCbyg offers the latter although the link to design models and cost libraries for direct calculations is not established. Hence, the AEC industry needs tools in which specific costs in the future can be imported and a link between cost databases, the design model and the LCC calculations can be made.

Therefore, the objectives of this study are threefold:

- to develop two different methods of data integration between design models and cost databases based on the principles of compatibility versus interoperability of software solutions,
- to test the two different methods on three different test cases, and
- to evaluate the lessons learned and summarise these in five hindrances to the implementation of LCC in the AEC industry.

2. METHODOLOGY

This study is based on the combination of four different methods. An extensive literature review was performed and followed by a small number of interviews. Based on insights from the literature review and interviews, two different methods for data integration were developed and tested in three case studies.

2.1 Literature review

An extensive literature review was conducted with regard to LCC, BIM and different approaches to data integration between different types of autonomous software applications. The literature review draws on other previous literature reviews done by Haugbølle & Raffnsøe (2018)in relation to LCC, Thurairajah & Boyd (2017) in relation to BIM, and Toth et al. (2012) and Negendahl (2015) in relation to data integration. These reviews were supplemented with additional searches using Google Scholar and various literature databases like EBSCOhost.

2.2 Interviews

Three interviews were conducted to identify current LCC practices in the Danish AEC industry. Collaboration was established with a leading engineering consultancy company for gathering information on current LCC practices and for testing the developed data integration methods. Two interviews were conducted with employees of the company. The first interviewee was a consultant/client advisor of the company who is responsible for the project and financial management of sustainable building projects. The second interviewee was a DGNB Practitioner from the Energy and Sustainability Group of the company. The aim of the two interviews was to clarify:

- The current work process of the company when performing LCC analysis.
- The different tools and software used for cost or LCC calculation.
- The data gathering procedure for LCC calculation.
- The challenges that the company faces when performing an LCC analysis.
- The room for improvements regarding the LCC analysis.

A third interview was conducted with a senior researcher of the Danish Building Research Institute (SBi). SBi has developed the application LCCbyg (LCCbyg, 2018), which is the main tool used for LCC calculations in the Danish construction industry, as it also supports the required calculations for DGNB certification. The aim of the interview was to clarify:

- The benefits and limitations of the LCCbyg application.
- The need for improvement of the LCCbyg application.

2.3 Development of two different methods

Two methods based on the compatible and the interoperable approaches were developed. The aim was to develop tools that can directly link design models and cost databases and accurately calculate the life-cycle costs of an entire building or individual building components. In both methods, the main results are generated through Sigma Estimates (Sigma Estimates, 2003) – a 5D BIM cost software that is commonly used in the Danish AEC industry. Sigma Estimates was chosen as it provides an established connection with Revit Autodesk software (design tool) (Autodesk Revit, 2018) and with Molio Price Database (a database on Danish construction prices) (Molio Prisdata, 2018). Through the connection with Revit Autodesk, data from a Revit Model can be extracted to Sigma Estimates through the plug-in function. The extraction creates a 'Sigma Project' in the Sigma Estimates software in which all the elements and their quantities from the Revit model are automatically imported. The Sigma project can then be connected with a 'Sigma Library', which includes all unit costs of the elements' activities and calculates the costs of the project. However, Sigma Estimates cannot be used for LCC calculations as it does not consider the effect of time on cost values (inflation and discount rates). Hence, in both approaches a tool is needed for transforming the cost values into life-cycle cost values.

In the compatible approach, the transformation of cost values is facilitated through an MS Excel-based tool. MS Excel is selected in this approach, as it is a standard tool that offers a graphical user interface and can be used by a wide target audience. Moreover, data from Sigma Estimates can be easily exported into and imported from an MS Excel file. In the interoperable approach, the transformation is performed through Visual Programming Language (VPL) which offers a more advanced and automated way of generating results. Dynamo, a VPL tool, is used in this case as it collaborates efficiently with Revit through its plug-in function.

2.4 Test cases

In order to identify the challenges of integration between different tools, an LCC analysis was performed of three different case studies: a simplified building model, a university building model and an office-building model by the engineering consultant company.

The initial intention was to calculate the life-cycle costs of the company's office building model and compare it with the analysis that is currently being carried out by the company. However, as significant challenges occurred early in the procedure, it was decided to design a simple building model in Revit and use it as 'test model' for the tools' development.

This simplified model consists of five basic types of components (four walls, six windows, one door, one roof, one floor and one floor covering). This simple building model could not only be easily handled, but also enabled the validation of the results by manual calculation due to the limited number of elements it contained.

Afterwards, a university building model was used for testing the functionality on a large scale and validating the methods. This large-scale model was also used for optimising the procedure of LCC calculations.

Finally, after the development, validation and optimisation of the methods, the company's office building model was examined. The model is an office building consisting of eight floors and with a gross floor area of 13,223 m^2, located in the metropolitan area. Due to the high level of complexity of the model, the research focused on the window elements only as these are the main elements of the building's façade and have a considerable impact on the total LCC of the project.

3. STATE-OF-THE-ART: LCC, BIM AND DATA INTEGRATION

3.1 Life-cycle costing and data requirements

While the term of a total cost of ownership (TCO) is applied in the recent European directive on public procurement (Directive 2014/24/EU) and more widely in other business sectors (Ellram, 1993), the term of life-cycle costing (LCC) or whole life costing (WLC) is more commonly used in building and construction industries. LCC/WLC belongs to the broader field of strategic investment and financing (Hedegaard and Hedegaard, 2008). The terminology is defined by the ISO 15686 series on service life planning (ISO, 2008) followed by the EN 15643 series on sustainability of construction works (CEN, 2012). Different approaches and guidelines of LCC have been described within various business areas of application (Dhillon, 2010), product development of complex systems (Farr, 2011), choice of materials (Caplehorn, 2012) and national guidelines e.g. in Norway (Bjørberg et al., 1993). The greatest advantage of LCC analysis is that it can be used to compare different alternatives (Dell'Isola and Kirk, 2003; Norman, 1990) based on several key factors such as costs, quality and comfort over the entire life cycle of the product (Haugbølle and Raffnsøe, 2019; Collier, 2009; Flanagan, 1989).

An LCC analysis requires data from different sources (Lansink, 2013) (FIG. 1):

- Data on actual costs in each of the five distinct life-cycle stages of the construction project. These costs include construction costs as well as costs for energy and water demand, drainage etc.
- Data regarding specific quantities of elements (e.g. areas, pieces etc.).
- Data for conversion of costs occurring in different time periods (discount rate, price development of different cost groups etc.).
- Data regarding the quality and purpose of the construction, its technical parameters and its expected lifespan as well as the life cycle of the materials used. Additionally, the frequency of maintenance and other work should be defined.

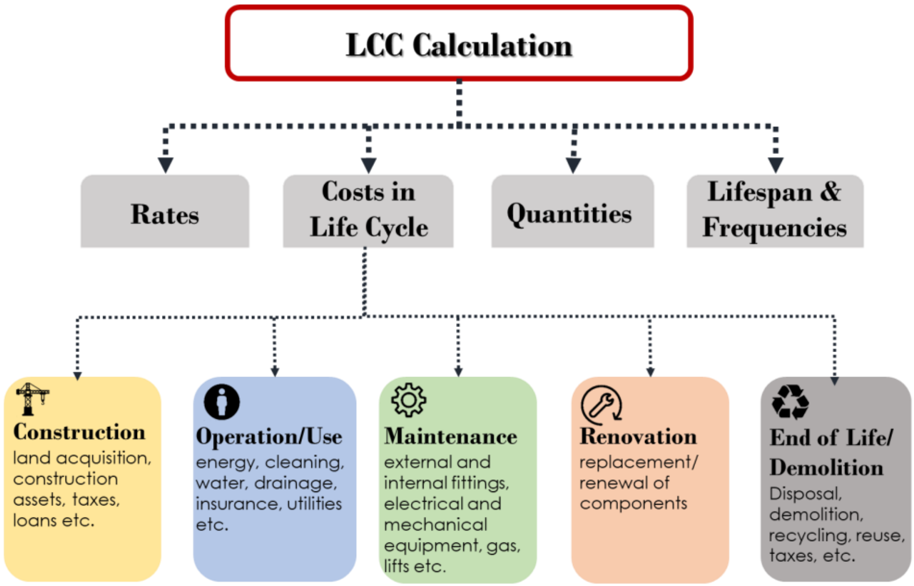

FIG. 1: Data requirements for LCC.

An LCC tool should be able to exchange data between various sources for example (FIG. 2):

- Design models in order to extract quantities (e.g. Revit, SketchUp).
- Data sheets containing product information in order to extract the information regarding the life cycle, maintenance, operation activities of the elements.
- Cost databases in order to extract the costs of different elements and activities.
- Financing data like inflation and discount rate.
- Facility management software in order to be used for e.g. maintenance planning.

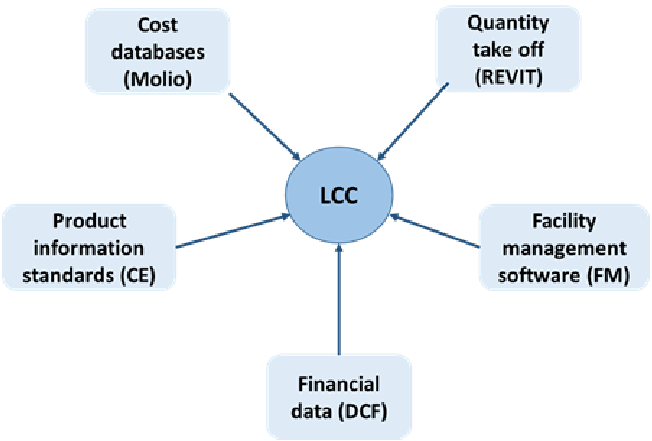

FIG. 2: Data requirements of an LCC tool.

3.2 Building Information Modelling

The concept of BIM is increasingly adopted by the AEC industry especially when performing sustainable building design as it offers significant advantages of increased productivity and collaboration (Bryde *et al.*, 2013; Doumbouya *et al.*, 2016; Liu *et al.*, 2015). In recent years, several definitions have been applied to describe the concept of BIM (Abbasnejad and Moud, 2013; Holzer, 2007; Latiffi *et al.*, 2014). The US BIM standard defines BIM as "a digital representation of physical characteristic of a facility, a shared knowledge source of information about a facility forming a reliable basis for decisions during its lifecycle, defined as existing from earliest conception to demolition" (NBIMS, 2010).

Although the concept has existed since the 1970s (Eastman *et al.*, 2018) the term of BIM as an innovative approach to building design and construction management was introduced by Autodesk in 2002 (Autodesk, 2008). In order to support the purpose of BIM, Autodesk acquired the software Revit, which is based on object-based parametric building modelling technology that represents the building as "an integrated database for coordinated information" and delivers all the BIM benefits (Autodesk, 2008; Demchak *et al.*, 2009). Other CAD software has been developed, adopting the object-based parametric modelling concept, like Graphisoft – ArchiCAD (1984); Bentley Building Information Modelling (2002); and Nemetscheck – AllPlan (2003) (Eastman et al., 2018). Currently, a variety of software and tools are used to support BIM in terms of designing, simulating, visualising, collaborating as well as gaining the advantages of data interconnection within a BIM model (Pluralsight, 2013). Nevertheless, the BIM concept does not rely on unique applications, but represents a process of gathering, holding, updating and exchanging information on a building through the project life cycle (Azhar et al., 2012; Tse et al., 2005).

BIM fosters an environment where the model information is contained (Aouad et al., 2006). Therefore, BIM models are files consisting of objects that hold, update and document all information related to the building, including its physical and functional characteristics and project life-cycle information. Those BIM objects consist of a unique set of information, which forms its identity. Thereby, it is crucial to enhance the information of a BIM object by calculating and adding additional information. Subsequently, information should be openly accessible by different software and be able to be extracted and used by other software in order to enrich the model by continuously adding new information (Hallberg and Tarandi, 2011).

The implementation of BIM can make the industry more flexible, effective and innovative (Patil and Khandare, 2017). As pointed out by Thurairajah and Boyd (2017), harvesting the digital dividends of BIM is not simply about efficient processes but also easy accessibility to information and more importantly the transformative power towards smart construction, new business and financing models, and the emerging digital economy based on e.g. Internet of Things. Even though the use of BIM has increased in the AEC industry, there are still limitations for its full adoption. There are several formats for data exchange such as IFC, BSDD etc., however one of the main challenges is the lack of harmonisation among BIM standards for model integration and management by different stakeholders. The standardisation activities in CEN TC 442 (DIN, 2018) and ISO TC59/SC 13 (ISO, 2018) are working towards the direction to unify those methods and increase the interoperability among different tools. .. Hence, a harmonised approach towards data integration still remains a crucial factor for the further development and enrichment of BIM models.

3.3 Approaches to data integration

Several approaches of BIM implementation have been described in the AIA diagram for digital technology in architectural practices (Singh et al., 2009) and BIM levels UK diagram (NBS, 2018). Both diagrams refer to various approaches that were used in the past, are currently being used and expected to be used in the future. However, in this study, the authors focus on the currently used approaches of data integration between different kinds of autonomous software that can be achieved by following two basic conceptual approaches: compatibility and interoperability (Zhang et al., 2006).

Compatibility is a controlled and restricted approach of data integration where one or more tools are 'built' on one main tool in order to address a specific issue or opportunity (FIG. 3). An example of compatible software is plug-in solutions and application-programming interfaces.

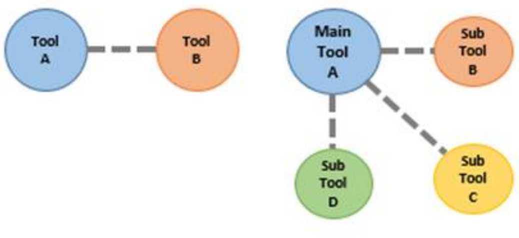

FIG. 3: Compatible approaches to data integration: 3a. Two main tools; 3b. One main tool and several sub-tools. Source: Adapted after (Zhang et al., 2006)

In both cases, the main tool (Tool A) is able to control the design and accuracy of the model, while the calculation functionalities are essentially integrated and thus enable domain integration of data between the tools (Davis and Brady, 2013). The main limitation of compatible approaches is that the user is restricted to the options that are offered by a specific software environment. Hence, this approach does not comply with the concept of BIM as the information that is generated is limited to the use of specific tools (Davis and Brady, 2013; Areo, 2016).

In contrast, interoperability refers to the ability of software to communicate, exchange data and use the information that has been exchanged (IEEE, 1990; Wegner, 1996). In interoperable approaches, the different kinds of software share the same work place to enhance the collaborative process and to achieve significant improvements in the life-cycle management of projects (Plume and Mitchell, 2007). At the highest level of interoperability, automation and avoidance of data re-entry can be accomplished.

More specifically, the main concept of interoperability refers to the ability of various tools to share the same data schema, and thereby, can read and write in the same data model (FIG.a). The introduction of shared data schemas such as IFC, COBie and XML has significantly contributed to solving interoperability issues (Pazlar and Turk, 2008; Smith and Tardif, 2009; Berlo *et al.*, 2012). However, the effectiveness of such a collaboration relies on the design and the quality of the model. Thereby, it imposes restrictions on how designs can be described and thus explored and shared (Plume and Mitchell, 2007; Patacas *et al.*, 2014).

FIG. 4: Different concepts of interoperability: 4a. Shared data schema; 4b. Shared mapping process; 4c. Linking individual tools via file transformation. Source: Adapted after (Toth et al., 2012; Negendahl, 2015)

Toth et al. (2012) suggest another method of achieving interoperable data integration by linking tools through a shared mapping process (FIG.b). In this approach, tools do not share the same schema, however, data of one tool are automatically transformed to the target data set of another tool through a custom data-mapping interface that includes visual definitions of transformation rules. An advanced algorithm will offer guidance to the users in matching data across schemas, so that mapping can be created in less time, with less errors and fewer mistakes (Fagin et al., 2009). Although this approach provides a framework to embed current tools in a more cohesive, shareable and customisable digital workflow, it requires great effort to script data-maps and transformation rules for the various tools (Toth et al., 2012).

Finally, another more decentralised approach of interoperability is achieved by linking individual tools through file transformation (FIG.c). In this case, VPL can be used not only as a simple converter between formats but also for adjusting, conforming, enhancing or eliminating data between the tools (Negendahl, 2015). The maximum number of converters that are required in this approach is n(n-1), where n is the number of tools. However, in theory but rarely in practice, a converter enables bi-directional link between the tools. In those cases, the maximum number of converters required is n(n-1)/2. Although this is a flexible approach, it relies on human interpretation of semantic meaning (Toth et al., 2012).

4. FINDINGS: TWO DIFFERENT APPROACHES

Before developing the two methods, the different activities of the elements during their life cycle and their current cost should be identified. For this reason, a new Sigma library of all the elements' activities during the life cycle was created in Sigma Estimates. The Sigma library was structured in three levels. At the first level, the examined elements are categorised based on their types in the Revit model (wall, window, etc.). At the second level, subcategories for the different life-cycle stages for each element are created (construction, maintenance, etc.). The life-cycle stages selected for this analysis are the construction stage, the maintenance stage, the operation stage and the renovation stage. At the third level, the different activities of each element for each stage are selected from the Molio Price Database. By creation of the library, all the costs of all the activities through the life cycle of the examined elements were set (FIG. 4).

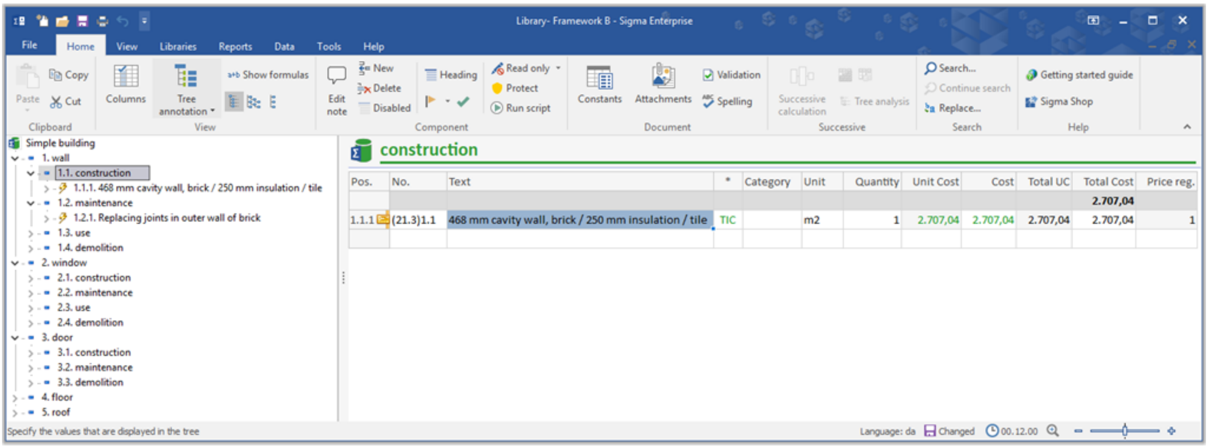

FIG. 4: Structure of Sigma Library (print screen from Sigma Estimates tool).

The following sections present the framework of each method along with the definition of the coding system used and the structure of the developed tool.

4.1 Method A – a spreadsheet-based tool

The first method is based on the principles of compatibility. The compatible solution includes the development of an MS Excel tool, which is used for transforming the costs of the activities that are included in the Sigma library into life-cycle costs. The method is based on the capability of Sigma Estimates to export and import files in excel format. In the MS Excel-based tool, the LCC equation is scripted and optimised by Visual Basic for Applications. FIG. 5 provides an overview of this method in six steps.

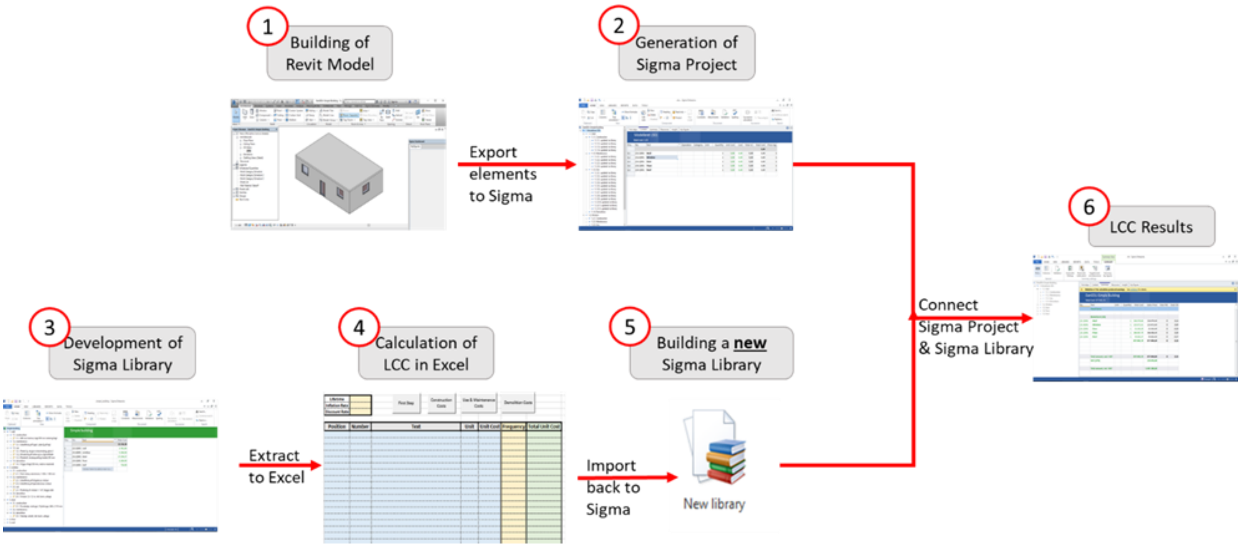

FIG. 5: Overview of method A: a spreadsheet based tool.

After building the Revit Model (Step 1), information from Revit (elements and quantities) is exported through the plug-in function in Sigma Estimates and a Sigma Project is generated (Step 2). Then a Sigma Library is developed in Sigma (Step 3). The library is extracted to the MS Excel-based tool where the elements' unit cost values are transformed into LCC unit values (Step 4). The next step is to import the new values back to Sigma Estimates by building a new Sigma Library (Step 5). Finally, the Sigma Project and the new Sigma Library are connected and the final LCC results are calculated (Step 6).

The connection of Sigma Project and Sigma Library is facilitated through a coding system. In this case, a coding system is proposed based on the BIM7AA encoding system (BIM7AA, 2017), which is based on the international classification system SfB. According to the proposed coding structure, each code consists of two parts: the first part is represented by the BIM7AA classification code of the element and the second part by a serial number of the elements of the same category (FIG. 6). The codes of all elements are first assigned in the Sigma Library in the field 'No.' and then set in the Revit Model as project parameter for each element type, which will later be exported in the Sigma Project along with the quantities.

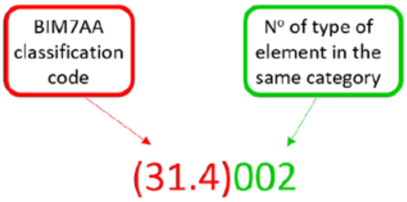

FIG. 6: Proposed coding system for method A – case related.

Finally, the structure of the MS Excel tool developed for the first method is presented in FIG. 7. As described above, the user exports the Sigma Library, where all the activities of the elements during their life cycle are included along with their units and costs, in the developed MS Excel tool. In the tool, first the user sets basic information regarding the project such as its lifetime, the inflation and discount rates as well as the frequency and the renovation year for each activity. Next, the unit costs are converted to unit life-cycle costs by simply clicking the appropriate buttons. The user can then import the life-cycle cost values back to Sigma Estimates by generating a new Sigma Library.

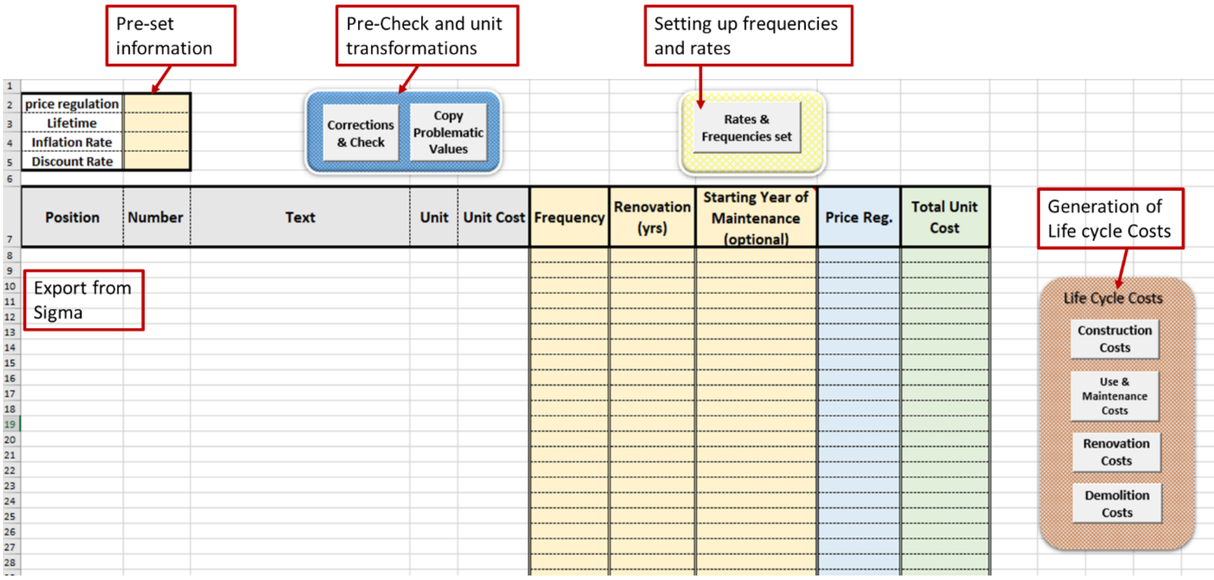

FIG. 7: Structure of the MS Excel- based tool.

4.2 Method B – a dynamic model based on VPL

The second method is based on the principles of interoperability. In particular, the approach of linking tool via file transformation (Section 3.3, Fig. 4c) is followed. In this case, Dynamo (DynamoBIM, 2017), a VPL tool, is used for performing the LCC analysis. FIG. 8 provides an overview of this method in five steps.

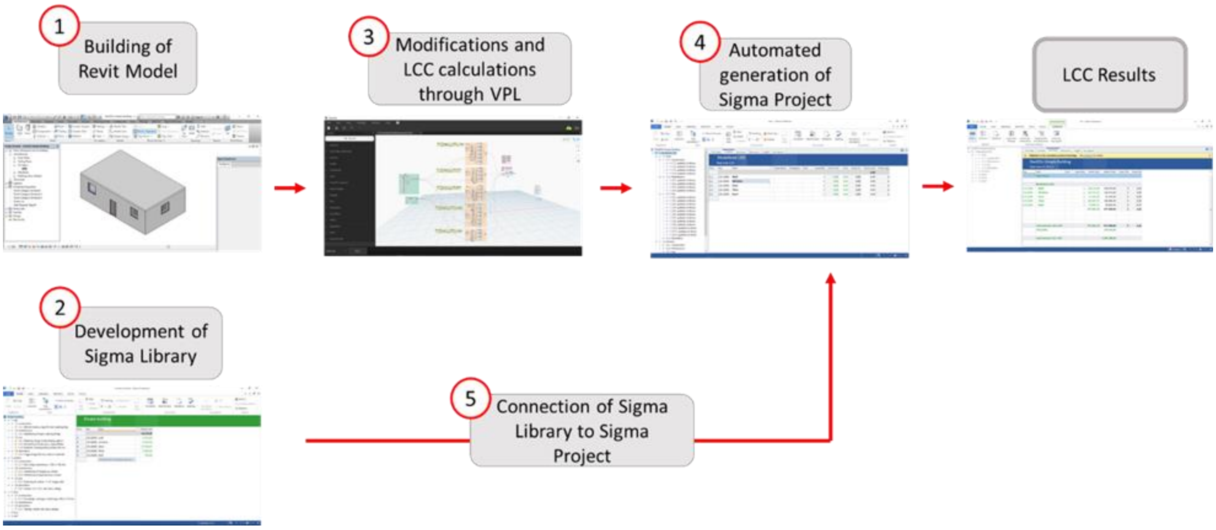

FIG. 8: Overview of Approach B: An integrated Dynamic Model.

In this method, the Revit model and Sigma Library are developed in parallel (Step 1 & Step 2). Then, the quantities of the examined elements are extracted from the Revit design model to the Dynamo model where the LCC calculation is performed (Step 3). The Dynamo model not only operates the LCC calculations but simultaneously controls, filters and enhances the integration of information between Revit and Sigma Estimates. According to Negendahl (2015), the model can be characterised as an integrated dynamic model as it is a middleware between two tools (Revit and Sigma Estimates) based on VPL. When running the Dynamo tool, a Sigma Project is automatically generated (Step 4). The Sigma Project is connected with the Sigma Library and the LCC results are calculated (Step 5).

A coding system is required to facilitate the connection between the Sigma Project and the Sigma Library. However, the coding system in this method differs from the one used in the first method as the code should refer not to each element but to each activity as each activity carries its own unique information. Subsequently, the coding system now consists of three parts (FIG. 9). The first part, which refers to the element, is based on the classification suggested by BIM7AA. The second part is a number that refers to the life-cycle stage based on its time sequence in the life cycle of the project. Finally, the last number is a serial number for the activities of an element of a specific life-cycle stage. The numbering in this part depends on the number of different works in the life-cycle stage of the unique element.

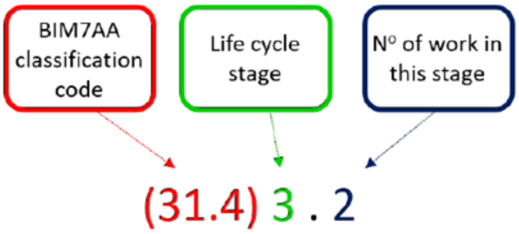

FIG. 9: Proposed coding system for method B – case related.

The codes are inserted in the field 'No.' in Sigma Library. Additionally, the same codes are set in Revit Model, by creating new project parameters for each element. The amount of project parameters for each element is equal to the amount of activities that are assigned to it (FIG. 10).

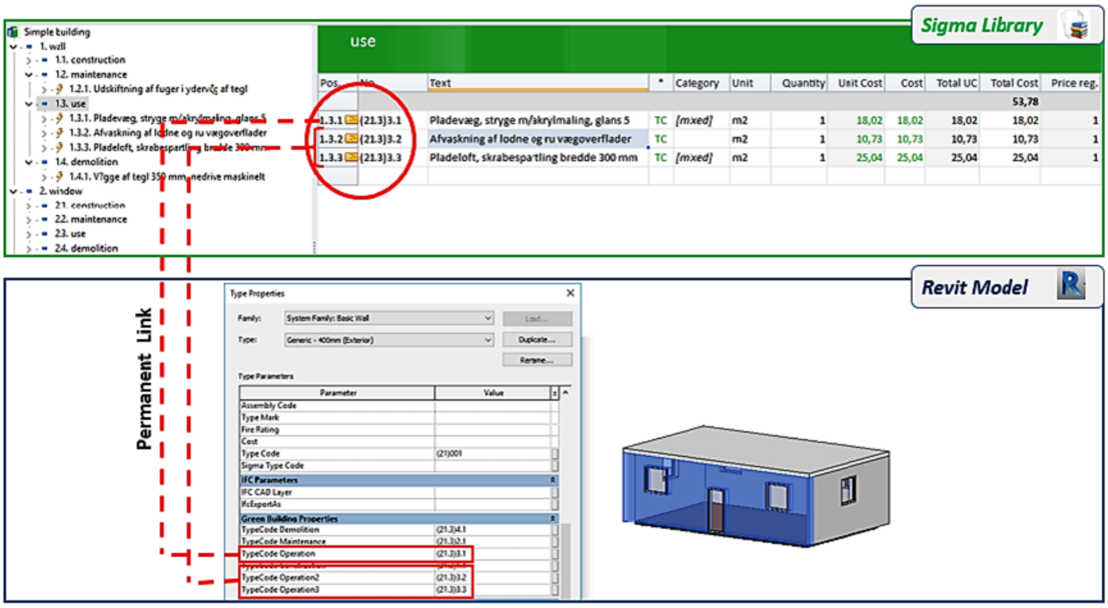

FIG. 10: Coding setting in Sigma Library and Revit Model.

Finally, the structure of the Dynamo model is illustrated in FIG. 11. In the figure, the different coloured areas represent a specific function of the model. In the light pink area on the right, all the pre-sets are defined. In the grey area on the left, the LCC calculations of an LCC parameter are processed as the LCC equation of the LCC parameter is scripted in Python (Python, 2018). The user can modify the default inputs of the LCC equation (the service life, inflation and discount rates as well as the price development). In the green area, the elements of the Revit Model are selected and grouped. In the orange area, the structure of the exported project is developed and in the blue area, the exportation is facilitated.

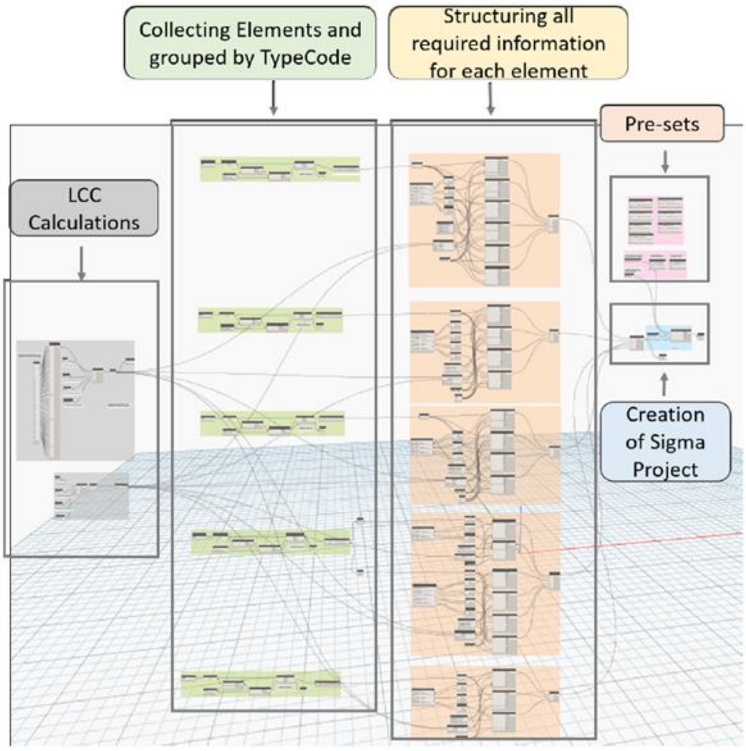

FIG. 11: Structure of Dynamo Model.

5. DISCUSSION: FIVE LESSONS LEARNED

Although both methods succeed on generating LCC results, during the development and the testing, five issues became apparent with regard to data integration between different approaches in order to support LCC calculations. These five issues, however, are not tied to the specific methods that are developed in this study, as similar methods can be developed by using different BIM tools (like ArchiCAD and Grasshopper, instead of Revit and Dynamo, respectively). Hence, they are in general relevant to data integration approaches and the existing limitations of BIM models. These issues include: non-conformity of unit values, lack of classifications and coding systems, extensive manual work requirements, poor design of models and insufficient methodology for and exchange of life-cycle data.

5.1 Non-conformity of unit values

Early during the development of the tools, it was observed that there is a significant issue of non-conformity between the unit quantities that are extracted from Revit to Sigma Estimates and the unit that costs are given in Molio Price Database. For instance, the number of window elements is exported automatically from Revit to Sigma Estimates as 'pieces' through the plug-in function. However, even if cost is given per piece for most of the activities that correspond to window elements, there are others where cost is given per square meter, for example in activities that are related to cleaning of window elements. Due to this misalignment of the unit value, the connection between the Sigma Project and Sigma Library cannot be performed correctly automatically. Therefore, the unit transformation should be executed before the connection either on the extracted quantities in Sigma Project or on the costs in Sigma Library, otherwise connection problems can occur. This challenge is not related to the developed tools nor to the LCC calculations, but to the restricted extraction of quantities from Revit to Sigma Estimates.

The integrated dynamic model, based on the principles of interoperability, is capable of extracting the requested unit quantity without any restrictions. However, in the first method the MS Excel-based tool is not interceded on the extraction of the elements as it is a simple transformer of costs into life-cycle costs based on the values offered by the Sigma Estimates (as the tool is compatible with Sigma Estimates). To handle this limitation, a VPL-Dynamo model is developed to correct the quantities and introduces a generic solution to this issue requiring minimum user interference, which will be applied subsequently to every project. The non-conforming values are identified in the MS Excel sheet (which had different unit measurement than the one extracted from Revit) and then, the VPL Dynamo model performs the unit transformation and imports them back into the spreadsheet tool.

The issue of mismatch between the units of building materials between the different tools is very common. Therefore, in order to cope with this issue unit convertors are required in order to enable the correct transfer of quantities between the tools.

5.2 Lack of commonly used coding system

In order to facilitate the connection between the tools in both methods, the establishment of a coding system is crucial. However, there is an urgent need to establish or rather implement common standards for the digital transfer of information. There is a lack of a generic coding system that is commonly adopted and integrated in the AEC industry. More precisely, there are several classification systems available to the Danish AEC industry, but there is a lack of industry consensus on which classification system to use and a lacking willingness and ability to pursue the implementation of one such system.

This study proposed using a coding system for each method based on the BIM7AA encoding system (BIM7AA, 2017). In both methods, effort and time are required to apply the codes for every element especially in case of large-scale projects. Although different Dynamo models are developed to facilitate the creation of the parameters and setting their values in Revit, it is still a challenging, mainly manual, procedure which is both time consuming and prone to human error. Additionally, the existing classification system does not cover facility management needs (Howard and Björk, 2008).

Since the establishment of a common classification system worldwide has proven unsuccessful so far, an achievable solution could be a shared mapping process, similar to the method 4b, introduced in section 3.3. In that respect, a translator would be required between different coding systems, in order to enable integration of information between models with different classification systems.

5.3 Extensive manual work required

The full integration of LCC and automation of calculation is crucial in order to speed up the procedures and make calculations less exposed to errors by minimising the human error and producing more reliable results. However, the automation of cost calculation is one of the main barriers of the current work processes. Due to the large amount of data required, LCC becomes an incredible time-consuming process when performed manually (Fu et al., 2007).

The two methods of this study proposed to integrate the calculations to avoid the manual insertion of values in an LCC application. However, both methods require human intervention to a varying degree. Especially the first method requires manual work at different steps (from Step 3 to Step 4, and from Step 4 to Step 5 as it is illustrated in FIG. 5) in order to produce LCC results. For instance, due to the performance of the specific tool to extract data only by creating a new spreadsheet, the user needs to transfer the extracted data from Sigma Project to the MS Excel tool manually (Step 3 to Step 4). Moreover, when a change is implemented in either the design model or the Sigma Library, the entire procedure has to be repeated from the beginning, and thus it takes time to generate LCC results. The second method follows a more automated procedure and provides a permanent link between the design program, Sigma Estimates and LCC calculations, offering the user the possibility to directly view the effect of any change to the costs by simply pressing a button. Even though implementation of changes is easier in this method, much effort and time are still required since the model must be correctly configured at the first time when it is used in a project.

Furthermore, in both methods manual effort and manual checks are required for setting the codes in both design model (Revit) and the cost library (Sigma Library) and for ensuring that all codes have been placed correctly. For this reason, both tools were optimised, and several checker models were additionally developed using Dynamo software. Nonetheless, the testing of the methods in the three test cases indicated that the main factor affecting the validity of the LCC results is often a human error.

Another time-consuming task proved to be the comparison between alternative solutions for the windows' material in the third case study, the company's office building model. As Revit is able to present only one design alternative at a time, the model has to be changed several times. Likewise, a new Sigma Library was required for each case of comparison and the whole procedure for producing results had repeatedly to be carried out from the beginning.

5.4 Poor design of models

As underlined by Plume et al. (2007) more than 10 years ago, one of the main challenges of data integration is that the engineers do not design with collaboration interchange in mind. Unfortunately, this still seems to be a main issue. During the testing of both methods, the inappropriate design of both the university and company's office design models turned out to be counterproductive for facilitating a proper BIM connection. The lack of distinctive types of elements in both models led to significant difficulties of extracting the required quantities and thus implementing an LCC analysis.

More specifically, window and door elements were designed as curtain walls in the design model of the university building, resulting in the existence of elements with different dimensions under the same type. The lack of distinctive types was a challenge when the first method was followed as in this method the functionality of the Sigma Library as well as the assignment of the codes is structured based on the assumption that all the elements of the same type have the same properties. However, this was not an issue when the second model applied.

Additionally, in the company's design model of the office building there are significant issues related to the design of the model. Specifically, the window elements are designed as part of 'sandwich panels' which belong to the 'Generic Model' category. The building contains 35 'sandwich panels' and each panel consists of a wall with one or two windows or none. Therefore, since the windows are not designed as window elements, they cannot be selected, and their quantities cannot be easily retrieved. Consequently, the methods could not be applied appropriately due to the design of the model, and manual modifications were required in order to implement the developed methods.

In order to overcome this challenge, the different sandwich panels were grouped according to the type of window they contained. Each group contained panels with windows of the same material and the same dimensions. Based on that description, ten different groups were created. A unique code was afterwards assigned to each group in order to facilitate the connection between Revit and Sigma Estimates. It is assumed that each extracted sandwich panel, depending on the number of windows in the specific sandwich panel, represents one or two pieces of windows.

To facilitate the process of LCC calculations, the integrated dynamic model of method B and the Dynamo model that was used for unit transformation in method A were modified, in order to group the sandwich panels based on their type code. After the categorisation, 10 different groups of sandwich panels were identified.

However, in Sigma Library there are activities the costs of which are given in square meters (m^2) or running meters (lbm). As the area and the length of the sandwich panels are not equal to the area and length of the windows, the Dynamo model should be modified in order to extract and use the correct area and length quantities of the windows. For this reason, a new group of nodes is created in the Dynamo model where the area of an element's material is retrieved from the sandwich panel.

Based on the case studies, it was concluded that the output of design models is usually still geometry-oriented and not actual BIM models. Hence, in order to enable data integration, the general common BIM requirements (COBIM) should be followed by the designers. COBIM series 3 (Oy and Henttinen, 2012) includes modelling principles in architectural design underlining the importance of proper design of the elements in distinctive types, as well as the content requirements for architectural BIM in different project phases.

5.5 Insufficient methodology for and exchange of life cycle data

When performing the LCC analysis, one of the main difficulties is the lack of global standards or standardised methodology to guide the exchange of life-cycle information (Monteiro and Martins, 2013). Specifically, there is seldom much available information regarding the future activities required for the operation and maintenance of a building component. Usually the manufacturers specify the service life of an element, but they rarely provide guidance regarding the maintenance and operation activities in a quantifiable manner. Moreover, there is no standardised way of exchanging information between the engineers, the manufacturers and the facility managers (Chiurugwi et al., 2015). This situation makes the analysis complicated, especially for an inexperienced user.

The lack of life-cycle data affected the analysis of the company's case study especially during the creation of the work library as there were neither standardised activities for the elements' life cycle nor available standardised cost data. Especially for inexperienced users, this lack of guidelines and standardised methods made the creation of a library a difficult and time-consuming procedure.

Additionally, as the manufacturers' environmental performance declarations (EPDs) showed significant discrepancies regarding the recommended works throughout the life cycle, meetings and interviews with windows manufacturing companies were conducted in order to identify the different activities through the life cycle. Moreover, assumptions regarding the different works were made based not only on the interviews but also on recommendations from the DGNB practitioner.

In order to enhance the availability of information, the manufacturers could include in EPD a list of maintenance and operational activities of materials, which can be used by engineers and facility managers. Moreover, the use of Construction Operations Building Information Exchange (COBie) standards that include information like equipment lists, product data sheets, warranties, preventive maintenance lists, etc. will enable communication of information among stakeholders involved in the project.

6. CONCLUSION

LCC is not yet fully adopted by the Danish AEC industry as it requires a high level of data management and data exchange between different types of software. This study developed and tested two methods for automated LCC calculations based on the principles of compatibility and interoperability in order to integrate data across different types of autonomous software packages.

In both approaches, the developed LCC tools were integrated with a cost calculation software (Sigma Estimates) which links with a cost database (Molio Price Database) and has an established connection with a design tool (Revit). Method A followed the principles of compatibility and was based on MS Excel that can be easily applied through a familiar graphical user interface. Method B followed the principle of interoperability and was based on VPL for filtering and controlling the information integration and simultaneously calculating LCC. This interoperable approach had the advantage of offering a permanent link with the design model which enabled the practitioner to see directly the effect of changes in the model to the total LCC by simply running it. Both methods were applied and validated in three different test cases: a simplistic building model, a large-scale university building and a private company's new office building.

Even the successful generation of LCC results, both methods faced a number of obstacles with regard to data integration across autonomous software packages and automated calculation of LCC. The first obstacle was the non-conformity of unit values between the design model and the cost calculation software. The second obstacle was the lack of a commonly used coding system for facilitating data integration. The third obstacle was the lack of fully integrated and automated procedures of LCC calculations. The fourth obstacle was the poor design of models, which often comprise non-geometric or non-distinctive types of elements. The fifth and final obstacle was the lack of a standardised methodology for exchanging life-cycle information.

In conclusion, this study indicates that there are still various hindrances related to data management that need to be overcome in order to integrate LCC and BIM. Even if the development of the two methods enable the integration of LCC into design practices, it still falls short of fully automated procedures which in turn leaves plenty of manual work and exposes the results to human errors.

7. ACKNOWLEDGMENTS

We would like to special thank Erik Falck Jørgensen, External Lecturer & Academic Staff, Technical University of Denmark and Jan Karlshøj, Associate Professor, Technical University of Denmark for their assistance as well as their ideas and constructive feedback thought the development of the two methods.

We also thank Solveig Nissen, Danish Building Research Institute, Aalborg University, for her corrections and comments that greatly improved the manuscript.

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Appendix 2

Paper B

Identifying Contradictions of Integrating Life-Cycle Costing in Design Practices

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Abstract

Purpose – The architecture, engineering and construction industry faces several challenges when performing life-cycle cost calculations. On the basis of activity theory, this study aims at improving our understanding of the current cost calculation in design practices as an activity system with a number of built-in contradictions.

Design/Methodology/Approach – Drawing on one of the authors' practical experience from a design office, the research design comprises a paradigmatic case study of a Danish architecture firm, in which data are gathered through documents, observations, interviews and physical artefacts. Moreover, this paper applies a literature review on barriers for adopting life-cycle costing.

Findings – The paper identifies a number of primary, secondary, tertiary and quaternary contradictions between practices of design, cost calculations and data management. Thus, hypotheses are formulated on how and to what extent these different contradictions shape cost calculations in design practices to obstruct or support the application of life cycle costing principles in design.

Research Limitations/Implications – This study is part of an ongoing research project. Thus, additional analysis is required before the authors may conclude on final results.

Practical Implications – This paper identifies a number of factors that obstruct or support the implementation of life cycle costing in current design practices.

Originality/Value – This paper provides new insights into the various contradictions that shape data management in architectural offices as a prerequisite for improving life cycle design practices.

Keywords Activity theory, Life Cycle Costing (LCC), Data management, BIM, Contradictions, Design practices

All papers within this proceedings volume have been peer reviewed by the scientific committee of the 10th Nordic Conference on Construction Economics and Organization (CEO 2019).

Emerald Reach Proceedings Series
Vol. 2
pp. 33–39
Emerald Publishing Limited
2516-2853
DOI 10.1108/S2516-285320190000002038

1. Introduction

The increased interest for sustainable construction challenges the architecture, engineering and construction (AEC) industry to focus on not only the environmental performance of buildings but also the economic assessment of alternative solutions in the long term. The concept of life-cycle costing (LCC) is used as a decision-making tool in construction and proved its value for strategic management. Despite the increased literature on LCC in the past years, there is a gap between theory and practice, as the industry faces various challenges on adopting LCC in work practices (Cole and Sterner, 2000).

This study applies activity theory (AT) as a theoretical base for understanding the LCC calculation practices of a Danish architectural firm as the outcome of an activity system of building design with a number of built-in contradictions. AT has proven highly useful in studies of information systems and practices (Allen *et al.*, 2011). The cross-disciplinary framework of AT is currently used in the construction industry for describing and analysing the complexity and interaction in actions in projects and for development of tools and applications (Lu *et al.*, 2018). Studies include AT as a framework of redesigning work (Engeström, 2000); for identifying contradictions of using BIM in life-cycle construction projects (Hannele *et al.*, 2012); for identifying information sharing and interoperability issues (Allen *et al.*, 2014); for examining the use of BIM and corresponding issues in the construction site management (Maki and Kerosuo, 2015); for adoption of flow techniques in software development (Dennehy and Conboy, 2017); for developing information research system (Karanasios, 2018); and for analysing BIM use in building operation and management (Lu *et al.*, 2018).

Therefore, the present study investigates the following research question: "How does the activity system of building design facilitate or obstruct adequate life-cycle cost calculation among building professionals?" Through literature review and case study analysis, the study will identify and analyse the main contradictions that support or hamper LCC adoption in the AEC industry. AT is proven beneficial in this particular research as the identification and analysis of contradictions will help practitioners to understand the core causes of the problem and redefine their practices to include LCC (Bonneau, 2013).

2. Methodology

AT was initiated by the Russian psychologists Lev Vygotsky (Vygotsky, 1978) and Alexei Leont'ev (Leont'ev, 1978) in the 1920s and 1930s. The first-generation of AT focuses on the triadic relation between an individual (the Subject) and a raw material or problem space (the Object) mediated by Tools and signs (Miettinen *et al.*, 2009). Engeström expanded that triadic model by emphasizing the collective nature of human activity and introducing the terms Community, Division of Labour (DoL) and Rules as additional interacting key elements of the second-generation activity system (Engeström, 1987). Later, Engeström introduced a third-generation activity model in which at least two activity systems are interacting (Engeström, 2001).

Various terms and principles are used for understanding and analysing the human activity in an activity system, including the concept of contradictions. Contradictions are "historically accumulating structural tensions within and between activity systems"; however, they generate "disturbances and conflicts, but also innovative attempts to change the activity" (Engeström, 2001, pg. 137). In an activity system, there are four types of contradictions, namely, primary, secondary, tertiary and quaternary. Each of them describes the misfit within one or more element, between two elements, between different developmental phases of a single activity or between neighbouring activities, respectively

(Foot and Groleau, 2011). The identification of contradictions is essential as they are forces for motivation of a change and development (Engeström, 2001).

The research approach that is followed in this study for the identification of contradictions in the activity system of building design includes a literature review and a single case study analysis.

2.1. Literature review

A literature review was performed on current application of LCC in the industry with emphasis on barriers of limited adoption as well as the use of AT in relevant research. Studies were gathered by using Google Scholar and various literature databases. The main key words of the research were LCC in relation with implementation, barriers and use as well as activity theory.

2.2. Case-study analysis

A case-study approach is followed in this research, as case studies have proved valuable for handling "practice-based issues where the experiences of the actors are important and the context of actions is critical" (Benbasat *et al.*, 1987, pg. 369). The research design of this study comprises a paradigmatic case study (Flyvbjerg, 2006), where the case company is a Danish architecture firm. That firm is selected as a case study as (i) its type and size are fairly typical, (ii) the process applies a range of elements typical of cost calculations during design, and (iii) the firm and its projects expose central contradictions induced by LCC when applied in design. Thus, this single-case is particularly suitable for analysing the present research, allowing connections between constructs that will lead to theoretical insights (Eisenhardt and Graebner, 2007).

To identify patterns and contradictions in the current design practices of the case study, internal multiple sub-case analysis is used. Specifically, three case-projects are selected for analysis. To ensure maximum variation of case selection, the case selection criteria were based on the performance of LCC calculations. The first project is an extraordinary case, as successful calculations have been performed (Project A), the second project is a typical case, including typical calculation methods (Project B), while the third projects lacks LCC calculations (Project C). The present study draws on qualitative analysis of data from documents, direct observations, interviews and physical artefacts of the architectural firm (Yin, 2009).

3. Findings

The literature review and the case study identified a number of challenges with regard to LCC adoption related to all four types of contradictions in the activity system.

3.1. Primary contradictions

Primary contradictions are located *within* the central activity system in relation to the elements of: subject, tools and community.

Subject: In the literature review, Gluch and Baumann (2004) pinpointed the lack of understanding of LCC definitions and methods as a critical issue for the practical usability of LCC. This is confirmed in the case study analysis, in which it was observed that despite extensive initiatives on sustainability matters, only a small percentage of individuals working in the case company have the necessary knowledge to conduct an LCC analysis.

Tools: According to literature, there are a considerable number of tools for LCC calculations (Sørensen *et al.*, 2016). However, practitioners have difficulties finding accessible and reliable data required for the calculations (Underwood and Dehily, 2017). Although, in the case study, cost data are retrieved from a Danish cost database, the LCC practitioner of Project A remarked that those data differ from the data provided by EPDs.

Community: In the research by Olsson *et al.* (2015), the lack of knowledge on sustainability issues is recognized as an important barrier for limited adoption of LCC in the AEC industry. Through the case study analysis, it was recognized that many of the stakeholders involved in the projects, including major clients, showed little awareness on sustainability, and it was challenging to acknowledge the importance of LCC implementation. Moreover, through the literature review, it is also identified that there is limited understanding of the AEC industry on the benefits of using LCC in investment decisions (Gluch and Baumann, 2004), which is also confirmed in the case study analysis as several clients were considering only short-term costs.

3.2. Secondary contradictions

Secondary contradictions are located *between* the elements of the central activity systems especially between the elements: Subject versus Tools, Subject versus DoL and Subject versus Community.

Subject versus tools: The interviews in the case study analysis identified that the practitioners of LCC face difficulties in implementing LCC with regards to the available tools. The tools include the mathematical methodology but lacked automated procedures, requiring manual intensive work. In the case of Projects A and B, LCC users insert all data (material quantities, cost data, future maintenance activities, etc.) manually, spending much time and effort in generating results. An LCC practitioner in the case company characterizes the LCC calculations as "a complex and tedious task". Thus, as it is also stated in the literature, the AEC industry lacks useable software (Goh and Sun, 2016) and the calculation of LCC is, currently, a time-consuming procedure, prone to human error (Fu *et al.*, 2007).

Subject versus DoL: In the case-study analysis, it was observed that the collaboration of the LCC practitioner and the rest of the project team was limited and not well structured. Specifically, in the case of Project A, it was observed that two LCC practitioners were involved in the calculations without having clearly divided tasks. Thereby, part of the procedure was executed twice due to the limited communication, while during that time, the communication with the design team was also limited. The LCC practitioners relied only on the information provided in the design model and were not aware about any change, thereby increasing the possibility of errors. The communication was still limited after the execution of the calculations as well as during the decision-making process.

Subject versus community: One additional contradiction of LCC application, which is identified in the literature and observed through the case study analysis, is the lack of standardized methodology for managing and exchanging life-cycle data (Monteiro and Martins, 2013). There is seldom information available about future maintenance activities, while manufacturers rarely provide guidelines for maintenance and renovation activities of the elements. Moreover, there is no standardized way of exchanging information between engineers, manufacturers and facility managers (Chiurugwi *et al.*, 2015). In the case study, the LCC practitioner of Project B emphasized that the LCC results are fluctuating depending on the price data that are used (data provided by either cost databases or manufacturers).

3.3. Tertiary contradictions

Tertiary contradictions occur when the object of a more advanced activity system is introduced to the central activity system, which was observed in this study between the elements of traditional design processes of the architectural firm and the current processes that include building information models (BIM) to facilitate LCC calculations.

The literature review noted that even though the use of BIM offers new technological opportunities for advanced life-cycle management (Xu *et al.*, 2014), there are still challenges in design practices to establish robust and reliable models (Edirisinghe *et al.*, 2017) because engineers and architects do not design the models with collaboration interchange in mind (Plume and Mitchell, 2007).

In the case-study analysis, contradictions with regard to design models and the use of BIM were identified in all case projects. In Projects A and C, the community resists using the BIM model, while in Projects B and C, the models lack reliable data for LCC calculation. More specifically, in Project C, 2D software was used by the project team to satisfy the need for highly detailed design, which is difficult to be represented by using 3D BIM software. However, 2D models do not include the appropriate information required for the LCC calculation, and thus, the implementation of LCC in those projects requires additional effort and time. Despite the use of BIM software in project B, the models are missing appropriate information, like the elements' materials, causing errors in the LCC results. Finally, in Project A, the stakeholders made use of software that does not support BIM models. However, for supporting the collaboration, the stakeholders conformed to the need of using BIM and thus facilitating the activity system of both model design and LCC calculation of the case company.

3.4. Quaternary contradictions

Quaternary contradictions occur between the elements of the central activity system and neighbouring activity systems, which were observed between the central activity of LCC application and the co-existing activities of project design in the architectural firm.

Through the case study analysis, it is recognized that even though the activity system of design practices has been improved in terms of information modelling to support the advanced requirements of LCC (BIM models are used in Projects A and B), the work allocation and work processes of co-existing design activities as well as the data management procedures have not been transformed yet to enable the decision-making process.

4. Conclusions

On the basis of a literature review and a case study analysis of a Danish architectural firm, this study uses activity theory to identify the factors that hampers or obstruct the implementation of LCC in design practices.

The findings pinpoint several contradictions in the activity system of design practices. In particular, the case study analysis revealed new insights to the limited adoption of LCC mostly related to secondary and quaternary contradictions. Specifically, the secondary contradiction between the elements of Subject versus DoL in the activity system expose that several errors in LCC calculation occur owing to the limited communication between the LCC practitioner and the design team as well as the unstructured division of tasks and responsibilities. Moreover, quaternary contradictions were observed when the activity system of work practices tries to move from design without to design with LCC calculations showing that the current way of collaboration and work allocation are barriers for realizing the benefits of LCC and impede its use as a decision-making tool for improved quality of design projects.

To conclude, the identification of contradictions may help AEC practitioners to understand the core causes of challenges in implementing LCC and redefining design practices, hence amplifying their motivation for change and development towards adoption of LCC in current design practices.

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Appendix 3

Paper C

Identifying LCC user types using the concept of personas

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Abstract

The increased interest of the Architecture, Engineering and Construction (AEC) industry on the economic aspect of sustainability has stimulated the development of tools and concepts for life cycle cost (LCC) calculations. Little is, however, known about how LCC users apply the concept in practice. The aim of this paper is to improve our understanding of the practices of LCC users and identify the requirements of LCC tools from the perspective of users. The study applies user-centric design methods, in particular the concept of personas, to explore the different approaches that building designers are willing to make use of LCC tools with regard to integration of data. The authors conducted qualitative and quantitative user research, including observations, interviews and questionnaire surveys, in a Danish architectural firm that is a frontrunner with a high sustainable profile including LCC. Through the analysis, the case-subjects were grouped by role and several behavioral variables were identified. Then, the case-subjects were mapped against each of those variables and three significant behavioral patterns of different user types were recognized. The first pattern indicates that users with low technical skills, are more feeling than thinking and usually face challenges of spending time and effort to perform tasks manually. The second pattern indicates that users who are more introvert and have medium programming skills, are dissatisfied for the lack of compatibility between the software that they use and face challenges of continuously repeating task. The third pattern indicates that users with advanced programming skills, are more adaptive in new technologies. Hence, they are willing to fully automate the procedures and reduce time spending on tasks. In conclusion, the identification of significant behavioral patterns of users is a fundamental step of constructing personas. Mapping potential users as personas provide a better understanding of the practices of LCC users, and the identification of their requirements is the first step towards the development of LCC tools and approaches that can be effectively used by the AEC industry.

Keywords: User-centric design, personas, user profile, Life Cycle Costing (LCC), smart design.

1. Introduction

The increased interest of the Architecture, Engineering and Construction (AEC) industry on the economic aspect of sustainability has stimulated the development of tools and concepts for life cycle cost (LCC) calculations. LCC belongs to the broader field of strategic investment and financing (Hedegaard and Hedegaard, 2008) and can be effectively used for assessing alternative solutions that have different cost effects over time and therefore, making sustainable decisions (Gluch and Baumann, 2004). LCC terms are defined by the international standard ISO15686 series on service life planning (ISO, 2008) followed by the European standard EN15643 series on sustainability of construction works (CEN, 2012).

The last few years, the Danish AEC industry shows significant interest for applying LCC in design practices. A wider use of LCC has stimulated due to several new trends: first, new governmental regulation of public construction issued in 2013, which requires all public clients (including municipalities and counties) to apply LCC in projects above certain thresholds; second, the establishment in 2012 of the certification scheme DGNB adopted by the Green Building Council Denmark for sustainable buildings and urban areas in which economics have a very prominent position (DK -GBC, 2012); and third, the new European procurement directive from 2014 supports the use of total cost of ownership as an award criterion in competitive tendering rather than just lowest price (European Commision, 2014). Moreover, LCC will be part of the new voluntary class of the Danish building regulations of 2020 (Mortensen et al., 2018).

For managing LCC, a range of different approaches and tools exist. As pointed out by Sørensen et al. (2016), existing LCC tools can be divided into three main types with distinct characteristics and associated benefits and drawbacks: 1) spreadsheets (often company-specific), 2) stand-alone applications, and 3) web services. In the Danish AEC industry, the most commonly used tools are internally developed spreadsheets and the LCCbyg application which also supports DGNB calculations (LCCbyg, 2018). Although the availability of multiple tools, LCC faces limited adoption not only in the Danish but also in international AEC industry. Several studies have been performed in order to understand the barriers of limited LCC adoption, shown various challenges of poor implementation, including: the lack of understanding of LCC definition and methods (Gluch and Baumann, 2004), lack of tool awareness (Olsson et al., 2015), lack of usable tools (Olubodun et al., 2010; Goh and Sun, 2016), lack of reliable data (Oduyemi et al., 2014; Fu et al., 2007), lack of formal guidelines (Kehily and Underwood, 2017), complexity of calculations (Fu et al., 2007), insufficient data management and poor data collection and storage (Fu et al., 2007).

Little is, however, known about how LCC users apply the concept in practice. This research focuses on the positive agenda of LCC use and instead of identifying additional barriers, it aims to improve our understanding on how people work with LCC in practice. The objective of this paper is, therefore, to recognize current and potential LCC users and their characteristics in work practices and thus, determine the requirements of LCC tools from user perspectives. The study applies user-centric design (UCD) methods and in particular, the concept of personas to explore the different approaches that building designers are willing to make use of LCC tools with regard to integration of data.

2. The concept of Personas in UCD

UCD is a human-computer interaction philosophy focusing on the development of systems based on users' requirements instead of technical requirements (Junior and Filgueiras, 2005). In UCD approaches, scenarios are used to assess users' actions capturing typical and critical uses of technology in a narrative form (Turner and Turner, 2011). Realistic user scenarios seem to be an ideal tool for design. To enhance engagement and reality in scenario development and also avoid the tendency of designers to design for themselves without thinking the actual users, the concept of personas is used (Floyd et al., 2008; Grudin and Pruitt, 2002). Personas represent concrete groups of users that the designers are designing for, and they are identified as *"a handy tool to facilitate user-center design"* (Floyd et al., 2008, p. 13).

The concept of personas introduced by Alan Cooper in 1999 (Cooper, 1999). Personas are archetypes that represent target groups of users that sharing similar behaviors, motivations and goals (Marshall et al., 2015). Although personas are functional, they represent real people throughout the design process (Grudin and Pruitt, 2002). Personas are used to communicate user requirements to designers (Kantola et al., 2007) and thus, facilitate useful and usable design (Grudin and Pruitt, 2002; Floyd et al., 2008). To enrich realistic representation and thereby engagement, designers give to personas life by adding personal information, like name and image as well as life story. However, personas are not made-up but are discovered through the contact with real users (Junior and Filgueiras, 2005). Usually, one to seven personas are developed to support a project (Marshall et al., 2015). They are used as UCD technique to help designers to guide decision about the interaction design and characteristics of product (Goodwin, 2001). According to Turner and Turner (2011), creation of personas is the first step of design life-cycle.

When personas have been developed, the design team can explore tasks by constructing scenarios around them (Grudin and Pruitt, 2002; Blomquist and Arvola, 2002; Cooper, 1999; Floyd et al., 2008). The most common types of persona-based scenarios are (Cooper et al., 2007): (1) the context scenario, which is created before the design and is used to identify how the tool can satisfy the user needs; (2) the key path scenario, which is focuses on user interaction with the tool; and (3) validation scenarios, to test the design of tool in a variety of situations.

There are several benefits of using the concept of persona compared to traditional user research techniques (Miaskiewicz and Kozar, 2011). In the literature, various advantages for using personas and persona-based scenarios have been identified including, among else, the engagement of designers and developers to integrate user needs into the systems, creation a common language between designers and users, making design decision based on a small set of specific users, and overcoming issues that arise when a full range of user data is presented (LeRouge et al., 2013; Pruitt and Adlin, 2006; Pruitt and Grudin, 2003; Chapman and Milham, 2006; Cooper, 1999).

Hence, there are several examples of using personas in practice and the concept is increasingly used among software designers (Cooper, 1999). For instance, personas have been applied for the development of a new computerized case-handling tool for administrators working with national registrations in a Swedish National tax board project (Gulliksen et al., 2003); for building usable information sites (Head, 2003); for evaluating two existing educational software packages that are used in the Business school of the University of Auckland, NZ (Dantin, 2005); for redesigning a work-integrated learning support system (Dotan et al., 2009); for increasing effectiveness on product design (Guo et al., 2011); for recognizing potential areas in which BIM can be useful for FM practices (Becerik-Gerber et al., 2012); for designing and developing consumer health technologies (LeRouge et al., 2013); for developing commercial products (Wilkinson and De Angeli, 2014); and in the process of developing Open source software (Llerena et al., 2016). Moreover, the concept has been adopted by Microsoft which applies a persona-centered interface design and uses personas in various projects since 2002 (Pruitt and Grudin, 2003).

3. Methodology

The research approach that is followed in this study for gathering data to design personas is a single case study analysis. The case company is a Danish architectural firm which is a frontrunner in the field of sustainable design in constructions including LCC. The case company implements LCC analysis in various design projects and it is selected as the case study as it consists of engineers and architects that represent the users that the authors are willing to design for. The data for the analysis are gathered through both qualitative and quantitative methods, including direct observations, participant observation, interviews and surveys (proposed by Baty, 2009; Kantola et al., 2007).

More specifically, firstly, potential users are identified internally in the case company through direct observation and surveys. Then, characteristics and behavioral information about those people are gathered through observations, semi-structured interviews and questionnaires. Following, the authors communicate directly with those people and contacted unstructured interviews in order to deeply understand how they work, what are their challenges and requirements and how they want to use LCC information; Finally, the author followed participant observation techniques to observe those people doing their works with great focus on how they handle the data for LCC calculations.

After the collection of data through the case study analysis, the 8 principles' steps for constructing personas proposed by Cooper et al. (2007) are followed (Figure 1). However, this is a primary study which aims attention in the 4-first steps of constructing personas, namely "Grouping interview subject by role", "Identifying behavioral variables", "Mapping subjects to behavioral variables" and "Identifying significant behavioral patterns" respectively, while Step 5, 6, 7 and 8 namely "Synthesizing characteristics and define goals", "Checking for redundancy and completeness", "Designate persona types" and "Expanding description of attributes and behaviors" respectively, will be investigated in further study.

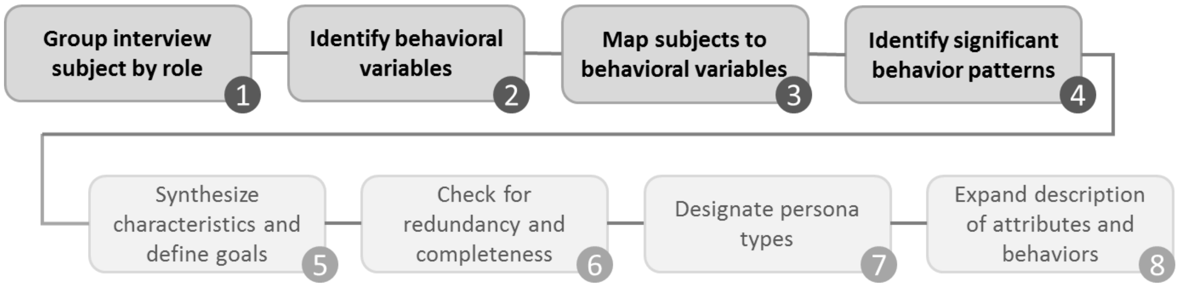


Figure 1: Steps of constructing user personas (Adapted by Cooper et al., 2007).

As it is illustrated in Figure 1, based on a preliminary analysis, the subjects were grouped by role (Step 1) and the role of case-subjects under examination was selected. Thereafter, through the case study analysis and the collection of data, the authors identified behavioral variables for the case-subjects (Step 2) and the case-subjects were mapped against each of those behavioral variables (Step 3). For facilitating Step 3, additional data were gathered through an online survey. The survey was sent in 60 case-subjects during November 2018 and included 22 questions which were developed based on the behavioral variables that identified in Step 2. During a period of 15 days, 48 responses were collected and analyzed. After analyzing the results and mapping the case-subjects, significant behavior patterns were observed (Step 4). The results of the analysis are described in the following section.

4. Findings

In this study, a case study analysis was performed, and the authors collected data from current and potentials LCC users in order to generating personas that will support the design of an LCC tool. In this section, Steps 1, 2, 3 and 4 of constructing personas (Figure 1) are further described. Those steps are fundamental for developing personas, as they include the main analysis of user data and the identification of characteristics of different users.

4.1 Step 1: Grouping interview subjects by role

The first step of constructing personas refers on grouping the interview subjects according to their roles. Through a preliminary analysis, the authors performed an extensive literature review and conducted several stakeholders' interviews in the Danish AEC industry in order to identify the different stakeholders along with their roles as well as their requirements in regard to the use of LCC tools. When the case study was selected, the authors participated in several meeting and seminars, and analyzed the internal workflows to identify factors that support or hamper the LCC implementation internally in the case company. Through the analysis, it was decided to narrow the focus research on current and potential LCC users as they are the most important stakeholders in terms of interest and impact on LCC. Hence, the role of the subjects under examination is architects and engineers of the case company that are current or potential users of LCC tools (refer to them as: case-subjects). Thereafter, the case study was further examined by gathering and analyzing data on case-subjects through a 4-month period.

4.2 Step 2: Identifying behavioral variables

The second step refers to the identification of behavioral variables, and it is crucial for developing effective users' archetypes. Through the case study analysis, 7 main categories of variables (A-G) were identified as it is presented in the first column of Table 1. Based on those categories, 22 behavioral variables were selected as it is presented in the second column of Table 1. All variables are significant for identification of different users' types.

Table 1: Behavioral variables of current and potential LCC users in the case company.

Categories	**Variables in each category**
A. Demographic	1. Gender 2. Age
B. Aptitude	3. Education 4. Role in the company 5. Years of experience
C. Personality	6. Introvert vs Extrovert 7. Judging vs Perceiving 8. Feeling vs Thinking 9. Resistance vs Adaptive
D. Skills	10. Familiarity with technology and programs 11. Programming skills 12. Familiarity with Microsoft Excel 13. Familiarity with graphical applications 14. Familiarity with CAD applications
E. Activities	15. Use of software in general 16. Use of software in work practices 17. Frequency of using software
F. Attitude	18. Evaluation of software in terms of usability 19. Challenges of using those software
G. Motivation	20. Expectation of improvement in software 21. Need of additional features or software 22. Goals by using different software

In the first category of demographic variables, two variables of gender and age were considered under examination. Both variables are important indicators for constructing personas as they give a basic idea of how a person likes. In category of aptitude, three variables namely users' education, role and years of experience, were used to indicate the users' level of knowledge as well as their ability to learn. Related to the personality, four variables were selected in relation to the curiosity of subjects on learning and developing skills. In category of skills, five variables were set to understand the skills of users and evaluate their software and programming skills as well as their familiarity with commonly used software. Another important indicator of users is related to their activities, and hence, three variables were set including software usage, along with volume and frequency. For indicating the attitude of users in relation to different software, two variables were used to identify users' perspective on usability. Finally, three variables were set to describe the challenges that users are facing, their expectations and what they would like to improve in their work processes in regard to the use of software.

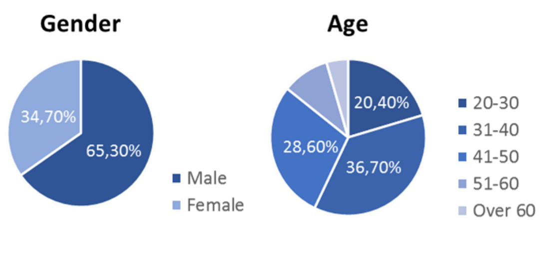
4.3 Step 3: Mapping case-subjects

After the identification of the behavioral variables, an online survey was sent out in the case company in order to facilitate the mapping of the case-subjects against each one of the behavioral variables of Table 1. Mapping of the case-subjects is a significant procedure for identifying the placement of each subject in relation to the others. In this step, the precision of the position of the case-subjects is less important than the relative position between them. However, due to the large sample of this analysis, the relativity of positions of case-subjects was not distinguished for each one of the case-subjects but instead, it was evaluated in a 6-levels scale. For instance, the personality variable number 6 of Table 1, is evaluated against a 6 levels linear scale, which indicates the volume of how introvert or extrovert are the case-subjects in levels from 1 to 6. Therefore, the case-subjects were distinguished relatively along this scale, meaning that for example, the case-subjects that belong to level 3 are more introvert than those that belong to level 4 in the scale, but more extrovert than those that belong in level 3. However, there is not additional differentiation between the case-subjects that belong to the same level.

When the responses of the survey were collected, the results were carefully checked and assessed by the authors as the answers in many variables, especially in the variables of categories C and D of Table 1, are highly objective since the case-subjects evaluated themselves – their personality and their skills. Hence, the authors evaluated and supplemented the results based on the findings of qualitative research that had been performed earlier in the case study analysis. The final results of mapping the case-subjects against each of the variables are following presented.

Regarding the demographic variables, the results shown that there are more males than females in the case company, in percentage of 65 % and 35%, respectively. Moreover, the majority of the case-subjects (in percentage of 37%) are in the age of 31-40, while high percentage of them are also in the age of 41-50 and 20-30 (29% and 20% respectively). Regarding the aptitude category of variables, the education of case-subjects is mainly in architecture, and most of them work in the case company as design architects or project leaders. The results of both demographic and aptitude variables are presented in Table 2.

Table 2. Mapping case-subjects against demographic and aptitude variables.

Demographic Variables	Aptitude Variables	
	**Education:**	90% Architects (incl. landscape architects) 10% Const. Managers & Engineers
	Education Level:	6% PhD degree 80% Master's degree
	Role/ Tasks in the company:	35% Design Architects 33% Project Managers 8% Urban Planning 6% Communication, R&D 18% Other (BIM coordinator, etc.)

Regarding the personality of the case-subjects, it is observed that there is high percentage of both introvert and extrovert users, however, most of the participants are more perceiving than judging, as 69% of case-subjects are placed in levels 4, 5 and 6 of the scale, while only 8% and 23% in levels 2 and 3, respectively. Moreover, the case-subjects are neither extremely feeling nor thinking as the higher percentage of them are placed in the middle levels 3 and 4. In addition, more case-subjects are adaptive than resistant since 82% of them are placed in levels 4, 5 and 6 of that scale. The results of mapping case-subjects in the variables of personality category are illustrated in Figure 2.

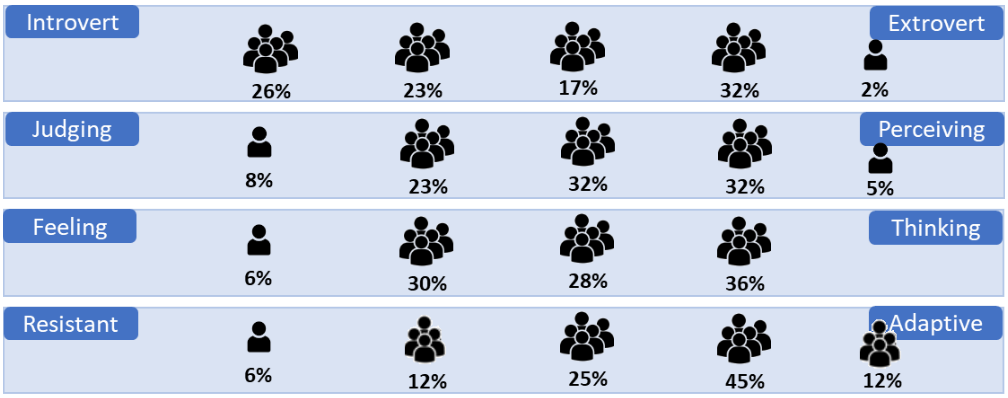


Figure 2: Mapping case-subjects against the behavior variables of personality's category.

Regarding the results of mapping the case-subject in relation to their skills, it was observed that although most participants are familiar with technologies and programs, a percentage of 23% has very low or not at all programming skills, in contrast to the only 2% that has high programming skills. However, in average, the case-subjects feel quite familiar with Microsoft Excel, graphical applications and CAD applications. The results of variables in the category of skills are presented in Figure 3.

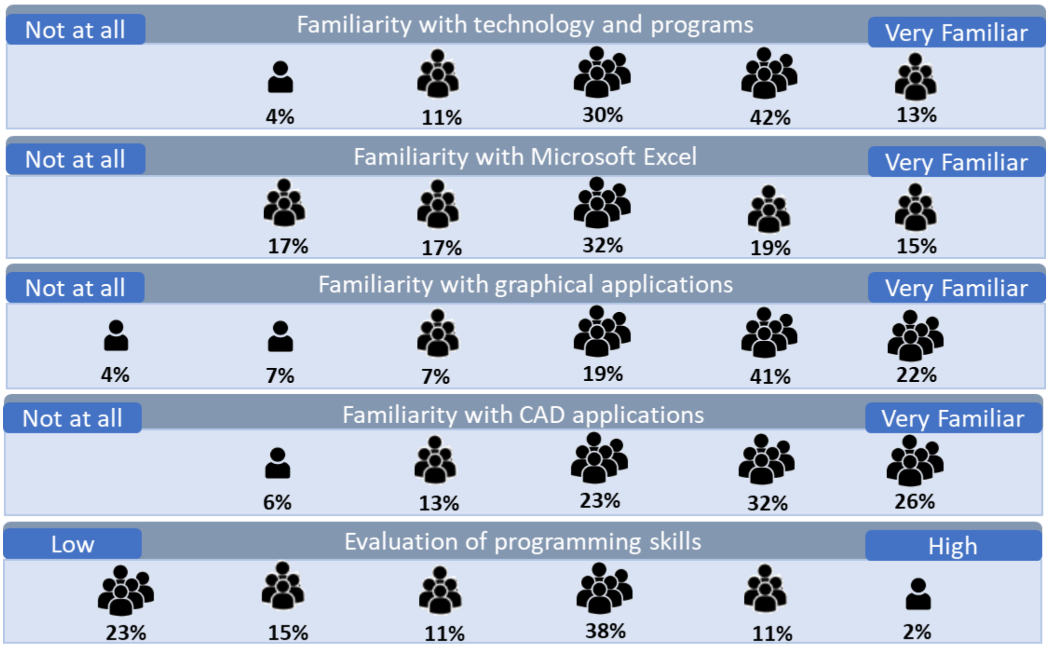


Figure 3: Mapping case-subjects against the behavior variables of skills' category.

Mapping case-subjects against the variable of activities' category, the results indicate that 85% of the case-subjects use Microsoft word and Excel, 83% use AutoCAD, while 60% use REVIT. Moreover, 29% of case-subjects use calculation software and a high percentage is also observed in the use of Adobe applications (InDesign, Illustrator, Photoshop, etc.). However, 50% and 35% of the case-subjects use AutoCAD and Revit, respectively, in their work processes in a weekly frequency.

However, regarding the attitude in relation to frequently-used software, 63% of AutoCAD users believe that AutoCAD is an easy to use software, while only 12% of REVIT users believe that REVIT is an easy-to-use software. In contrast, 41% of REVIT users believe that is really hard to use it. In general, the challenges that the case-subjects are facing in regard to the use of software are mostly related to lack of interoperability, default setting, different keyboard shortcuts between software even from the same producer, crashes of software as well as the use of different software in different stages of the project. Finally, the case-subjects are willing to reduce the time by using software more effectively and also to reduce effort of manual tasks by automating procedures and increase compatibility. Moreover, they would like to have more templates and standards to guide them through the use of new software and in general to work with simpler software.

4.4 Step 4: Identifying significant behavioral patterns

After concluding the third step of mapping all case-subjects against each of the variables, the next step of identifying significant behavioral patterns was performed. According to (Cooper et al., 2007), significant behavioral patterns are considered when a set of six to eight variables are observed to be followed by a group of case-subjects. The patterns should also present a logical and causative connection in order to be valid.

For identifying significant behavioral patterns, the authors observed and analyzed the correlation of the results of Step 3: mapping the case-subjects against each of the variables. Specifically, several hypotheses for different patterns were assumed based on the observations of the preliminary research and checked based on the mapping results for validity or rejection. The analysis indicated three significant patterns which are shown in Table 3. Those patterns will be used in further research to construct the personas of different type of users by performing the following steps of the process (Steps 5, 6, 7 and 8 in Figure 1).

Table 3: Significant behavioral patterns of case subjects.

Pattern 1	Pattern 2	Pattern 3
• Age between 41-50 • Architect • Less thinking –more feeling • Low programming skills • Use of Microsoft office • Use of AutoCAD • Challenge: Manual work • Goal: Save time Reduce effort	• Age between 31-40 • Architect • More introvert-less extrovert • Medium programming skills • Use of REVIT • Use of Microsoft Excel • Challenges: Compatibility • Goal: Minimize errors Ease procedures	• Age between 31-40 • Engineering skills • More judging -less perceiving • Less resistant-more adaptive • High programming skills • Use of REVIT • Challenges: Interoperability • Goals: Automation Reduce time

5. Conclusion and further research

This study used USD methods and specifically the concept of personas in order to recognize current and potential LCC users and their characteristics in work practices and thus, determine the requirements of LCC tools from users' perspective. A Danish architectural firm was used as a case study for this analysis, and data were gathered by using qualitative and quantitative methods.

In this research, the four-first steps of the procedure of constructing personas was followed. Firstly, the authors identified the role of the subjects and narrowed the research focus on architects and engineers in the case company. As a second step, behavioral variables were identified through the case study analysis. Specifically, 22 behavioral variables were identified that are grouped in seven categories: demographic, aptitude, personality, skills, activities, attitude and motivations. Following, a survey was sent out in the case company, including various questions in relation to those behavioral variables. The results of the survey were checked and assessed by the authors in order to eliminate bias of results. In the third step, based on the results of the survey and preliminary observations and analysis, the authors mapped the case-subjects against each of the variables. Finally, several hypotheses on behavioral pattern were examined and three significant behavioral patterns were recognized.

The first pattern indicated that architects in the age of 41-50, are more feeling than thinking and have lower programming skills. They use Microsoft offices and AutoCAD in high frequency and their main challenge is the manual work that is required when performing different tasks. They are willing to complete tasks in less time and less effort. The second pattern indicated that architects in the age of 31 to 40 are more introvert than extrovert and have medium programming skills. They use REVIT and Microsoft Excel in their work processes. The main challenge that they are facing is the lack of compatibility in software, and they would like to minimize errors and ease procedures. The third pattern indicated that younger case-subjects with engineering skills are more judging than perceiving, however, they are very adaptive in changes. They have advanced programming skills and use Revit in their work practices. The main challenge they are facing is the lack of interoperability of software and their goal is to automate procedures and save time.

In conclusion, the first steps of the procedure of constructing personas was completed in this research. The identification of significant behavioral patterns was a fundamental step as pinpointed the amount of different types of users and the basic characteristic of personas. In further research, those patterns will be synthesized with details for users and personas will be designed. Those personas will be used to construct scenarios in order to identify how different users are willing to make use of LCC tools.

Acknowledgements

The authors would like to acknowledge the case company and all its employees (case-subjects) for participating in this research.

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Appendix 4

Paper D

IOP Conf. Series: Earth and Environmental Science **588** (2020) 052051 doi:10.1088/1755-1315/588/5/052051

Towards sustainable design: Integrating data from operation of buildings in design practices.

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Abstract. In recent years, the Danish Architecture, Engineering and Construction industry has shown increased interest in sustainability in contributing to the achievement of the UN 17 sustainable development goals. Sustainable design is, however, hampered by lack of information and weak data integration especially in the early design stages of building projects. In order to overcome these challenges, research has proposed transferring information from operation to the design of new buildings. By conducting a case study analysis in a Danish architecture firm, this research aims to explore the form of collaboration between architects and building client, and how this collaboration can support or inhibit the calculations of life cycle costing as an essential part of sustainable design practices. The data, for this exploratory research, are gathered through direct observations, surveys and semi-structured interviews. Structured analysis is used as the theoretical methodology to map the flow of data in a paradigmatic building project of the case company and recognize existing forms of knowledge transfer and areas of improvement. The results indicate that there are significant potentials of collaboration, however, several actions should be taken from both sides in order to enable information and data exchange. By improving the collaboration with building clients, architects will gain access to information from operation of buildings, which can be effectively used in architecture design improving the sustainability of buildings and contributing to SDG-9: Industry, Innovation and Infrastructure.

1. Introduction

In recent years, the Architecture, Engineering and Construction (AEC) industry has shown increased interest in sustainability in contributing to the achievement of the UN 17 sustainable developments goals. The main topic of SDG-9: Industry, Innovation and Infrastructure includes the adoption of sustainable technologies in buildings and targets on developing quality, reliable, sustainable and resilient infrastructures. Sustainable design takes into consideration not only environmental and social performance of buildings, but also economic assessment in long term perspective. Thus, the concept of Life Cycle Costing (LCC) is used by architects and engineers as a decision-making tool for assessing alternative design solutions based on several key factors such as costs, quality and comfort over the entire life cycle of a building [1].

The last few years, the Danish AEC industry has increased the application of LCC in design practices due to significant new initiatives, including, among else, LCC adoption by governmental regulations, European procurement policies and various certification schemes (see [2]). However, there are various real-word challenges that hamper the fully integration of the concept. In the recent study of Saridaki and

Haugbølle, the authors conducted a case study analysis in a Danish architecture firm and identified several contradictions of integrating LCC in the Danish design practices [3].

Although the challenges, currently, design teams timidly apply LCC in late design stages of building projects in order to comply with regulations and obtain certifications. However, the inclusion of LCC is proven more valuable in early design stages, where the ability to impact the cost and performance of a building is significant. Specifically, Bogenstätter U. identified that decisions that are made early in the design determine up to 80% of building operational and maintenance costs [4]. Nevertheless, the implementation of LCC in early stages is even more challenging due to lack of available information and data.

Recently, researchers and practitioners have shown increased interest on transferring knowledge from operation of existing building to design of new buildings. Although the wide recognition of this approach (a literature review is made by [5]) and various proposed typologies of transfer mechanisms (like [6]), currently, necessary initiatives are lacking, and the concept faces resistance in practices [7].

The aim of this research is to examine the collaboration between architects and building clients of social housing projects, and investigate how this collaboration can support or inhibit the transferring of information from operation of existing buildings in the design of new building in regard to LCC calculations as an essential part of sustainable design practices, contributing to SDG-9. By conducting a case study analysis in a Danish architecture firm, the author uses structured analysis (SA) to map the flow of data in a paradigmatic building project of the case company and recognize existing forms of knowledge transfer and areas of improvement.

2. Methodology

In this research, the authors conduct a single case study analysis in a Danish architecture firm, in order to explore the form of collaboration between architects and building clients and use SA as theoretical approach to map the dataflow of a social housing project of the case company.

2.1. Research approach: Case study analysis

The case company that is selected for the analysis is an architecture firm located in Copenhagen, Denmark, and it is a frontrunner in the field of sustainable design and constructions including LCC. The company is continuously working on social housing projects that demand significant collaboration with building clients of social housing organizations.

The project that is selected for the analysis is a paradigmatic social housing project that is completed in January 2019. The research data are collected through direct observations, participant observations and semi-structured interviews. More specifically, three semi-structured interviews were conducted in the case company during November 2019. The interviewees were architects that are working in social housing projects and have increased overview of building projects and processes.

2.2. Theoretical approach: Structured analysis

In order to map the dataflow of the project under examination, structured analysis is applied as the theoretical approach in this case study research. SA was developed in late 1960s by Ross and his colleagues, who use it as a methodology to describe complex IT systems such as the US Air Force Computer-Aided Manufacturing Project [8]. The methodology was commercially introduced in 1973, and since then, it has been applied in various project in diverse industries [9].

SA is successfully used for analysing complex IT systems and business requirements by describing a system of activities from a perspective of data flowing through it. Congram and Epelman [9] stated that SA is helpful to understand what happens in delivering of a service, and it is a well suited methodology to structurally providing significant attributes of service description, such as: (i) who and what performs the activity (mechanism), and (ii) what guides or limits the activity (controls).

Thereby, SA is identified highly useful in this research project, and it is used to understand the flow of data on a selected project of the case company, to map the actors and the tools as significant mechanism of the project activity, and finally identify what guides and what limits the activity in relation to LCC analysis.

3. Findings

The results of using SA in the selected case project of the Danish architectural firm are presented in figure 1.

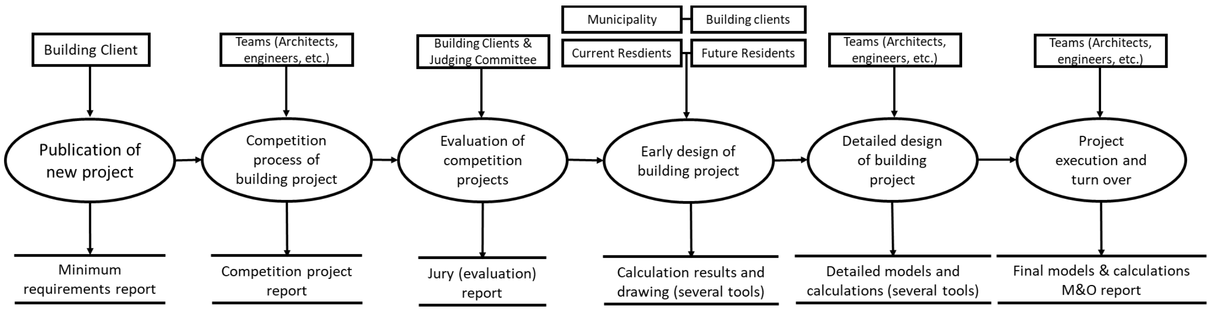

Figure 1. Flow of data in the case project by using SA.

As it is illustrated in the Figure, the processes that are taken place in a building project are: (a) public announcement of a new project, (b) competition process of the project, (c) evaluation of submitted projects, (d) early design of building project, (e) detailed design of building project, and (f) project execution and turn over.

When a new project begins, the building client publishes the project announcement along with a report that includes detailed requirements for the project submission. The report includes among else, requirements for housing size, architecture quality, energy class calculations, indoor climate, etc. Requirements in relation to LCC are also reported, including expected lifetime of building components, maintainability of materials and low operational costs. In addition, a detailed schedule of maintenance activities and expected expenditures for the upcoming 30 years is offered by the building client. Those requirements indicate the desire of building clients to consider long-term cost in the building project.

When the new project is published, pre-qualified teams work on the competition of the project. In this step, architects develop design proposals that satisfy the requirements of the project and submit their report. The report includes case analysis, drawings and various calculation results. In this step of the process, it is observed that the case project does not include sufficient LCC information to support the design proposals in the competition report.

When the competition projects are submitted, the building clients together with a judging committee evaluate all submitted competition projects. In the case project, the award criterion is the most economically advantageous tender, however, a number of sub -criteria are used for evaluation: (1) The building system: Architecture idea, building technology and quality, variety of options and flexibility; (2) Price: compliance with given price per m2, unit price, price of advices; (3) Cooperation: the contract team and their organization. However, there is not any criterion that evaluates the consideration of long-term economical design solutions.

In the following process, the winning team works in the early design of the project. Through the early design, the team conducts several meetings with different stakeholders, including meetings with current residents of similar existing building projects. In those meeting, the team has the opportunity to discuss with the residents about the performance of the building and unexpected operational and maintenance issues. Following the early design, a detailed design is performed where detailed models of the building project and calculation are developed. Through the case analysis was noticed that LCC is not considered in those processes.

Building execution and turn-over is the last process of the building project. In this process, the architects submit the final models, all the detailed calculations of the project, as well as a M&O

(maintenance and operation) report. This report contains many information about the building materials, however, not enough information about any maintenance and operation strategy.

Through the analysis, it is observed that there are initial actions for transferring knowledge from operation to design in process (a), through the availability of the 30-year maintenance expected budget, which is calculated based on existing buildings; and process (d), through the meetings with residents of existing buildings. However, it is concluded that there is limited use of the given information by the architect, who do not consider LCC in their processes.

4. Conclusion

In order to meet the UN 17 sustainable development goals, the AEC industry focuses on sustainable design, considering, among else, LCC as a decision-making tool for sustainable design of new buildings. However, LCC analysis requires data that are rarely available, especially in early design. Nonetheless, researchers have recently shown increased interest on transferring data and knowledge from operation of existing building in the design of new buildings.

This study used SA analysis to map the flow of data on a paradigmatic project of a Danish Architectural firm in order to recognize existing forms of collaboration and information transfer between architects and building clients that support or inhibit LCC calculation. The results exhibited very little attempt to use LCC in current practices. However there are significant potentials of collaboration, since there are initiatives of LCC related information sharing in both processes of publication of a new project and in early design of building project in the SA system. Nevertheless, several actions should be taken in all processes and from both sides in order to enable information and data exchange. In future research, the authors will give a more elaborate insight in the design process and identify the processes where enabler or inhibitors may occur when adopting LCC.

By improving the collaboration with building clients, architects will gain access to information from operation of buildings that can be effectively used in architecture design, improving the sustainability of buildings and contributing to SDG-9: Industry, Innovation and Infrastructure.

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Appendix 5

Paper E

INFORMING EARLY STAGE DESIGN THROUGH LCC DATA

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Life cycle costing (LCC) has been proved to be a valuable decision-making tool for strategic facility management considering life cycle perspective of buildings. However, its application by the Architecture, Engineering and Construction industry is limited due to lack of available and reliable information. In order to overcome this challenge, researchers have proposed transferring information from operation of existing buildings to the design of new buildings. By using structured analysis methods and specifically, data flow diagram techniques, this study aims to explore how can data from existing social housing building projects with regard to cost drivers of LCC inform the design of new projects. To support the analysis, a social housing project in a Danish architecture firm is used as the case study, and data are gathered through physical artefacts and five semi-structured interviews in both the architect and building client organisation. The results indicate the availability of operational data in several of the processes in the data flow diagram of the case project. The discussion focusses on different ways that O&M data from existing buildings that are provided to the design team through a requirements' report when a new project is published, can be effectively used to identify cost drivers of LCC and inform the design of new projects. The consideration of cost drivers of LCC in early design stages will contribute to designing more economically sustainable constructions that are easy and affordable to operate and maintain.

Keywords: cost drivers, Life cycle Cost (LCC), social housing, structured analysis

INTRODUCTION

The past few years, the Architecture, Engineering and Construction (AEC) industry has shown increased interest in sustainability, focusing on the environmental performance, social quality and economic assessment of buildings in a long-term perspective. Life cycle costing (LCC) is a methodology that promotes life cycle perspective of buildings, considering not only construction costs, but also cost to operate and maintain them through their entire lifetime. Thus, LCC is used by architects and engineers as a decision-making tool to evaluate different design solutions that have different cost effect over time, based on several key factors like cost, quality and comfort (Haugbølle and Raffnsøe 2019).

Currently, there is an increased use of LCC in the design practices of the Danish AEC industry due to several new initiatives including the adoption of LCC by governmental regulations (Bygningsstyrelsen 2017) (Mortensen *et al.,* 2018), European procurement

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Saridaki, M and Haugbølle, K (2020) Informing Early Stage Design Through LCC Data *In:* Scott, L and Neilson, C J (Eds) *Proceedings of the 36th Annual ARCOM Conference,* 7-8 September 2020, UK, Association of Researchers in Construction Management, 655-664

policies (European Commission 2014) and various certification schemes (DK-GBC 2012) (a detailed description can be found in the research by Saridaki *et al.,* (2019)).

Despite the increased application of LCC, there are still several challenges that obstruct the full integration of the concept. In a recent study by Saridaki and Haugbølle (2019), the authors conducted an extensive literature review and a case study analysis in a Danish architecture firm and identified several contradictions of integrating LCC in the Danish design practices. The results indicated that main contradictions are related to poor availability of data and the form of collaboration in the current design practices. Other researchers have also identified the lack of reliable data as a critical hindrance of applying LCC (Fu *et al.,* 2007, Gluch and Baumann 2004, Ruparathna and Hewage 2015).

In order to overcome the challenge of poor data availability, researchers and practitioners have proposed to transfer information and data from operation of existing buildings to the design of new projects. In their literature review, Rasmussen *et al.,* (2017) investigated different ways for transferring knowledge from operation to design, while Jensen (2009 and 2012) proposed different transfer mechanisms, like: codification of knowledge from building operation to increase awareness among designers, continuous briefing of facility managers and users during design process, project reviews to ensure that designers take considerations for building operation seriously as well as regulations to ensure that codified knowledge from building operation is used by the design team. However, several actors need to be involved in the process to successfully achieve knowledge transferring, including building clients to ensure knowledge transfer (Jensen 2009 and 2012), facility managers to provide great insights to new building projects (Jensen 2009 and 2012, Meng 2013) and buildings' users (Chandra and Loosemore 2012).

Throughout the practical experience of one of the authors in a Danish architecture firm, the authors recognize opportunities for transferring operational knowledge to design practices through social housing projects. Social housing (in Danish: Almen bolig), also known as affordable housing or non-profit housing, refers to residential houses owned by social housing organisations, which are characterised by a non-profit business. In Denmark, the social housing sector constitutes one fifth of the housing stock (Alves and Andersen 2015), as there are more than 600,000 social housing units that are distributed among 25 social housing organisations. Social housing organisations are, at the same time, building clients and facility managers as well as they also have close relationship with the buildings' users (tenants). Thereby, they are reasonably considered as critical actors for transferring operational knowledge to new building design.

The aim of this research is to explore the processes of social housing projects and identify cost-related data from operating existing social housing buildings floating between design processes that can be used as cost drivers with regard to LCC to inform the design of new building projects in relation to LCC. By using Structured Analysis (SA) methods, and in particular Data Flow Diagrams (DFDs) in a social housing project of a Danish architecture firm, the study aims to answer the following research question: "How can data from existing social housing projects with regard to cost drivers of LCC inform the design of new projects?"

This is the initial part of a research study that focuses on analysing the processes of social housing projects and identifying data with regards to cost drivers of LCC that can be used to inform the design. In future research, the authors aim to propose interventions to the system that support the use of cost drivers of LCC to inform the design of new projects.

METHODOLOGY

In order to analyse the processes and identify data floating between the processes of social housing projects that can be used as cost drivers of LCC, the authors use structured analysis (SA) as an information analysis methodology.

SA was developed in late 1960s by Ross and his colleagues who use it as a methodology to describe complex IT systems such as the US Air Force Computer-Aided Manufacturing Project (Ross 1977). The methodology was commercially introduced in 1973, and since then, it has been applied in various project in diverse industries (Congram and Epelman 1995).

SA is successfully used for analysing complex systems and business requirements by describing a system of activities from a perspective of data flowing through it. Congram and Epelman (1995) stated that SA is helpful to understand what happens in delivering of a service, and it is a well suited methodology to structurally providing significant attributes of service description, such as: (i) who and what performs the activity (mechanism), and (ii) what guides or limits the activity (controls).

Various modelling tools are used to analyse systems in SA methods including, among else, data flow diagrams (DFDs). A set of interrelated DFDs, which are decomposed with the top-down approach, is used to represent a system (Wang and Tzui 1991). The top diagram summarises the diagrams below, which are arranged hierarchically and become increasingly more detailed at each level. DFDs are usually underpinned by a data dictionary and a process description document.

DFDs show the relationship between processes and data by using the following component (see Figure 1) (DeMarco 1979).

Figure 1: Data flow diagrams' components (Source: Adapted after DeMarco 1979)

- External entities, which are represented by a rectangle, are related to elements of the outside world that communicates with the system. An external entity could be an organisation, a group of peoples, a department or even another system that the model system communicates with.
- Processes/Activities, which are represented by a cycle, an oval, or a rectangle with rounded corners, are part of the system that transforms inputs to outputs.
- Data flow, which is represented by an arrow, shows the transfer of information from one part of the system to another.
- Registers/Datastores, which are presented with two horizontal lines, represent the place where data are stored to the system.

The research approach that is used in this study for analysis the processes of social housing projects is a single case study analysis. The case company is a Danish architecture firm, located in Copenhagen, Denmark, and it is a frontrunner on sustainable design and constructions including LCC. The case company is strategically selected as a paradigmatic case study in the Danish AEC, since it is a typical Danish architecture firm in terms of type and size, and it has been involved in several social housing projects for different social housing organisations around Denmark.

To support the analysis, a typical social housing project is selected as the internal sub-case project. The case project is also a paradigmatic social housing project, managed by one of the bigger social housing organisations in Denmark. The project is designed by the case company, and it is now under operation since January 2019. In order to create DFDs of the case project, qualitative data were gathered though semi-structured interviews and collection of physical artefacts (as proposed by Yin 2009). Specifically, in total five interviews were conducted during autumn 2019; three of them were conducted internally in the case company, while the other two were conducted with employees of the social housing organisation that owns the project under examination. To support the interviews, physical artefacts of the case project were carefully collected, including several reports from both architects and the social housing organisation.

The collected data were used to create a set of DFDs for analysing the case project. Due to the limited space, this paper shows an initial part of the research study presenting the top two DFDs of the SA system, Level 0 and Level 1, underpinned by their process descriptions. More detailed levels will be reported in future studies. It is important to mention that the developed DFDs are structured from architect's point of view since architects should identify potential data that can be used to inform the design of new projects.

Findings

In this section, the results of the case project analysis by using SA are presented. More specifically, the DFDs of the top-two levels (level 0 to level 1) of the analysis are illustrated, followed by a process description in each level.

DFD - Level 0

The top-level diagram of the case project analysis indicates that there are three main recurrent processes throughout the social-housing projects' lifetime (see Figure 2).

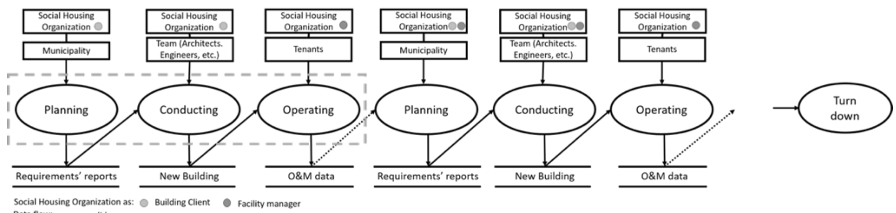

Figure 2: DFD of the case project - Level 0

As it is indicated in Figure 2, a social housing project begins with the planning process, which is initiated by the building client which is the social housing organisation and the municipality in which the project is located. The planning process results in a set of requirements' reports for the new building project which are used as input data for the next process, namely conducting the building project. The project is conducted mainly by a project team that consists of architects and engineers. Other actors are also involved in this process, including, among else, the social housing organisation, the municipality, tenants of social housing buildings, etc. When the project is executed, the new building is operated by the tenants. In the operating process, the social housing organisation is also involved having the role of the facility manager of the building that gathers several operational and maintenance (O&M)

data. Those three processes, namely planning, conducting and operating, constitute the main processes of social housing projects and are illustrated in Figure 2 with a dashed grey square. After several years of building operation, a renovation project is taken place and a new round of processes begins. Considering the performance and the O&M data of the existing building, a renovation project is, again, planned by the social housing organisation and the municipality, is conducted by a project team under the supervision of the social housing organisation, and the renovated building is operated by the tenants and managed by the social housing organisation. Those processes are repeated several times throughout the lifetime of the project until the building is turned down.

The DFD of level 0 indicates that the social housing organisation is involved in all processes of a social housing project throughout its lifetime, having different roles. Thereby, it can be reasonably assumed that social housing organisations have an overview of the building project's performance under all processes throughout its lifetime and thus, are considered as sources of plentiful data, including LCC related data. However, although the evident assumption of data sources, it is not yet fully recognizable how and in what volume those data are gathered, analysed and used in the recurrent processes of the same housing project or in similar processes of different projects in order to inform the design and improve performance of buildings. Nevertheless, is observed that the dataflow between processes of existing and new building projects is quite unstructured and this is indicated by a black dashed arrow in Figure 2.

DFD - Level 1

The DFD of level 1 is one step down in the hierarchy compared to the DFD of level 0, presenting a higher level of details. The case project that is used to map the DFD in level 1, is a completed new social housing building project, and thus, it is currently under the initial operating process, while the initial planning and conducting processes are already completed.

In this research, the authors are interested in how data for existing social housing project with regards to cost drivers of LCC can inform the design of new projects. Therefore, the analysis is focused on the sub-processes that occur at the end of planning and beginning of conducting process of level 0, in which the initial process of designing of the new project are taken place. The level 1- DFD is presented in Figure 3.

As illustrated in Figure 3, level 1 consists of four processes under examination: (a) public announcement of a new project, (b) competition process of the project, (c) evaluation of submitted projects, and (d) early design of building project.

In process (a), the social housing organisation in the role of building client announces the publication of the new project. The publication of the new project comes along with two reports that include some minimum requirements for the project submission. The one report, called Competition program, focuses on the competition procedures and describes, among else, the organisational and planning conditions, process prerequisites, requirements for tendering documents, competition theme, approval requirements, etc. The other report, called Standard Building program, focuses on the building and includes descriptions about the overall layout and architecture design, rooms' specifications, buildings' elements and materials, technical installations, electrical systems, outdoor areas as well as maintenance planning.

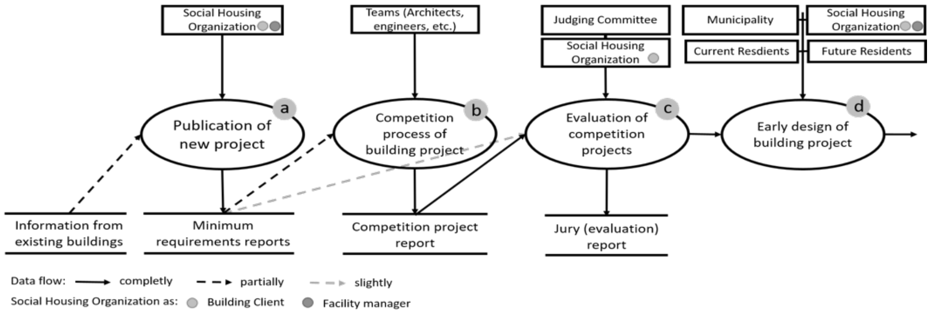

Figure 3: DFD of the case project -Level 1

Both reports include, among else, requirements for housing size, architecture quality, energy class calculations, indoor climate, daylight and sound conditions, etc. There are also several qualitative requirements in relation to LCC, like expected long lifetime of building components, low maintainability of materials and low operational costs. In addition, the Standard Building program report contains a detailed quantitative schedule of expected expenditures for maintenance activities for the upcoming 30 years of building operation (Figure 4). Specifically, the principle schedule for maintenance payments, as it is called, includes yearly expected payments for eighteen (18) maintenance activities for the first 30 years of operation (11 activities for external maintenance and 7 activities for internal maintenance). This maintenance schedule is arguably created based on cost data from other similar social housing projects; however, this is not yet clarified (illustrated by a dashed arrow between information from existing buildings datastore and process (a) in Figure 3). Thereby, it is also assumed that the social housing organisation is involved in this process of publication of the new project, having the role of facility manager of other social housing building.

Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
*All amounts in DKK 1000																														
Exterior maintenance																														
Joint around windows	0	0	0	0	0	0	0	0	0	0	25	25	25	50	50	400	0	0	0	0	0	0	0	0	0	25	25	25	50	400
Replacing double-glazing units	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	30	45	60	75	90	105	120	135	150	165	180	195	210	225
Gutter repair	0	0	0	0	3	0	3	0	3	3	3	0	3	3	3	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Roof surface maintenance	0	10	10	10	10	10	15	10	10	15	10	10	15	10	10	15	10	10	15	10	10	15	10	10	15	10	10	15	10	15
Covering roof	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Exterior lighting	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Outdoor areas, paving/ asphalt	0	0	0	0	0	0	0	0	0	0	800	0	0	0	0	0	0	0	0	0	800	0	0	0	0	0	0	0	0	800

Figure 4: Part of the Principle schedule of maintenance payments (translation from Social Housing's Standard Building Program report)

In process (b), pre-qualified teams consisting of architects and engineers compete for winning the project. In this process, architects use the data from the minimum requirements reports of process (a) to develop an architectural proposal that satisfies those requirements and submit their competition project report (outcome of process (b)). The competition document of the case project includes a case analysis, several drawings along with building elements' specifications and various calculation results. However, it is observed that the competition document under examination does not include any information about the lifetime of the selected materials or their maintainability, or any other LCC information to support the architectural choices. This means that the data stored in the minimum requirements' reports as an outcome of process (a), are only partially used in process (b), and this is represented in Figure 3 by a dashed arrow.

The competition project report as an outcome of process (b) is used as an input in process (c), where several reports from different design teams are evaluated by the social housing organisation together with a judging committee. The judging committee consists of people from the local municipality as well as from other social housing organisations. In this case project, the main award criterion is the most economically advantageous tender; however, a number of sub-criteria are used for the evaluation. Those sub-criteria refer to: (1) The building system: Architecture idea, building technology and quality, variety of options and flexibility; (2) Price: compliance with given price per m2, unit price, price of advices; (3) Cooperation: the contract team and their organisation.

It is observed that, although the emphasis that is given on LCC related requirements in the initial reports of process (a), there is not any criterion that evaluates the consideration of long-term cost-effective design proposals in process (c). The grey dashed arrow between the datastore in process (a) and process (c) indicates that the minimum requirements' reports are slightly used as an input in process (c).

In this case project, the case company was part of the winning team, and thus it continued in process (d) working on early design of the project. During the early design process, the winning team had continuous communication with several external actors, who support the design by providing useful information in order to ensure high quality of the project. Those actors are the local municipality, the social housing organisation as well as current tenants of other existing social housing buildings and future tenants of this building project (represented as external entities of process (d) in Figure 3). The communication between the winning team and the external actors is performed through regular meeting, where information about the cost performance of existing buildings or unexpected operational and maintenance issues is transferred to the winning team through dialogue-based briefing processes. The dataflow between architects and social housing organisation apparently seems to be quite unstructured. In level 1, however is not yet visible if and how this LCC related knowledge is used by the architects.

DISCUSSION

Through the analysis, it is observed that in the DFD-level 1 of the case-project, there are few activities where LCC related data and knowledge from existing buildings are transferred to the design team. The discussion here, however, is focusing on the LCC related data that are stored after process (a) and specifically, the schedule of maintained payments that is part of the minimum requirements' report.

As a result of process (a), cost-related data are transferred explicitly to the design team through the 30-year maintenance payment schedule, which is part of the minimum requirements' report. As it mentioned-above the maintenance payment schedule includes LCC cost data for 18 maintenance activities that are expected to take place throughout the first 30 years of building's operation. According to Jensen (2012), this can be considered as codified knowledge from building operation that contributes to increase awareness among building designers. Since the social housing organisation provide this written specification report to the design team, it can be concluded that those cost data should be used by architects to drive the design of the new building, and therefore, they are fairly recognized as cost drivers.

However, the potentials of considering those cost drivers to inform the design of new project are not fully utilized in this case-study (data from the minimum requirement report are partially used in the competition process - dashed arrow in Figure 3). A reason for this might be the lack of criteria to evaluate the compliance of the competition project with the LCC related requirements in process (c). That indicates the lack of attention by social housing organisations to ensure that the design team will take consideration of the given data seriously. Another reason is that the design team fails to understand the value and the opportunities that are offered through this process.

However, answering the research question of this study, those cost drivers can be effectively used to inform the design of new projects. Firstly, the design team should propose alternative design solutions along with LCC calculation for a lifetime of 30 years including elements that their maintenance costs at the very least comply with the given maintenance schedule. In addition, by analysing the schedule of maintenance payments, the design team can also pinpoint the most critical cost drivers (the maintenance activities with the highest total cost throughout the 30 years) and propose alternative design solutions with lower LCC than expected. For example, in the case project's maintenance schedule report, the higher LCC in a lifetime of 30 years are related to the maintenance of the ventilation system, the paved/asphalt outdoor areas and the double-glazing units, indicating three critical cost drivers through buildings' operation. Those cost drivers of LCC can be used by the design team to inform the design of the new project, for instance, by proposing alternative design and maintenance strategies to improve long-term performance of ventilation systems, reducing the pavement in outdoor areas or designing solutions that can increase the lifetime of double-glazing units.

This is one activity that underlies valuable cost drivers of LCC that the architects may use to inform the design of the new project and propose solutions that are easy and affordable to operate and maintain. In addition, the case analysis reveals potentials also through other activities, for example through the inputs from external entities of process (d), where information from external actors about cost related performance or unexpected maintenance issues of existing social housing projects is communicated to the design team.

CONCLUSION

Life cycle costing has been proved to be a valuable decision-making tool for strategic facility management, considering life cycle perspective of buildings. Although several new initiatives have stimulated the increased use of LCC in the Danish AEC, its application in the design practices is still limited due to several challenges. One of the main challenges is the lack of available and reliable data, especially in early design stages. In order to overcome this challenge, research has proposed transferring information from the operation of existing buildings to the design of new buildings. Building client, facility managers and users are considered critical actors that can contribute on knowledge transferring.

This study focuses on social housing organisations in Denmark since they are at the same time the building clients and the facility managers of several residential buildings, as well as they have close relationship with the buildings' users (tenants). By using SA methods and specifically, data flow diagrams techniques, this study aims to identify how can data from existing social housing building projects with regards to cost drivers of LCC inform the design of new projects. To support the analysis, a social housing project from a Danish architecture firm is selected as the case project, and data are gathered through physical artefacts and five semi-structured interviews in both architects and building client organisations. The research data were used to create the DFDs of Level 0 and Level 1 of the SA system underpinned by their process descriptions. Through the analysis, it is observed that in the DFD-level 1 of the case-project, there are few activities where LCC related data and knowledge from existing buildings are transferred to the design team. However, the potentials of using this knowledge to inform design of new projects are not utilized by the design team.

The activity that is discussed in this study, refers to the outcome of the process of publication of a new project, where the social housing organisation publishes a payments' schedule of maintenance activities as part of the minimum requirements' report. The maintenance payments schedule includes yearly expected payments for 18 maintenance activities for the first 30 years of operation. Those activities are considered cost drivers for the operation of the building for the next 30 years, since the social housing organisation calls for a design that conforms to this payments schedule. In addition to that, by analysing the schedule of maintenance payments, the design team can pinpoint the most critical cost drivers (the maintenance activities with the highest cost) and propose more affordable design solutions with lower LCC than expected. For example, in the case project maintenance schedule, one of the most costly activities in a lifetime of 30 years is related to the maintenance of the ventilation system, so the design team can use this information as a cost driver and propose alternative design and maintenance strategies to improve long-term performance of ventilation systems and reduce the LCC that are related to the ventilation system.

The consideration of cost drivers of LCC when designing new projects will contribute on more sustainable constructions that are easy and affordable to operate and maintain. In future research, other activities that are disclosing potentials for identification of cost drivers with regards to LCC will be further analysed. Moreover, the authors will propose interventions in each of the processes of the SA system in order to ensure the integration of LCC in the processes of social housing projects contributing on better design of new projects with regards to LCC.

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Appendix 6

Paper F

Saridaki, M. and Haugbølle, K. (2022) "Understanding the diversity of users of life cycle costing through personas". Submitted in *Journal of Information Technology in Construction (ITcon)*

RECOGNISING DIVERSITY OF DATA MANAGEMENT APPROACHES TOWARDS LIFECYCLE COSTING THROUGH PERSONAS

SUBMITTED: September 2022.

SUMMARY: By adopting user-centred design methods, this study aims to improve our understanding of the diversity of lifecycle costing (LCC) users as users of technology with regard to their characteristics, aspirations and work processes towards data management. The research is based on a single case study analysis of a Danish architectural firm. Data are gathered through mixed methods, including quantitative surveys and qualitative observations and interviews. The findings reveal three user personas: the clip-boarder persona, who manually copies and pastes data from one application to another in order to perform calculations; the spreadsheet expert persona, who prefers to work with spreadsheet-based tools for importing and exporting data between tools; the programmer persona, who uses programming language for integrating data from one application to another. This research provides novel information on users of technology that can advance integration of LCC in design practices and improve design of more useful adequate LCC tools.

KEYWORDS: User-centred design, personas, lifecycle costing (LCC), design practices, data management, data integration.

1. INTRODUCTION

The Architecture, Engineering, Construction and Operations (AECO) industry is showing increased interest in sustainability focusing on environmental quality as well as social and economic performance of buildings. In order to assess the economic performance, lifecycle costing (LCC) is used as a decision-making methodology for evaluating alternative design solutions that have different cost profiles over time. LCC terms are defined by the international standard ISO15686 series on service life planning (ISO, 2008) followed by the European standard EN15643 series on sustainability of construction works (CEN, 2012).

Although the LCC concept appeared internationally in the mid-1960s (Ellram, 1993), the focus of the Danish AECO industry on LCC has been revitalized the past few years due to a number of new trends (Haugbølle and Raffnsøe, 2019). First, LCC is part of various certification schemes including DGNB certification, which was adopted in 2012 by Green Building Council Denmark for sustainable building and urban areas that include economic quality with high weight (DK -GBC, 2012). Second, due to new governmental regulations in 2013, LCC is now a mandatory requirement for public construction (Bygningsstyrelsen, 2017). Third, the European procurement directive of 2014 supports the use of total cost of ownership as an award criterion in competitive tendering (European Commision, 2014). Fourth, the new Danish building regulation of 2020 includes LCC as part of the new voluntary sustainability building class (Mortensen *et al.*, 2018). Moreover, the voluntary building class is expected to become a mandatory requirement for all large new buildings in 2023 (Bolig- og Planstyrelsen, 2021).

For managing LCC in practice, a range of guidelines, methodologies and tools exists (Caplehorn, 2012; Dhillon, 2010; Farr, 2011). As pointed out by Sørensen et al. (Sørensen *et al.*, 2016), the existing LCC tools are classified in three main categories with distinct characteristics and associated benefits and drawbacks: (1) spreadsheets (usually company-specific), (2) stand-alone applications, and (3) web services. The Danish AECO industry typically performs LCC calculations based on a combination of three tools (Saridaki *et al.*, 2019): (1) Sigma Estimates: a 5D BIM cost estimation tool (Sigma Estimates, 2003); (2) LCCbyg: a Danish application for LCC analysis that also support DGNB calculations (LCCbyg, 2021); and (3) internally developed spreadsheets.

Despite the availability of various methodologies and tools, there are still significant challenges in applying LCC in work practices. Several studies have investigated the barriers of a limited adoption and implementation of LCC. These include: insufficient understanding of LCC definitions and methods (Gluch and Baumann, 2004), limited tool awareness (Olsson *et al.*, 2015), lack of usable tools (Goh and Sun, 2016; Olubodun *et al.*, 2010), lack of reliable data (Fu *et al.*, 2007; Oduyemi *et al.*, 2014), lack of formal guidelines (Kehily and Underwood, 2017), complexity of calculations (Fu *et al.*, 2007), insufficient methodology for data management and poor data collection and storage (Fu *et al.*, 2007; Saridaki *et al.*, 2019), and limited communication and collaboration between the LCC practitioners and the design team (Saridaki and Haugbølle, 2019).

Despite the technological opportunities offered by Building Information Modelling (BIM) in relation to different approaches of data integration (NBS, 2018; Singh *et al.*, 2009) and LCC (Liu *et al.*, 2015; Lu *et al.*, 2014; Miettinen and Paavola, 2014; Saridaki *et al.*, 2019; Xu *et al.*, 2014), the current strategies of the AECO industry towards data integration do not enable the design of fruitful intervention towards LCC adoption. In order to handle this challenge, it is important to understand how users in the AECO industry apply digital technologies in their practices, and how the current practices can support or hinder the application of LCC.

Rather than focusing on the limited adoption of LCC, this study adopts a positive agenda aiming to improve our understanding on how people work with LCC in real work practices. Adopting a generic user-centred design approach that focuses on how people work with technology in general, this study aims to provide novel information about the diversity of practitioners in the AECO industry as users of technology. This information will be valuable for both improving LCC integration in design practices and designing more useful LCC tools. Hence, the research objectives of this study are:

- to understand the diversity of LCC users in the AECO industry;
- to categorize their distinct core characteristics, work practices and data management approaches;
- to summarize the diversity of LCC users in distinct personas.

2. METHODOLOGY

The present research relies upon a user-centred design approach and more specifically the concept of personas. The data in this research were collected by conducting a case study analysis in a Danish architectural firm. In the following subsections, both the theoretical background on user-centred design and the practical methodology along with the data collection methods are described.

2.1 Theoretical background: User-centred design and personas

User-centred design (UCD) is a human-computer interaction philosophy (LeRouge *et al.*, 2013) that focuses on developing systems based on users' requirements instead of technical requirements (Junior and Filgueiras, 2005). The UCD approach originates with Donald Norman, who used the term to describe design processes that are influenced by the end-users (Norman and Draper, 1986). The key aspect in UCD is to enable usability and usefulness in products and services through the active involvement of users in the design processes (Ji-Ye Mao *et al.*, 2005). Various methods are used in UCD such as users' interviews and surveys, focus group, participatory design, usability testing, ethnographic design and user scenarios with and without personas (Grudin and Pruitt, 2002).

The concept of personas was introduced by Alan Cooper in 1999 (Cooper, 1999) and is increasingly used for software design, product development and marketing purposes. There are several examples of using personas in both practice and academia, for instance for developing or evaluating systems and tools (Dantin, 2005; Gulliksen *et al.*, 2003; Hjalmarsson *et al.*, 2015; Lindgren *et al.*, 2007; Llerena *et al.*, 2016; Sakao and Shimomura, 2007); for educational purposes (Almahri *et al.*, 2019; Dotan *et al.*, 2009); for product design (Guo *et al.*, 2011; Wilkinson and De Angeli, 2014); and for health informatics research (Holden *et al.*, 2017; Wärnestål *et al.*, 2017). Moreover, personas have been used as a design tool in a number of world-leading firms in various business sectors (Miaskiewicz and Kozar, 2011; Pruitt and Grudin, 2003).

Although personas are not widely used in the AECO industry, there are a few examples that personas have been a useful tool contributing to increase the understanding of current practices and finding areas of improvement. Personas have been used e.g. to identify potential areas for BIM application in the FM stage (Becerik-Gerber *et al.*, 2012); for optimising sustainable solutions in buildings design towards circular economy (De los Rios and Charnley, 2017); on understanding users' needs, motivating human-centred design instead of cost-driven or technology-centred design e.g. to the design of smart-homes (Agee *et al.*, 2021); and for evaluating processes and tools e.g. a framework for supporting constructability analysis meetings with immersive VR-based collaborative 4D simulation (Boton, 2018).

Personas represent concrete group of users that designers are willing to design for (Floyd *et al.*, 2008), and it is a methodology that helps designers to make user-centred design possible (Pruitt and Adlin, 2006). Personas are hypothetical archetypes that represent groups of people that share similar characteristics, motivations and needs (Pruitt and Adlin, 2006; Turner and Turner, 2011). Although they are fictional, they represent real people through the design process. However, they are not made-up, but they are discovered with precision and rigor through the contact with real users (Junior and Filgueiras, 2005). Usually, one to seven personas are built to support a project (Marshall *et al.*, 2015). They are used to communicate user requirements to designers (Kantola *et al.*, 2007) and drive decision-making processes about interaction design and characteristics of a product (Goodwin, 2001) facilitating useful and usable design (Floyd *et al.*, 2008; Grudin and Pruitt, 2002). In order to make personas more realistic, memorable and engaging, designers add to them fictional characteristics like names, images and personal details (Cooper *et al.*, 2014; Pruitt and Adlin, 2006; Pruitt and Grudin, 2003). Creation of personas is the first step of design lifecycle (Turner and Turner, 2011) and helps organizations to be more user-focused (Pruitt and Adlin, 2006).

There are several benefits of using personas compared to traditional research methods (Chapman and Milham, 2006; Miaskiewicz and Kozar, 2011) including:

- Personas evoke design teams to think about users and their goals as well as to integrate user needs into the system leading to more user-friendly design (Chapman and Milham, 2006; Cooper, 1999; Grudin and Pruitt, 2002; LeRouge *et al.*, 2013; Long, 2009).
- Personas facilitate effective communication between designers and users since they create a common language (Cooper, 1999; Pruitt and Grudin, 2003).
- Personas increase engagement and effective communication among the design team and can be used as a useful reference throughout the entire design process (Cooper *et al.*, 2014; Grudin and Pruitt, 2002; LeRouge *et al.*, 2013; Stickdorn *et al.*, 2018).
- Personas guide the decision-making process and help design teams to address problems that arise when a full range of user data is presented (Chapman and Milham, 2006; LeRouge *et al.*, 2013; Long, 2009).
- Personas make knowledge about users and their needs explicit and help designer to make explicit assumptions about the users (Grudin and Pruitt, 2002).
- Personas enable more effective and faster design, since designers are able to prioritize features and make decisions based on a small group of users (Wodtke and Govella, 2009).
- Personas build empathy for users among designers (Pruitt and Adlin, 2006).

2.2 Practical methodology and data collection methods

Research activities and collection of research data is a one of the core tools in UCD. In order to build personas, research data are made of facts from users, which are collected, synthesized, interpreted and analysed in order to identify recurring patterns within users (Junior and Filgueiras, 2005). There are multiple sources for data collection to support personas' creation such as interviews, observations, surveys, dramaturgical reading methods, ethnographic studies, web analytics and contextual inquiries (Dayton, 2003; Junior and Filgueiras, 2005; Kantola *et al.*, 2007).

In this study, a single case study analysis was performed in a Danish architectural firm, which is located in Copenhagen, Denmark and is a frontrunner in sustainable design, including LCC. The case company applies LCC in various projects, and it is selected as the case of the analysis since it employs constructing architects, architects and engineers.

The research process followed the eight-principle steps of constructing personas proposed by Cooper et al. (Cooper *et al.*, 2014), which are illustrated in Fig. 1.

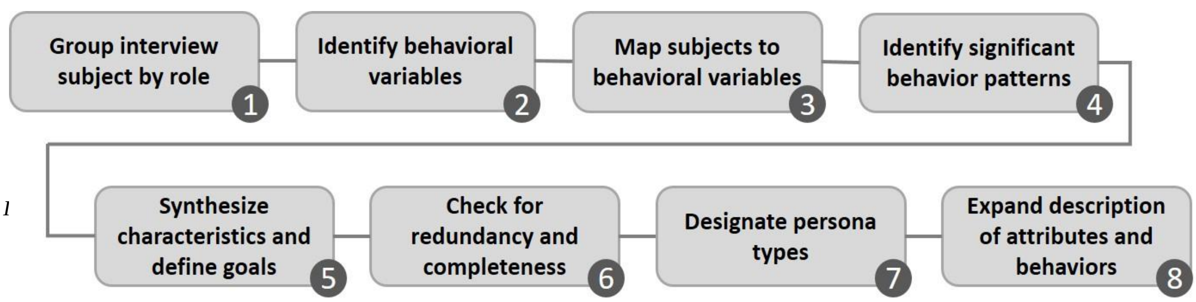

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FIG. 1: Eight-principle steps for constructing personas (Adapted after Cooper et al. 2014).

Throughout the entire process, mixed methods of data collection were used in order to triangulate the understanding of users, including interviews, questionnaire survey and observations in the company. The data-collection methods that were used in each step of this process are presented in Table 1.

TABLE 1: Data collection methods used in each of the eight steps of constructing persona process.

Step of constructing personas	**Data Collection Methods**
1: Grouping interview subject by role	Literature review on LCC application in practice Stakeholder analysis Selection of case study Case study: semi-structured interviews, observations, meetings and seminars
2: Identifying behavioural variables	Case study: observations on case subjects' behaviours for identifying behavioural variables
3: Mapping case subjects	Case study: online survey via Google Forms, 20 questions corresponding the behavioural variables, 48 responses (out of 60)
4: Identifying significant behavioural patterns	Analysis of surveys results Case study: direct observations to support the results
5: Synthesise characteristics and define goals	Revision of qualitative and quantitative data Case study: additional observations and goal-oriented interviews
6: Check for completeness and redundancy	Revision of data collected in all previous steps Case study: five days on observations and interviews of the case subjects Two meetings with case company's representatives
7: Designate personas	Case study: internal meetings with case company's representatives
8: Expand the description of attributes and behaviours	Further analysis of already gathered results

3. FINDINGS: CONSTRUCTING PERSONAS

In the following sections, the findings are presented throughout the process of constructing personas by following the eight principles' framework of Fig. 1.

3.1 Step 1: Grouping interview subjects by role

In Step 1, the authors conducted a preliminary analysis, a literature review, and a stakeholder analysis in order to recognize and group the different stakeholders of LCC by role. The analysis resulted in the identification of three main roles of LCC stakeholders in the AECO industry, which are:

1) providers, including all stakeholders that provide software or the required data for an LCC analysis;
2) users, including all stakeholders that use an LCC tool to perform an LCC analysis, like architects, engineers, consultants and facility managers; and
3) clients, including all stakeholders that make decisions based on the results of the LCC analysis, like building clients.

Those stakeholders along with their roles have different interest and influence on the adoption of LCC in the work practices. LCC providers, for instance, have increased interest in LCC adoption since the increased use of LCC will be beneficial for their businesses and earnings, however, they do not have enough power to influence the LCC adoption. On the other hand, building clients have high power on increasing the use of LCC in the AECO industry. However, they usually consider only short-term costs for making investment decisions (Gluch and Baumann, 2004). On the contrary, LCC users have higher interest and higher influence on LCC adoption than providers and clients respectively. LCC users are interested in using LCC since it contributes to their businesses and earnings, and it contributes to sustainable design and constructions. Moreover, they can influence the adoption of LCC by providing services to their clients that indicate the benefits of using LCC in order to make decisions in the project. As a result of the analysis, it was decided to narrow the research focus to current and potential LCC users since they are important stakeholders in terms of both interest and influence on LCC application in work practices.

After a series of meetings and seminars, a case company (the architectural office mentioned previously) employing of current or potential LCC users was selected as the case study. The authors analysed the internal workflow of the architectural office as case study and identified factors and conditions that support or prevent the application of LCC in design practices.

3.2 Step 2: Identifying behavioural variables

After the identification of the case study, the second step of the process included observation of behaviours of the case subjects and identification of behavioural variables. According to Cooper et al. (2014), demographic variables such as gender, age or demographic location can also affect behaviour; however, the identification of behavioural variables is more useful for creating effective archetypes. The number of behavioural variables varies from project to project; however, it usually ranges from 15 to 30 variables per role (Cooper *et al.*, 2014).

Through the case study analysis, six categories of behavioural variables were identified (A-F) and presented in the first column of Table 2. Under each category, two to five behavioural variables were selected for examination.

TABLE 2: Data collection methods used in each of the eight steps of constructing persona process.

Categories	No	Variables in each category
A. Aptitude	1 2 3	Education Education level Role in the company
B. Personality	4 5 6 7	Introvert vs extrovert Judging vs perceiving Feeling vs thinking Resistant vs adaptive
C. Skills	8 9 10 11 12	Familiarity with technology and programs Programming skills Familiarity with spreadsheets Familiarity with graphical applications Familiarity with CAD applications
D. Activities	13 14 15	Use of software in general Use of software in work practices Frequency of using software
E. Attitude	16 17	Evaluation of software in terms of usability Challenges of using those software
F. Motivation	18 19 20	Expectation of improvement in software Need of additional features or software Goals by using different software

In the category of aptitude, three variables were identified namely users' education, level of education and role in the company, which indicate users' level of knowledge and ability to learn. Under the personality category, four variables were selected that reveal the curiosity of users on learning and developing skills. Those variables indicate how introvert or extrovert, how judging or perceiving, how feeling or thinking and how resistant or adaptive the users are. Under the category of skills, five variables are used to evaluate users' skills on technology and programs as well as to understand their familiarity with commonly used applications such as office applications, graphical applications (that processing via pixels array) and CAD applications. In the activities' category, three variables were used to understand the activities of users in terms of frequency and volume. In the attitude category, two variables were selected, the one to understand what users think about those activities and the other to identify users' challenges. Lastly, under the motivation category, three variables were set to describe users' expectations, needs and goals.

3.3 Step 3: Mapping case subjects

In step 3, the case subjects were mapped against each of the behavioural variables that was identified in the previous step. Mapping of the case subjects is a significant procedure for identifying the placement of each subject in relation to the others (Cooper *et al.*, 2014). Here, the precision of the position of the case subjects is less important than the relative position between them. However, due to the large sample of this analysis, the relativity of positions of case subjects was not distinguished for each one of the case subjects; instead, it was evaluated in a 6-levels scale. For instance, for mapping the case subjects against the fourth variable of Table 2

(Category: Personality, Variable 4: introvert or extrovert) a six-level linear scale was used, and the case subjects were placed relatively along this scale. Thus, a case subject that is placed in level 3 of the scale is more introvert than the case subjects that are placed in level 4. However, there is no further categorization between the case subjects that belong to the same level.

The results were carefully checked and assessed by the researchers since in many variables, especially in categories B and C, the results are highly subjective since the case subjects evaluate themselves. Hence, before mapping the case subjects against those variables, the researchers evaluated and supplemented the results based on the finding of the qualitative analysis that was performed in the earlier step, and additional observations in the case study. The results of mapping the case subjects are presented below.

Regarding the aptitude variable, the results indicate that the education of the case subjects is mainly on architecture, since 90% of the case subjects are architects. The level of education in the case company is high, since 64% of the case subjects have either PhD or master's degree. In addition, most of the case subjects work as design architects or project manager with percentage of 35% and 33% respectively. The results are presented in Table 3.

TABLE 3: Mapping case subjects against behavioural variables of aptitude category.

Aptitude Category		
Education	Architects, including landscape architects Construction managers and engineers	90% 10%
Education Level	PhD degree Master of Art/Master of Architecture, or similar Diploma Intern/student	4% 60% 19% 17%
Role/Task in the company	Design architect Project manager Urban planner Communication, R&D Other	35% 33% 8% 6% 18%

By mapping the case subjects against the behavioural variables of the personality category, it was observed that there are both introvert and extrovert participants. However, there are more perceiving, thinking and adaptive case subjects compared to judging, feeling and resistant, respectively (Table 4). More specifically, in total 69% of the case subjects are placed in levels 4, 5 and 6, meaning that they are more perceiving compared to the rest of the 31% case subjects that are placed in levels 2 and 3 of the scale. Moreover, most of the participants are thinking with a percentage of 28% and 36% to be placed in levels 4 and 5 of the scale, respectively. In addition, it was observed that 12% of participants are highly adaptive, while none of them is highly resistant. However, 18% of the case subjects are placed in levels 2 and 3, and 70% are placed in level 4 and 5, indicating that the majority of the participants are relative adaptive to new technologies and practices.

TABLE 4: Mapping case subjects against the behavioural variables of personality category.

Personality category							
	1	2	3	4	5	6	
Introvert	0%	26%	23%	17%	32%	2%	Extrovert
Judging	0%	8%	23%	32%	32%	5%	Perceiving
Feeling	0%	6%	30%	28%	36%	0%	Thinking
Resistant	0%	6%	12%	25%	45%	12%	Adaptive

Regarding the results of mapping the case subjects against the behavioural variable in the category of skills, it is remarked that most of the participants are familiar with technology and programs, and there is a high level of knowledge on using spreadsheets, graphical applications and CAD applications in the case company. Counter wise, only a small percentage of participants have high programming skills (Table 5). In particular, in total 55%

of the case subjects are very familiar with technology and are placed in level 5 and 6 of the scale, while in total 41% are placed on levels 3 and 4, and only 4% on level 2. Regarding the familiarity with spreadsheet applications, graphical application, and CAD applications, in total 34%, 63% and 58% are placed in sum of level 5 and 6, respectively. By contrast, only 4% of the case subjects are completely unfamiliar with graphical applications and are placed in level 1 of the scale. In addition, a high percentage of the case subjects have low or none programming skills, in contrast to 2% that have high programming skills. However, half of the case subjects (49%) have medium programming skills and are placed in level 3 and 4 of the scale.

TABLE 5: Mapping case subjects against the behavioural variables of skill category.

Skills category						
(From 1: low to 6: high)	1	2	3	4	5	6
Familiarity with technology and programs	0%	4%	11%	30%	42%	13%
Familiarity with spreadsheets	0%	17%	17%	32%	19%	15%
Familiarity with graphical applications	4%	7%	7%	19%	41%	22%
Familiarity with CAD application	0%	6%	13%	23%	32%	26%
Evaluation of programming skills	23%	15%	11%	38%	11%	2%

Regarding the activities of the case subjects, the results of the case study analysis indicated that 85% of the case subjects use word processing or spreadsheet applications in their work processes. Likewise, CAD and BIM applications are used by 83% and 60% of the participants, respectively, while only 29% work with cost calculation tool. However, 50% of the case subjects use CAD applications weekly on their work practices, while 35% use BIM applications and spreadsheets, 33% use word processing applications and 1% use cost calculation software. The results are illustrated in Table 6.

TABLE 6: Mapping case subjects against the behavioural variable of the activities' category.

Activities category		
Use of software in work practices	In general	Weekly
Word processing applications	85%	33%
Spreadsheet applications	85%	35%
CAD applications	83%	50%
BIM applications	60%	35%
Cost calculation applications	29%	1%

Mapping the case subjects against the attitude category of behavioural variable, the results indicate that the majority of word processing applications' users and CAD users believe that word processing and CAD applications are either very easy or easy to use tools, in contrast to BIM users who believe that BIM applications are very hard to use. Regarding spreadsheet applications and cost calculation applications, 35% and 61 % of the users stated that it is normal to use spreadsheets and cost calculation tools respectively, while 38% and 21% stated that it is hard to use spreadsheets and cost calculation applications respectively. The results are presented on Fig. 2. All case subjects, however, face different challenges regarding the use of software. Through the case study analysis, it was observed that those challenges are mainly related to the lack of interoperability between software, default settings, different keyboard shortcuts between software, even between software of the same vendor, crashes of software and the need for different software in different phases of the project.

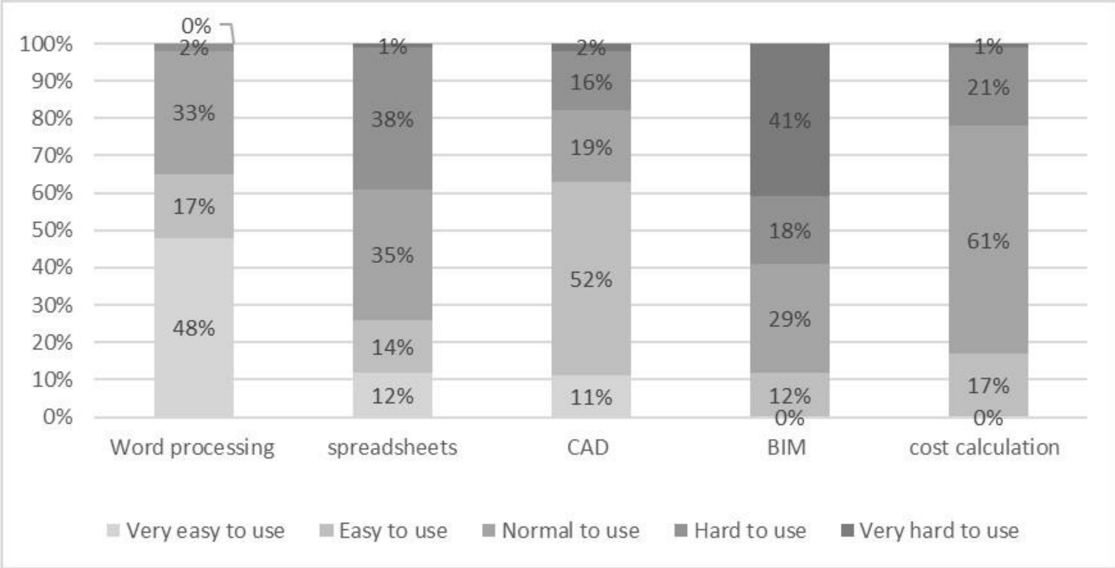

FIG 2: Mapping case subjects against the behavioural variable of the attitude category.

Regarding the results of the motivation category, the case subjects are willing to reduce time by using the software more effectively, reduce effort and manual work to produce results and increase compatibility between software. As it is indicated in Fig.3, for improving software usage, the majority of the case subjects would like to have simpler software that are compatible with other application and offer automate features. Moreover, they would like to have more templates and standards to guide them by the use of new software.

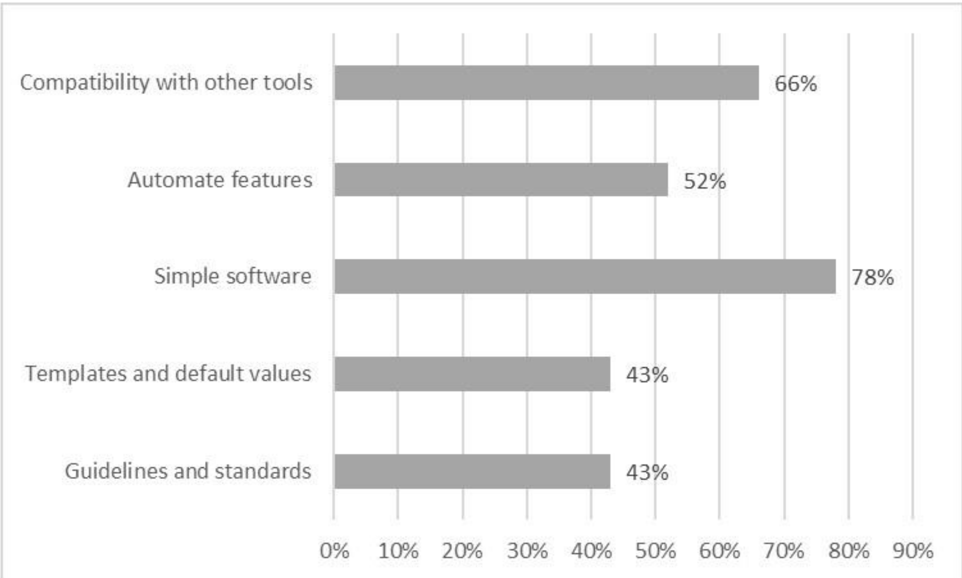

FIG 3: Mapping case subjects against the behavioural variable of the motivation category.

3.4 Step 4: Identifying significant behavioural patterns

After mapping the case subjects against the behavioural variables, the next step of constructing personas is the identification of significant behavioural patterns. Significant behavioural patterns are considered when a set of six to eight variables is observed to be followed by a group of case subjects (Cooper *et al.*, 2014). A pattern should present a causative and logical connection and not just a random correlation in order to be valid.

For identifying significant behavioural patterns, the authors analysed the correlation of the results of the previous step. Through the preliminary research and the initial steps of the process, several hypotheses for different patterns were assumed based on the qualitative analysis of the case study that was checked for validity or rejection. The analysis indicated three significant behavioural patterns, which form the basis of the personas.

The first pattern indicates a group of case subjects that are architects, more feeling than thinking, have low programming skills and work with word processing applications and CAD applications in their work practices. They face challenges of extensive manual work, and they need to save time and reduce effort. The second pattern shows a group of architects that are more introvert and less extrovert, have medium programming skills and work with BIM applications and spreadsheets. They challenge compatibility of software, and they would like to minimize errors and have easy procedures. The third pattern indicates that some of the participants with engineering skills are more judging than perceiving, however, more adaptive to new technologies. They have high programming skills and work with BIM applications. They would like to have interoperability between software in order to enable automation and reduce time spending on transferring data between software (Table 7).

TABLE 7: Significant behavioural patterns of the case subjects.

Pattern 1	**Pattern 2**	**Pattern 3**
Architect	Architect	Engineering skills
Less thinking - more feeling	More introvert - less extrovert	More judging - less perceiving
Low programming skills	Medium programming skills	Less resistant - more adaptive
Use of word processing applications	Use of spreadsheets	High programming skills
Use of CAD applications	Use of BIM applications	Use of BIM applications
Challenge: Manual work	Challenges: Compatibility	Challenges: Interoperability
Goal: Save time. Reduce effort	Goal: Minimise errors. Easy procedures	Goals: Automation. Reduce time

3.5 Step 5: Synthesize characteristics and define goals

After the identification of significant behavioural patterns, the next step of synthesizing characteristics and defining goals was performed. Personas goals were defined through their behaviours by observing typical usage of tools and work practices. Therefore, in this step, each significant pattern of the previous step 4 was synthesized with details regarding behaviours, emotions associated with the behaviour, pain-points, skills and experiences related to the behaviour, etc. as it is suggested by Cooper et al. (Cooper *et al.*, 2014). Moreover, at this step the most significant fictional details were also added: the persona's first and last name. In this study, for generating random names for personas, the authors used a random-name-generator application. However, since this research adopts a more generic perspective, it was decided to omit the personas' names in order to avoid nationality bias etc. Counter wise, demographic information such as age and job title were added, since this information is significant to visualize personas (as it suggested by Cooper et al. (2014)).

The analysis resulted in additional bullet points describing behavioural characteristics of the three personas (Table 8). Persona 1 presents traditional behaviours of working, and he is well-known for his office skills. He manually copies and pastes data from one application to another, and he usually asks for help from his colleagues to perform calculations. His goal is to finish task on time, and he thinks it will be easier if the software were simpler. Persona 2 uses spreadsheets for her calculations. She prefers to perform LCC in spreadsheets because she is restricted by the default setting of several applications. However, she is challenged by several errors that ends up with a lot of manual work. Her goal is to have more structured data. Persona 3 likes to use programming languages in order to automate the calculation processes and avoid repetition of tasks. He is flexible on using different tools and methods; however, he is also critical about them.

TABLE 8: Synthesized significant behavioural patterns with details for users.

	Pattern 1	**Pattern 2**	**Pattern 3**
Age	46 years old	37 years old	31 years old

Characteristics	Traditional character Manually copy-pastes data Need assistance from his/her colleagues	Independent – no need for assistance Calculations in spreadsheets	Technology enthusiast Develops scripts to minimize manual work
Pains	Unsure about data input Manual work Time-consuming tasks	Manual work to correct and structure data in spreadsheets Restricted by the default settings	Unstructured data Software crashes
Gains	Finish tasks on time Minimize errors	Better workflow Reduce time	Automate processes Reduce time

3.6 Step 6: Check for completeness and redundancy

After the identification of personas characteristics and goals, personas were checked for completeness and redundancy. In this step, it is important to ensure that personas sufficiently represent the diversity of behaviours and needs in the study. The analysis confirmed the representation of the identified personas; however, it resulted in identifying some missing information and filling in important gaps about the three personas. For instance, with regard to LCC it was observed that Persona 1 usually works in early design stages of projects, while Persona 2 has been involved in using LCC for DGNB certifications at the late design stages.

3.7 Step 7: Designate personas

By this step, personas' characteristics were completed and validated, and personas already feel like real people. Next step of the process for constructing personas was to designate persona types. According to Cooper et al. (2014), this is a key step since the research data are turning into a powerful set of design tools. Personas are prioritized, and the design target becomes explicit.

There are six types of personas namely primary, secondary, supplemental, customer, served and negative (Cooper *et al.*, 2014). Primary persona is the main target of design and the designers' focus on satisfying its goals. Usually there is only one primary persona per design interface. A secondary persona is mostly satisfying with primary personas interface; however, it has specific additional needs that can be accommodated without upsetting the product's ability to serve the primary persona.

In this study, however, the authors did not prioritize between the three personas that have been identified, since all three personas are equally important for analysing and understanding different types of LCC users.

3.8 Step 8: Expand the description of attributes and behaviours

In the last step, the description of attributes and behaviours of personas were expanded, and personas' narrative and photo were added. Personas' narrative should be short and quick, and it should introduce the persona in terms of significant characteristics and goals. Photos make personas feel more real, and it is helpful for increasing understanding and engagement (Pruitt and Adlin, 2006).

In Fig. 4, 5 and 6, the profiles of the three personas that have been uncovered through this study are presented. In those personas' profiles, the different characteristics of each persona are indicated along with aspiration and work processes.

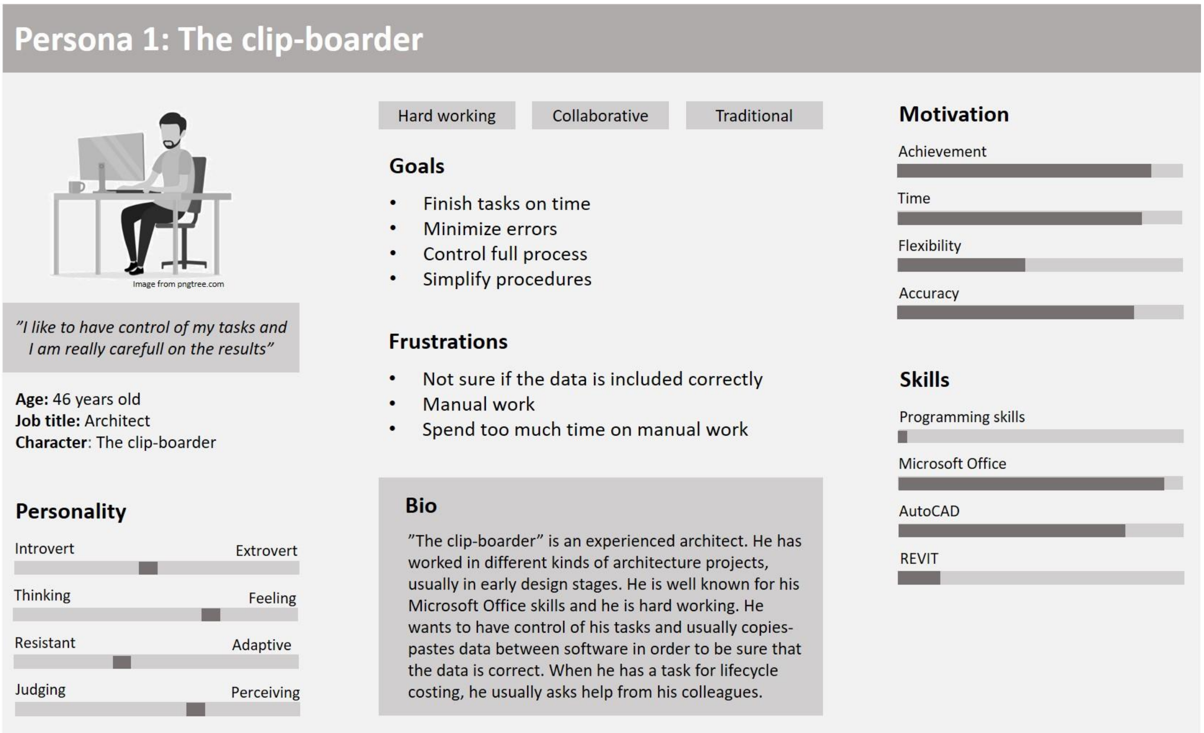

FIG. 4: Full profile of persona 1, the clip-boarder.

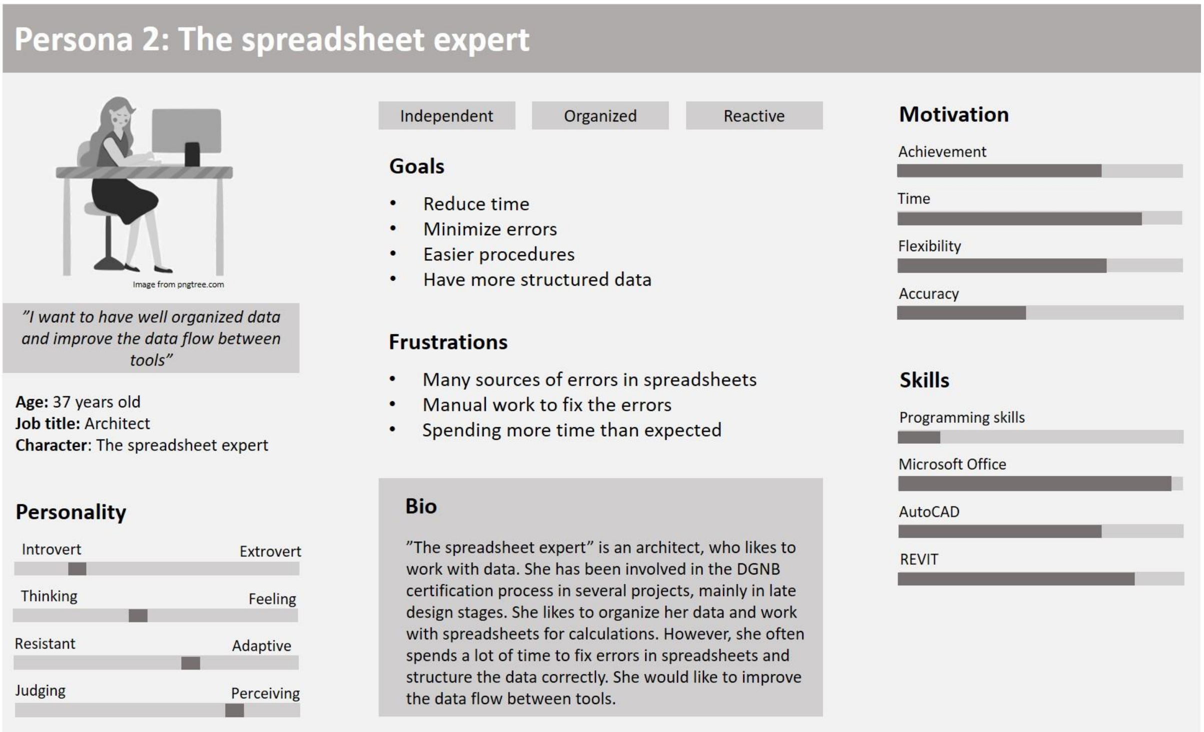

FIG. 5: Full profile of persona 2, the spreadsheet expert.

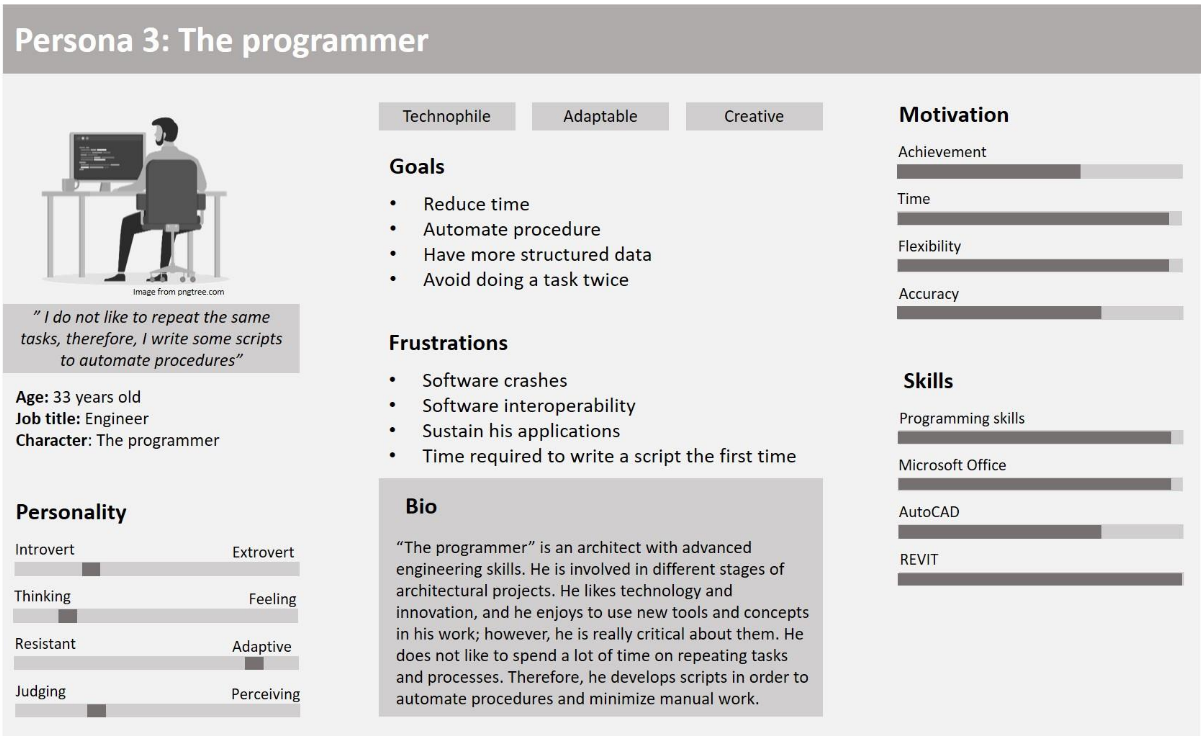

FIG. 6: Full profile of persona 3, the programmer.

4. DISCUSSION

The application of LCC is highly dependent on the adoption of the processes and tools by the practitioners, and therefore by any new intervention in their work practices should be accomplished through their active participation. Consequently, the study places the practitioners in the centre of the research process and applies UCD methods, and specifically the concept of personas, in order to achieve the research objectives. Although UCD is a design-oriented methodology (LeRouge *et al.*, 2013), this study adopts a more analytical approach and rather than using personas as a design tool for LCC, this study uses personas for improving our understanding about users in general.

In this analytical context, the benefits of applying UCD in work practices are recognised in this study since the use of personas exposes valuable information on the characteristics and work processes of different types of users. The results contribute also to an improved understanding of how people would like to work with LCC in practice by providing valuable insights on current and potential LCC users.

There is however one main restriction in the process of constructing personas, that is too restrictive in a more analytical study like this compared to a more design-oriented study, namely the designation between the different personas in Step 7. The designation between personas is useful in design-oriented processes where the design is focused on accommodating one dominant persona (Cooper *et al.*, 2014). However, this seemed to be a too strong limitation in an analytical perspective. Hence, this study aims to uncover the different user types instead of eliminating them or narrowing the research focus to only one dominant persona. Therefore, this study does not prioritize between the personas. Instead, it emphasizes the diversity of users and underlines the importance of thinking in precisely that diversity when developing interventions for increasing the application of LCC in the AECO industry. Failure to do so will seriously hamper the available intervention options and reduce the likelihood of success of adoption when developing new tools.

Moreover, the results highlight the diverse types of users by explicitly pointing out three different user personas. A significant difference between the three constructed personas is the way of working with technology and processing data, reflecting in three different methods of data integration methods that are summarized in Table 9.

TABLE 9: Personas in relation to data processing, data integration methods and tools requirements

	The clip-boarder	**The spreadsheet expert**	**The programmer**
Data processing	Manually select, copy and paste data from one application / position to another	Export and import data from an application to another in csv file / spreadsheet	Exchange data between applications automatically by using programming
Data integration method	Independent and stand-alone tools	Set up pipelines between tools and uses spreadsheets as the mediator of calculations	Interoperability methods to link individual tools through file transformation
Tool requirements	Simple and easy to use tool that include default values	A tool in a spreadsheet format, where data can be imported and exported easily	An open tool that supports interoperability

This increases our awareness that there are at least three different approaches in relation to tools and processes that should be taken into consideration when developing new solutions. While the findings of this study on users are related to LCC application, it also discloses different approaches to the use of digital technologies in general and thus important differences in the requirements of users towards not only LCC tools, but digital technologies in general.

As indicated in Table 9, the *clip-boarder persona* would benefit from a simple stand-alone tool that contains a number of default values in order to reduce manual work and minimize uncertainty about data. The *spreadsheet expert* persona on the other hand will benefit from tools in for example spreadsheets format that offer csv/spreadsheet import and export features. Finally, a tool that support interoperability will be valuable for *the programmer* persona, who could be able to automate their procedures.

In summary, rather than simplistically dividing practitioners into being either an LCC user or a non-LCC user, this study urges a more reflective approach with a stronger awareness of users' diversity and emphasis on the need for understanding the different users and their different requirements before designing tailor-made solutions. Being sensitive to these differences and the diversity of users encourages a more pluralistic approach towards developing tools, practices and data that may in turn increase the chances of implementing LCC in the AECO industry and ultimately improve the economic sustainability of buildings and constructions.

5. CONCLUSION

This study adopted user-centred design methods and specifically the concept of personas to increase our understanding on the diversity of users of technology and LCC in the AECO industry, recognize their characteristics and understand their aspiration and work practices. A Danish architectural firm was used as a case study for the analysis, and data from users was collected through both qualitative and quantitative methods.

For constructing personas, the eight-principle steps that are proposed by Alan Cooper was followed systematically (Cooper *et al.*, 2014). The analysis resulted in the construction of three personas:

1) *The clip-boarder* persona, who usually copies and pastes data from one application to another since he wants to have the control of the process. However, he spends a lot of time on manual work.

2) *The spreadsheet expert* persona, who imports and exports data in csv files/spreadsheets. However, she is challenged by correcting errors and structure data in spreadsheets.

3) *The programmer* persona, who uses programming language for transferring data from one application to another, since he wants to automate procedures, avoid repetitions of tasks and save time. However, he struggles with sustaining the scripts and the lack of software interoperability.

By constructing user personas, this study reveals valuable insights on how people work with technology in practice. The analytical approach emphasizes the importance of recognizing the diversity of users and their different approaches with regard to work processes and data integration. In relation to LCC, the three personas indicate three different approaches towards adopting LCC in design practices. Hence, the results provide valuable information that can be used for both designing novel LCC tools and increasing LCC implementation in the AECO industry.

6. ACKNOWLEDGEMENT

Removed for blind review process

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Appendix 7

Paper G

Saridaki, M. and Haugbølle, K. (2022) “Transforming the activity systems involved in building design to include LCC”. Submitted in *Construction Management and Economics*

Title: Towards lifecycle costing in building design: Transforming the activity systems of operation and design

In recent years, the Architecture, Engineering, Construction and Operations (AECO) industry has shown increased interest in economic sustainability and lifecycle costing (LCC) in building design, construction and operation. Despite the benefits of applying LCC, the concept faces limited adoption in practice due to lack of available data and lack of collaboration between design and operation. Using activity theory to analyse a case study, this research aims at mapping the interaction between two activity systems of building design & construction and building operation in social housing projects and identify actions that support data utilization and exchange with regard to LCC. The analysis identified three key actions that support LCC data utilization and exchange between the two activity systems: (1) LCC introduction in the tendering process, (2) operation and maintenance planning in early and late design processes, and (3) provision of an operation and maintenance guide and budget along the project handover. Despite collaboration between the two activity systems, it is observed that LCC-related data are not fully utilized due to several misalignments between the elements of the two activity systems. The discussion points out how the elements of the two activity systems could be transformed in order to ensure a stronger consideration of LCC throughout the lifetime of social housing projects.

Keywords social housing, lifecycle costing (LCC), building design, building operation, activity theory

Paper type Research paper

Introduction

In the past few years, the architecture, engineering, construction and operation (AECO) industry has shown an increasing interest in sustainability contributing to achieving the UN sustainability development goals. Sustainable design, construction and operation needs to focus not only on the environmental performance, but also social quality and economic assessment of buildings. In order to ensure economic sustainability, lifecycle costing is a core decision-making tool that assess the economic quality of different materials and design solution that have different cost profiles over time (Haugbølle and Raffnsøe, 2019).

The adoption of LCC methodology in building design and construction is directed by European procurement policies (European Commision, 2014), various certifications schemes like LEED and DGNB (DK-GBC, 2012), and new building regulations (Saridaki *et al.*, 2019). In the Danish AECO industry, LCC assessment is a mandatory for public construction (Bygningsstyrelsen, 2017), while it is included in the voluntary sustainable building class of the national building regulations as of 2020 (Mortensen *et al.*, 2018) which is expected to become mandatory for all new buildings in 2023 (Bolig- og Planstyrelsen, 2021).

Although the new initiatives have stimulated an increased use of LCC in the Danish AECO industry, its application in work practices is still limited due to several challenges (e.g. (Cole and Sterner, 2000; Fu *et al.*, 2007; Gluch and Baumann, 2004; Goh and Sun, 2016; Salvado *et al.*, 2018)). In the recent study of (Saridaki and Haugbølle, 2019), the authors identified a number of prohibitive contradictions towards integrating LCC in Danish design practices. The results indicated that the main prohibitive contradictions are related to poor availability of lcc-related data and the current practices for exchanging data.

Few years ago, (Jensen, 2012a) suggested to overcome the challenges of poor data availability by strengthening the collaboration between design and operation practices and by transferring of information and knowledge from operating existing buildings to the design of new buildings. In the literature, studies investigate ways of transferring knowledge from operation to design (summarized in (Rasmussen *et al.*, 2017)) and propose a typology of transfer mechanisms, including: codification of operation knowledge, continued briefing of facility managers and users in design processes, project reviews and regulations to ensure that the codified knowledge is used in the design (Jensen, 2009, 2012a). However, in order to transfer operation knowledge to design, several actors should be involved, including facility managers and building users to provide insights of operating existing buildings (Chandra and Loosemore, 2011; Jensen, 2009, 2012a; Meng, 2013), building clients to ensure knowledge codification and transfer (Jensen, 2009, 2012a), and building designers to ensure integration of operational knowledge into design (Jensen, 2009; Rasmussen *et al.*, 2019).

This study takes a closer look at the opportunities for transferring knowledge between operation and design in Danish social housing projects. Social housing (in Danish: almen bolig), also known as affordable housing or non-profit housing, are residential buildings that are owned by social housing organizations. Social housing organizations manage 20 per cent of the housing market in Denmark and are obliged to centrally register a large range of operational data from existing buildings. Moreover, they are at the same time facility managers, building clients and collaborate closely with building designers etc.

The study aims at describing the collaboration and data exchange between design and operation with regard to LCC in two paradigmatic social housing projects of the case study under analysis. By adopting activity theory as the theoretical framework for describing the activities in the case projects under examination, the objectives of this research are:

- To characterize the interaction between the activities systems of building design & construction and building operation in social housing projects.
- To identify actions that support data utilization and exchange with regard to LCC between design and operation.
- To discuss how the elements of activity systems could be transformed in order to ensure LCC consideration in the actions throughout the lifetime of social housing projects.

Research methodology

Activity theory as theoretical grounding

This study applies activity theory (AT) for analyzing the activities in the case projects under examination and identify actions in relation to LCC.

AT is a conceptual framework for describing the structure, development and context of human activity (Bertelsen and Bødker, 2003) and has proven useful for underpinning complex and dynamic problems of human research and practices (Hashim and Jones, 2007). The framework was originally developed by Lev Vygotsky (Vygotsky, 1978) and Alexei Leont’ev (Leont’ev, 1978) in the 1920s and 1930s, and it was expanded by the finish educational researcher Yrjö Engeström in 1980s (Engeström, 1987). Since 1990s, AT theory has mainly been used as an analytical framework for human-computer interaction and furtherly for designing computer supported corporative work. Currently, the framework is being widely used interdisciplinary in a range of fields including education, organizational learning and cultural studies.

In the AECO industry, AT has been used for analyzing the complexity and interaction of actions in projects and interpreting the development of tools in activities. For instance, it is used as a conceptual framework to analyze the role of technology in project management (Floricel *et al.*, 2014); to highlight information sharing and interoperability issues in emergency response (Allen *et al.*, 2014); to study the uses of BIM and corresponding issues in the daily work of site managers (Mäki and Kerosuo, 2015); to analyse BIM implementation in building O&M (Lu *et al.*, 2018); and identify contradiction of applying LCC in design practices (Saridaki and Haugbølle, 2019).

The first generation of AT describes an activity through the triadic relation between a subject and an object mediated by tools and artefacts (Miettinen *et al.*, 2009). However, empathizing the collective nature of human activities, Engeström expanded the original triadic model by incorporating three additional interacting elements: Community, Division of Labor (DoL) and Rules that frames the human behavior in a more consistent and systematic way in the second-generation activity system (Engeström, 1987). Later, Engeström introduced a third-generation activity model in which at least two activity systems are interacting (Engeström, 2001). The activity theory triangle is illustrated in Figure 1.

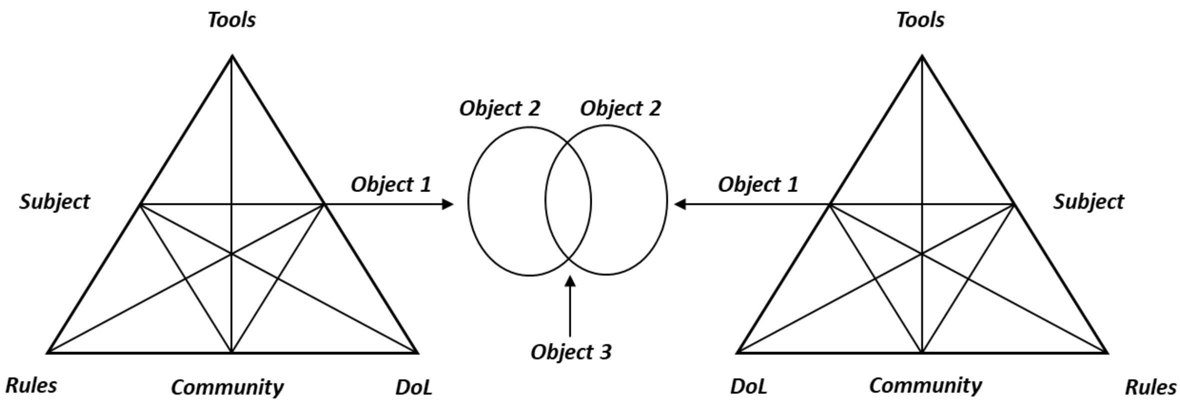

Figure 1. Third generation activity system with two interacting activity systems (adapted after (Engeström, 2001).

The different interacting and mediating elements of activity systems are described in the following table (Table 1):

Table 1. Description of the elements of an activity system.

Elements	Description of elements in an activity system
Subject	Individual or group of individuals who perform the activity

Object	The immediate goal of the activity
Outcome	Long term results of performing the activity
Tools	Instruments, information and knowledge that are used to perform the activity
Community	Individuals and groups who share the same knowledge, interests and goals for the activity
Rules	Regulations, norms and conventions that constrain actions and interactions within the activity system
Division of Labour	Division of tasks between the subjects or between the members of the community

Five basic principles guide the analysis of an activity system (Kaptelinin and Nardi, 2006):

a) *Object-orientedness*: this principle is related to the subject-object relationship, emphasizing that all human activities are directed towards their objects that motivate and direct activities.

b) *Hierarchical structure of activities*: activities are organized in three hierarchical layers. The top layer is the activity itself that is oriented towards motives. Activities consist of actions that are in the middle layer. Actions are processes directed at goals and are undertaken to fulfill the objects. Actions are implemented through lower units of activity, called operations. Operations are oriented toward the conditions under which the subject is trying to achieve a goal.

c) Mediation: human processes are defined by mediation. Mediating tools not only shape the external behavior but also influence the functions of individuals' perception and interaction with the world.

d) Internalization & externalization: in the process of internalization external components of an activity become internal, while in the process of externalization, internal components of an activity become external.

e) *Historical development*: activities are analyzed in the context of development. Development of activity systems can be the object of the study or a research strategy. A research strategy that analyzes how the object of study transforms over time is considered essential for a deep understanding of the object.

Based on the above-mentioned principles, an activity can further be analyzed through the following key terms:

- Interaction: the main interacting elements of an activity system is the subject, the object and community. Therefore, there are three main types of interactions: subject-object, subject-community and community-object.

- Mediation: the mediating elements tools, rules and division of labour incur three primary mediating relationships in an activity system. Tools mediate the interaction between the subject and the object, rules mediate the interaction between subject and community, and division of labour mediates the interaction between community and the object of the activity. However, there are also secondary mediating relationships, for instance, rules may mediate the interaction between the subject and the object or the community and the object.

- Disturbances: disturbances are surface problems that occur due to development and transformation of the activity system. Disturbances indicate the existence of contradictions, which are persistent tensions in the activity, and therefore is significant to identify and analyze from different perspectives.
- Contradictions: contradictions are *"historically accumulating structural tensions within and between activity systems"* that generate *"disturbances and conflicts, but also innovative attempts to change the activity"* (Engeström, 2001, pg.137). In an activity system, there are four types of contradictions, namely primary, secondary, tertiary and quaternary that describe a misfit within an element, between two elements, between different developmental phases of a single activity or between neighboring activities, respectively (Engeström, 2001). The identification of contradictions is essential as they are forces of change and development.
- Evolution: contradictions lead to evolution of the activity system. Evolution occurs to relieve contradictions within and between elements and in previous status of an activity (Georg *et al.*, 2015).

In this study, the above-mentioned principles are used to analyze the activity systems throughout the lifetime of the projects under examination.

Method design and data collection

The research design of this study compromises a case study analysis of a Danish architecture firm, located in Copenhagen, Denmark, that is a frontrunner on sustainable design including LCC. The case company has a long track record of collaborating with social housing organizations, and it has been involved in many renovations and new building projects.

Two building projects were selected as embedded case studies under examination (Yin, 2018): a new building project that is in the design phase and a renovation building project that is in operation. Both projects are typical social housing projects, and they belong to the same building client, who is one of the biggest social housing organizations in Denmark. In addition, this social housing organization has shown increased interest in all aspect of sustainability including economic sustainability and LCC.

By active participation of one of the authors in the selected case-projects, qualitative and quantitative data were collected over a period of 9 months through a series of interviews, participant and direct observations and analysis of physical artifacts (Yin, 2018). Specifically, nine semi-structured interviews were conducted during autumn/winter 2020 aiming to understand the activities throughout the building lifecycle with regards to LCC. The interviewees were architects and engineers that are involved in the design and construction of the building projects (five interviews) as well as employees from the social housing organization operating the building projects and planning new project (two interviews with senior project manager and two interviews with operation managers). In addition, various e-mails and calls followed the interviews with employees of social housing organization in order to clarify aspects in relation to the documentation provided by them. In addition, continued informal discussions and observations were performed with the architects of the case-projects under examination since one of the authors was closely collaborating with them. The observation included the activities performed by the architects as well as their collaboration with engineers and the social housing organization. The physical artifacts that were collected for analysis included among others competition tenders, projects' documents and reports throughout the design phase, operation and maintenance financial documents and reports from the social housing organization for projects in the operation phase, and LCC related data of the case-projects from a building database that is provided by the National Building Foundation (in Danish: Landsbyggefonden, abbreviated LBF).

Findings: three actions towards integration of LCC

In the past few years, activities related to social housing projects are slowly transforming their object-orientation towards economic sustainability. In this research, the ongoing development of the activity systems involved in social housing projects towards long-term economic considerations and LCC is described, highlighting the internalization of tools and rules that are integrated in the activity systems as mediating elements, and interact with the existing elements provoking new actions and interactions towards LCC.

This section starts with describing the activities of social housing organizations and mapping the two activity systems of building operation and building design & construction and their interactions throughout the case-projects lifetime. Then, three actions that mediates data utilization and exchange with regard to LCC between design and operation are identified and analyzed.

The activity system of building operation

Social housing (in Danish: Almen bolig), also known as affordable housing or non-profit housing, refers to a residential house owned by a social housing organization operating as a private non-profit business. The Danish social housing sector was founded in 1920s, and today constitutes one fifth of the housing stock (Alves and Andersen, 2015; Denmarks' statistics, 2022). Specifically, there are around 600,000 social housing units in Denmark, of which approximately 60,000 are located in the city of Copenhagen and distributed among 25 social housing organizations.

Danish social housing is constructed and operated by social housing organizations. Social housing organizations (***the subject)*** aim at providing modern and well-maintained dwellings at affordable costs for all in need hereof regardless of income. The manifest of social housing is a non-profit sector that aims at being both financially, physically and socially sustainable and well-functioning (***outcome***).

A main principle in the Danish social housing model is the tenant's democracy (***subject***). All social housing organization are managed by tenants since each individual housing estate elects its own tenant board yearly. The tenants (***subject***) constitute the majority in the board of the entire organization, together with representatives of the municipality (***community***) that the social housing belongs to.

The Danish social housing sector has remained independent throughout the years; however, it has close links to local municipalities and central government. The sector is regulated by a range of detailed central government policies and directives (***rules***). There are two strict regulations to ensure the efficiency and appropriate operation of social housing sector in Denmark:

- Law on renting of social housing, which describes the relationship between housing organization (landlord) and individual occupants (tenants) (Social Housing Act, 2016).
- General Social Housing Law, which describes the social housing, resident democracy, and the municipality's supervision of the social housing organizations (Social housing Act, 2020).

The activities of social housing organizations are related to:

- operation and maintenance of housing estates,
- renting out apartments, and
- managing construction of new buildings and renovation of existing buildings (***object***).

The activity system of operation and maintenance for social housing along with the interacting elements are presented in Figure 2.

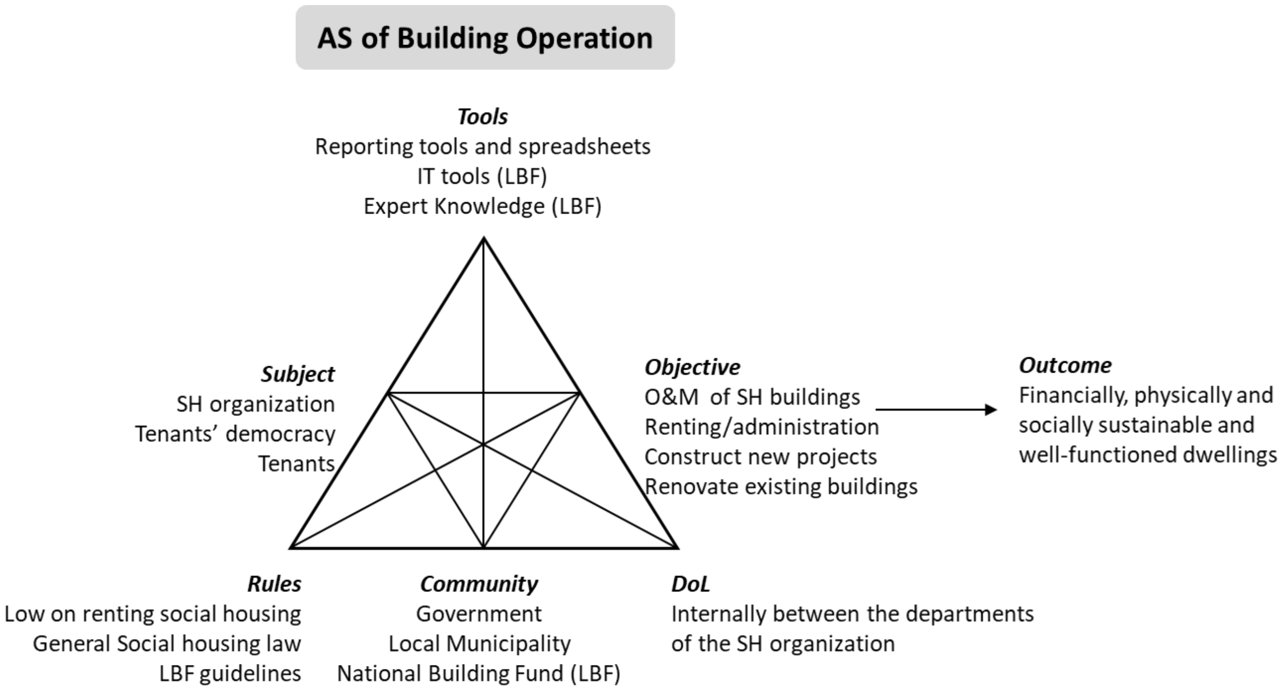

Figure 2. Activity system of building operation and its elements.

The activity system of building design & construction

An additional ***objective*** of social housing organizations was the initiation of new building projects and renovation of existing buildings (Figure 2). The construction of new social housing building projects was financed by loans and public funds from both municipality and the state along with a minor contribution from the tenants (***community***). Renovations and social developments plan of existing housing estates were supported by the National Building Foundation (LBF) (***community***), a self-governing organization founded by public housing organizations and established by law that aimed to promote the self-financing of social housing. LBF was an important part of the social housing sector in Denmark since it provided financial support, expert knowledge and various statistics and IT-tools (***tools***).

Through the development of new projects either new construction or renovation of existing projects, the activity system of building operation interacted with another activity system, namely the activity system of building design and construction (Figure 3). The activities of the activity system of building design and construction were initiated by a different department of the social housing organization with the hired support of a team of architects and engineers (***subject***) aiming to design and construct the building projects (***object***).

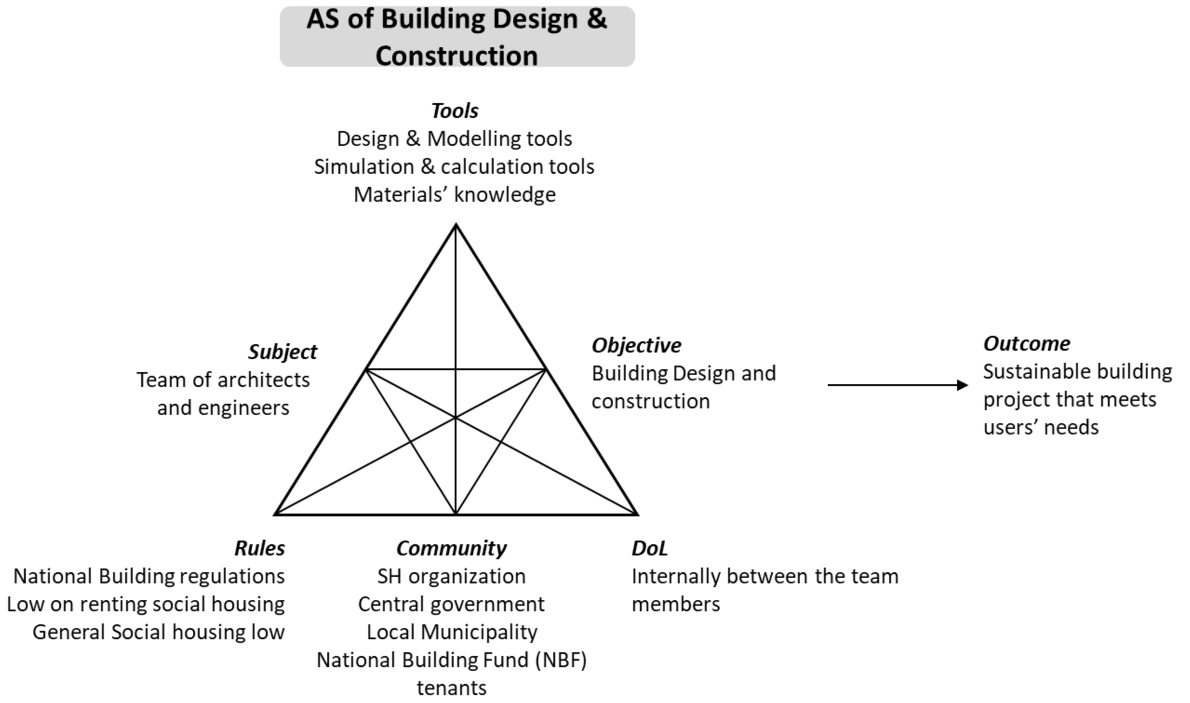

Figure 3. Activity system of building design and construction.

Three actions towards integration LCC in building design

The tangible objective of the activity system of building design & construction was to design and construct a residential building to be owned and operated by the social housing organization. Therefore, it was significant for the social housing organization to ensure that the activities of building design were performed with consideration of the operation of the building to achieve the long-term goal of financially, physically, and socially sustainable and well-functioning dwellings. However, these two objectives raised challenges that needed mediation.

Through the processes of building design and construction, the two activity systems interacted and exchanged LCC related data. Three actions were observed that mediated (supported or inhibited) the adoption of LCC from both activity systems:

- Action 1: Introducing a novel Model Maintenance Plan in project competitions
- Action 2: Designing for operation and maintenance
- Action 3: Planning for long-term operation and maintenance

In the following sections the above-mentioned actions are described with emphasis on the interaction between the elements of the activity systems as well as the role of the mediating elements and especially, LCC-related data (***tools***) flowing between the activity systems in order to achieve the goal of long-term economic sustainability of the social housing sector.

Action 1: Introducing a novel Model Maintenance Plan in design competitions

The activities of the social housing organization as building client (***the subject***) under supervision of the municipality, in which the project was located (***community***) was to plan the new project and prepare the project competition. The tendering documents for the design competition included two critical documents: (1) the competition program (In Danish: Konkurrenceprogram) that described the competition process, including process description and requirements for tendering documents; and (2) the Standard Building program (In Danish: Standardbyggeprogram) that described the requirements of the new project, including descriptions of the overall layout and architectural design, rooms' specifications, buildings' elements and materials, technical installations, electrical systems, outdoor areas as well as maintenance planning. The tendering documents also included generic and qualitative requirements in relation to LCC of the new project, like expected long lifetime of building components, low maintainability of materials and low operational costs.

In order to further stimulate LCC considerations in the project tendering, the social housing organization introduced a novel model maintenance plan (***tools***). The model maintenance plan included yearly expected expenditures expressed in monetary value for eighteen (18) maintenance activities for the first 30 years of operation (Table 2). Specifically, the plan included 11 activities that were related to external maintenance, for instance roof surface maintenance, maintenance of outdoor areas, etc., and 7 activities for internal maintenance, for instance replacement of ventilation system, maintenance of electrical system, etc.

Table 2. Model maintenance plan.

Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	*All amounts in DKK 1000														
Exterior maintenance															
Joint around windows	0	0	0	0	0	0	0	0	0	0	25	25	25	50	50
Replacing double-glazing units	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gutter repair	0	0	0	0	3	0	3	0	3	3	3	0	3	3	3
Roof surface maintenance	0	10	10	10	10	10	15	10	10	15	10	10	15	10	10
Covering roof	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2
Exterior lighting	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Outdoor areas, paving/ asphalt	0	0	0	0	0	0	0	0	0	0	800	0	0	0	0
Other outdoor areas	0	0	5	0	5	0	5	0	5	0	5	0	5	0	5
waste disposal	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5
sewage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
purification of rainwater	0	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Internal maintenance															
Electrical systems	0	10	10	10	10	10	10	10	10	10	10	10	10	10	10
ventilation and heat pump service	0	50	50	50	50	150	50	50	50	50	150	50	50	50	50
Replacement ventilation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
sanitation replacement kitchen & bath	0	0	0	0	0	0	0	9	18	36	72	144	279	0	4.5
sanitation repair	0	10	10	10	10	10	10	10	10	10	10	10	10	10	10
replacing wash basin	0	0	0	0	0	0	0	9	18	36	72	144	279	0	4.5
Abrasion and aging of surfaces	0	0	0	0	0	0	30	30	30	30	30	30	30	30	30
Consumption per year (sum)	**0**	**100**	**105**	**100**	**110**	**202**	**145**	**150**	**176**	**212**	**1209**	**445**	**728**	**185**	**199**
provisions DKK per m2	0.03	0.03	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.06	0.061	0.06	0.07	0.07	0.07
Provision per year	300	331	362	393	424	455	486	517	548	579	610.3	641	672	703	734
Initial balance	0	300	531	788	1081	1395	1649	1990	2357	2729	3097	2498	2694	2639	3157
Expenditure in the year	0	100	105	100	110	202	145	150	176	212	1209	445	728	185	199
Balance before deposit	0	200	426	688	971	1193	1504	1840	2181	2517	1888	2053	1966	2454	2958
Balance to transfer	300	531	788	1081	1395	1649	1990	2357	2729	3097	2498	2694	2639	3157	3693

Year	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Exterior maintenance															
Joint around windows	400	0	0	0	0	0	0	0	0	0	25	25	25	50	400
Replacing double-glazing units	15	30	45	60	75	90	105	120	135	150	165	180	195	210	225
Gutter repair	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Roof surface maintenance	15	10	10	15	10	10	15	10	10	15	10	10	15	10	15
Covering roof	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Exterior lighting	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Outdoor areas, paving/ asphalt	0	0	0	0	0	800	0	0	0	0	0	0	0	0	800
Other outdoor areas	0	5	0	5	0	5	0	5	0	5	0	5	0	5	0
waste disposal	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
sewage	80	0	0	0	0	0	0	0	0	0	0	0	0	0	80
purification of rainwater	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Internal maintenance															
Electrical systems	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
ventilation and heat pump service	150	50	50	50	50	150	50	50	50	50	150	50	50	50	50
Replacement ventilation	500	1000	1000	1000	1000	0	0	0	0	0	1000	1000	1000	1000	0
sanitation replacement kitchen & bath	9	9	18	36	72	144	279	0	4.5	9	9	18	36	72	144
sanitation repair	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
replacing wash basin	9	9	18	36	72	144	0	4.5	9	9	18	36	72	144	279
Abrasion and aging of surfaces	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Consumption per year (sum)	**1256**	**1191**	**1219**	**1280**	**1357**	**1421**	**527**	**268**	**287**	**316**	**1455**	**1402**	**1471**	**1619**	**2071**
provisions DKK per m2	0.077	0.08	0.08	0.086	0.089	0.09	0.1	0.1	0.1	0.1	0.11	0.111	0.11	0.12	0.12
Provision per year	765.5	797	828	858.6	889.7	921	952	983	1014	1045	1076	1107	1138	1169	1200
Initial balance	3693	3202	2808	2416	1995	1528	1027	1452	2167	2895	3623	3244	2949	2616	2166
Expenditure in the year	1256	1191	1219	1280	1357	1421	527	268	287	316	1455	1402	1471	1619	2071
Balance before deposit	2437	2011	1589	1136	637.9	107	500	1184	1881	2579	2168	1842	1478	997	95
Balance to transfer	3202	2808	2416	1995	1528	1027	1452	2167	2895	3623	3244	2949	2616	2166	1295

After the project competition was published, the different elements of the activity system of building design & construction interacted to prepare a project proposal for the competition. In the activity system of building design & construction, pre-qualified teams consisting of architects and engineers (***subject***) used the information in the tender documents (***tools***) as well as considering the requirements that were specified in the tender documents (***rules***) to prepare the competition projects by internally dividing tasks in the team (***DoL***). Hence, the tendering document that was prepared by the activity system of building operation was adopted by the co-existing activity system of building design & construction as a mediating element that influenced its activities for achieving the goal of winning the competition (Figure 4). The tendering document included information and data that flowed from one activity system to the other activity system.

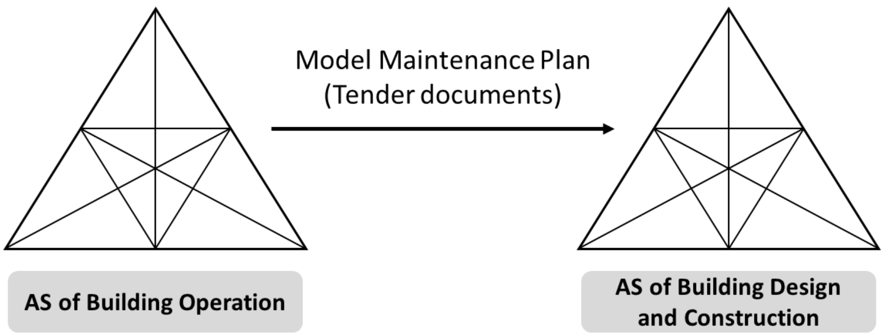

Figure 4. Data with regards to LCC flowing from the activity system of building operation to the activity system of building design & construction through the competition process.

The tendering reports were evaluated by the social housing organization, the municipality, and members of other social housing organization that all constituted the assessment committee (***community***). Through the analysis of the assessment committee, it was pinpointed that the award criterion was the most economically advantageous tender with regard to initial cost. Additional sub-criteria included (a) the building system: architectural idea, building technology and quality, flexibility of options, (b) price: unit price, compliance with given price per m^2, and (c) cooperation: the contract team and their organization.

The result of the action of building design & construction towards winning the competition was a project proposal that included a case analysis, several drawings along with building elements' specifications and various calculations/simulations. However, the tender reports under examination (***the object** of this action*) did not include any information about the lifetime of the selected materials or their maintainability, or any other LCC information to support the architectural choices.

In interviews, the social housing organization explained that the model maintenance plan was not developed as a case specific requirement for the project under examination. Instead, it was used for every new building project that was initiated by the social housing organization. Moreover, it was found that the model maintenance plan contained generic information based on estimations, while available data from operating buildings were not utilized in an efficient way to reveal new insights about cost-drivers of building operation as well as develop more precise and useful maintenance plans.

Action 2: Designing for operation and maintenance

A second action attempting to bring operational concerns and LCC into the activity system of design & construction was the consideration of O&M during early and late design of the project.

After winning the competition, the team of architects and engineers (***subjects***) worked on the design and construction of the building project (***objective***). During the early design process, the architects and engineers had continuous communication with the building department of the social housing organization, the local municipality as well as current tenants of other existing social housing buildings and future tenants of this building project (***community***) in order to discuss the expected design and performance of the building project but also to gain information from operating buildings that could be used to ensure high quality of the new building project. In relation to LCC, the community provided valuable information (***tools***) regarding current operation and maintenance performance of various elements of the building (especially in renovation projects) and unexpected operation and maintenance issues and costs. This action indicated flow of data from operation to design through the early design processes (Figure 5). However, it was not observed any structured action in the activity system of building design & construction that indicated the exploitation of the information gained through the meetings.

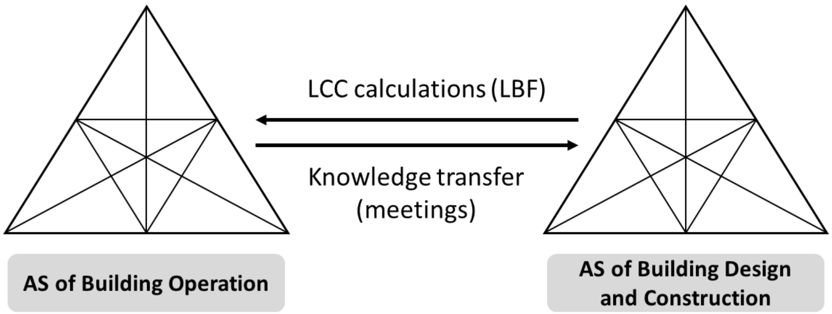

Figure 5. Data with regards to LCC flowing between the activity system of building design and construction and the activity system of building operation through the actions of building design.

However, an action towards LCC was observed in the late design stage of the case-projects in the activity system of building design & construction, and more specifically at the so-called Scheme B (time for tender for construction). The motivation of the ***subjects*** towards this action, however, was directed by the ***rules*** that were set by the government. Since 1998, each project should contain a life cycle costing assessment in connection to both new and renovation constructions of social housing projects in order to get municipality's approval. Since 2010, the subjects are required to report LCC calculations digitally by using the web-based LCC ***tool*** developed by LBF (COWI, 2018). The LCC tool (https://totaloekonomi.lbf.dk/) is used to perform net present value calculations for three building parts - windows, façade and roofs - since those elements are believed to constitute the majority of the costs to both construction and operation. A corresponding LCC assessment had to be made for at least one relevant alternative for each of the building parts. The data required for the LCC calculations were the construction cost, maintenance activities and intervals as well as the lifetime of the materials under examination, while maintenance cost was added as a percentage of the construction cost. The tool included predefined assumptions for maintenance intervals, maintenance percentage and lifetimes for specific materials under the three above-mentioned categories, however, there was a possibility to correct the assumptions if it was required.

LBF encouraged the use of the tool throughout the design processes as an opportunity for dialogue between the subject and the community regarding effect of the proposed materials in long-term. However, the analysis indicated that in the projects under examination, the tool was merely used for performing LCC calculations for materials under the three predefined categories in a later design stage of the projects in order to comply with the ***rules***, while the results of the LCC analysis were not utilized to inform the decision-making process. This observation is also pinpointed in a study on the Danish social housing sector by (COWI, 2018). Although the intention of LBF was to use the LCC tool to inform the decision-making process, in practice, the tool was only used immediately before reporting. Therefore, the application of the tool became a post-rationalization and control measure with little practical importance.

Action 3: Planning for long-term operation and maintenance

A third action was observed in the end of the design and construction of the building projects under examination where an operation and maintenance guide and budget report was handed over from the activity system of building design & construction to the activity system of building operation. The O&M guide and budget included description and information on the building components used in the project including components' lifetime, O&M activities and intervals, instructions for use, product data sheets and guarantees (Figure 6).

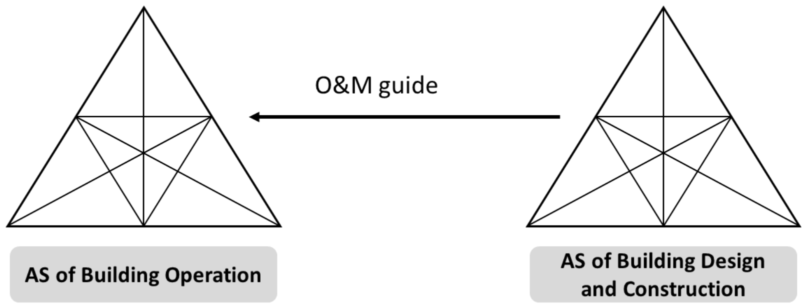

Figure 6. Data with regards to LCC flowing from the activity system of building design & construction to the activity system of building operation through the handover of the social housing project.

The O&M guide presented a proactive approach on building operation providing data that could in principle be incorporated in the activities of the activity system of building operation for scheduling and optimizing O&M activities in the long term. The analysis indicated that although the introduction of the O&M guide as valuable tool for developing the O&M planning strategy of the building under operation, the subjects of the activity system of building operation performed the action towards the 30-years O&M planning based on their own experience instead of utilizing the information that was provided in the O&M guide and budget by the consultants. Hence, the O&M guide and budget appeared as a disturbance to the current activities of building operation rather than a mediating tool for achieving its objective towards LCC consideration. Taking a closer look at the activity system of building operation revealed two reasons for these disturbances.

First, the operation and maintenance guide and budget only addressed a limited part of the activities to be executed by the activity system of building operation, and not the job in its entirety. Focusing on the O&M objective in the activity system of building operation, the social housing organization (***the subject***) on behalf of the tenants and the tenant democracy (***subjects***) interacted with the elements of the system shown in Figure 2 and undertook actions to achieve this objective. Those actions involved performing O&M activities, planning future O&M activities as well as registration of the expenses/budget that were related to O&M in financial accounts.

Specifically, social housing organizations prepared financial reports for their expenses on a yearly basis, including O&M related expenditures of each year. In the past, financial reports were manually prepared by the social housing organizations but are now fully digitalized in an online accounting system that allowed for extracting key figures on all social housing estates in the country. Since 2014 all social housing organizations in Denmark has been required to prepare and register their yearly financial reports and O&M expenses, due to a new rule that attempted to make more precise predictions of anticipated and unforeseen expenditures for the upcoming years

(Landsbyggefonden, 2014). Both financial reports and O&M budgets were registered in specific accounts that was developed by the Danish Transport, Construction and Housing Authorities (Lejerbo, 2019). Specifically, there are eight main groups of accounts under which financial data and budget were registered. Those groups were the following:

- net capital expenditure (accounts 101-105),
- public and other fixed expenses (accounts 106 -113),
- variable expenses (accounts 114-119),
- provisions (accounts 120-125),
- extraordinary expenses (accounts 125 - 140),
- ordinary income (accounts 200-203),
- extraordinary income (accounts 203- 210), and
- rent determination.

The groups related to O&M expenditures are the groups of variable expenses and provisions. In the group of variable expenses, in account 115 the general maintenance of buildings, installation and other facilities that are carried out in ongoing basis are registered and in account 116, scheduled and periodic maintenance and replacements are registered. In addition, in the provisions group there is account 120 where all planned and periodic maintenance expenses for the upcoming year are registered. Expenses under account 120 are calculated based on the O&M budget planning that is developed by the board of Social Housing organization. Since 2017, by an executive order of the ministry of Transport, Building and Housing in Denmark, it is a mandatory requirement that social housing organization calculate provisions and O&M budgets on a basis of a 30-year maintenance plan (Danmarks Almene Boliger, 2018).

Second, the operation and maintenance guide and budget made by the activity system of design & construction was typically applying the predominant classification systems of building elements used by designers and contractors in their practices e.g., SfB or BIM7AA. However, the activity system of building operation within social housing has been using a different classification system called DFK (In Danish: "Dansk Forvaltnings Klassifikation" - DFK). DFK was developed by LBF in 2009 to provide a more precise and relevant classification system for facility management compared to the SfB classification that was used until that time. According to the order of the Danish Ministry of Housing, Urban and Rural Affairs, it is a mandatory requirement for all public building and social housing since 2012 (Landsbyggefonden, 2013).

Discussion

According to the academic literature (see e.g. Fu *et al.*, 2004; Gluch and Baumann, 2004; Oduyemi *et al.*, 2014), one of the main challenges of the limited adoption of LCC in the AEC industry is the lack of available and reliable data. This study challenges this long-standing hypothesis since the analysis indicates that there is a range of available LCC-related data flowing between the activity systems of building design & construction and building operation that enables LCC consideration in different stages of building projects.

Specifically, the analysis identified three actions aiming at increased collaboration and data exchange regarding LCC between the two activity systems. LCC related data are particularly transferred from building operation to building design & construction through the model maintenance plan as well as from building design and construction to building operation through the O&M guide and budget.

Despite the attempts to improve collaboration towards LCC, the LCC-related data exchanged between the two activity systems in the case-projects under examination are not fully adopted or utilized (Figure 7). On the contrary, the exchanged data tends to create disturbances in the current activities instead of being useful mediating tools that can be used to achieve LCC integration throughout the building's lifecycle. Put differently, the attempts of one activity system to exchange data "bounces off" at the other activity system.

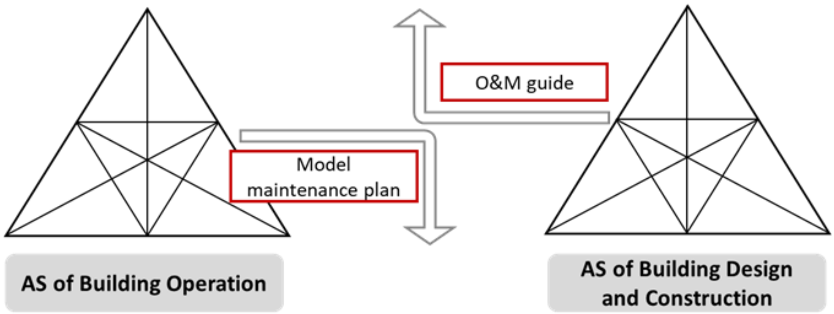

Figure 7. Limited collaboration between the activity systems towards LCC.

Instead, this study points out that the LCC limited adoption in the case-projects under examination is challenged due to different objectives of the two activity systems and the lack of creation of a shared objective towards LCC. Specifically, it is observed that the activity system of building operation aims to initiate new or renovation building projects, operate and maintain existing dwellings (Figure 2), while the activity system of building design and construction aims on designing and constructing a building (Figure 3). It is also observed that throughout the lifetime of the building project, activities are handled and performed independently from either one or the other activity system, while there is limited collaboration between the two activity systems in either design & construction or operation phase of the building project.

Hence, the creation of a shared objective between the two activity systems to improve LCC integration is significant. In order to achieve that, existing misalignments between the elements of the two activity systems should be resolved and transformed towards a new shared objective.

The following sections present existing misalignments between two activity systems that further obstruct the collaboration in regard to LCC and discuss how the elements of the activity systems should be transformed to support the creation of a shared objective towards LCC.

Misalignments between the elements of the activity systems

Misalignments are observed between several of the mediating elements of the activity systems, namely rules, tools and division of labor (Figure 8). The misalignments do not reveal manifest contradictions in the current practices, but they present latent challenges of the activity systems to collaborate. The three misalignments between the elements of the two activity systems are seen as hindrances of collaboration and data utilization, that further inhibit the creation of a *shared objective* towards LCC.

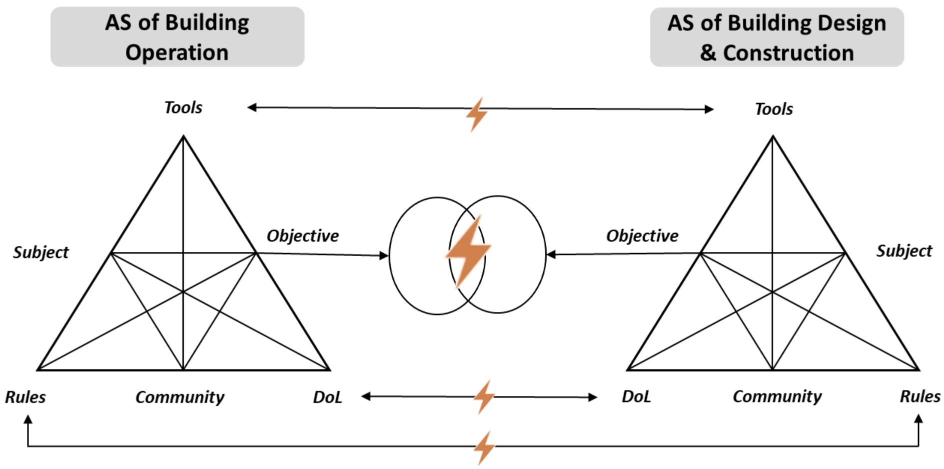

Figure 8. Misalignments between the elements of the two activity systems under examination.

Misalignment between Tools: Misalignments was observed between the tools that are used by the two activity systems. The two activity systems used different classification systems for classifying the building components. Specifically, the activity system of building design & construction used BIM7AA (BIM7AA, 2017) that is basically derived from the international SfB system when developing BIM models and perform calculations, while the activity system of building operation used DFK classification (Landsbyggefonden, 2013) to O&M calculation, registration, and planning. Despite the benefits of using different classification systems in the two activity systems, it also presents a challenge for collaboration and especially for exchanging information in relation to LCC.

Misalignment between the DoL: As discussed above, there were intentions for collaboration between the subjects of the two activity systems. For instance, during the activities of building design there was a dialogue based briefing process between the social housing organization and the design team regarding O&M performance of different building components. However, it was also observed that the collaboration took place only few times through the building lifecycle, and the process lacked continuous briefing and commissioning mechanisms to ensure LCC data utilization and exchange.

Misalignment between Rules: Through the observations in the case projects under examination, it was observed that the activities in each of the activity systems were primarily driven by *rules* towards long term economic consideration. However, there was a lack of *common defined rules* that could act as reviewing mechanisms (e.g., project reviews or regulations) to ensure that the information that was exchanged was utilized.

Transformation of activity systems towards creating a shared objective

The creation of a shared objective towards LCC is significant to enable LCC integration in a project's lifetime. However, the existing misalignments between the elements of the activity systems is hampering the collaboration and creation of a shared objective. The following sections will discuss how tools, rules and division of labour can be transformed in order to improve collaboration and encourage the creation of shared objectives towards LCC.

Transformation of tools

The lack of a commonly used classification system is a common challenge for exchanging data in the AECO industry (Howard and Björk, 2008; Saridaki *et al.*, 2019). However, in order to support collaboration and enable data exchange and utilization, it is important to align the different classification systems that eases the data transfer between the BIM7AA classification used by designers and the DFK classification used by social housing organizations for operation and maintenance.

In addition, data reliability needs to be improved. To increase data reliability both activity systems should improve the way of gathering, storing and analysing LCC related data. For instance, the activity system of building operation could improve the data management processes (gathering and storage) as well as the precision of data analysis with regard to O&M data from operating existing buildings in order to develop more reliable and project-specific model maintenance plans (MMP). On the other hand, the activity system of building design & construction could improve the utilization of information in the model maintenance plan (MMP) e.g. by performing cost driver analysis and optimize LCC calculations. Based on this analysis and the calculation results the activity system of building design may provide to the activity system of building operation, a more accurate O&M plan that is not only better tailored to the specific building design but also adds value to the work that the activity system of operation is required to do e.g. in relation to the reporting to LBF on the annual accounts. Finally, the O&M plan could be continuously updated during the operation of the building project by the activity system of building operation and thus, provide more accurate data for future projects.

Transformation of division of labour (DoL)

For creating a shared objective towards LCC, the two activity systems should collaborate closely during the building project's lifetime. Therefore, it is important that the DoL is not considered only internally in each of the activity systems but also across the two activity systems. In addition, the DoL should not be limited in only a few times through the building lifecycle but rely on a continuous collaboration and DoL between the two activity systems. This can be achieved through the active involvement of facility manager in the design processes, where facility manager can provide insights from building operation and increase awareness among designer as suggested by (Jensen *et al.*, 2018; Jensen, 2012b), as well as through a prolonged responsibility of building designers in the operation. More importantly, the activity system of operation should continuously ensure that the activity system of design & construction is held accountable for all major decisions in relation to the estimates of the model maintenance plan e.g. when the assessment committee evaluates the project competition.

Transformation of rules

In order to ensure that LCC-related data are developed, exchanged and utilized, it is important that the two activity systems should adopt commonly defined rules that standardize the processes of collaboration and data exchange (Goh and Sun, 2016; Kehily and Underwood, 2017; Olubodun *et al.*, 2010) as well as develop reviewing mechanisms to ensure that the information that is exchanged is utilized. Regarding the review processes, for instance, the activity system of building operation can provide project reviews in building design in order to ensure that the data that is provided through the model maintenance plan is integrated in the design. In addition, regulations or reporting may contribute on ensuring that the building is operated based on the O&M guide that is provided by the building design & construction to operation.

Conclusion

Adopting activity theory as the theoretical framework for analyzing human activities, this study aims to map the *characteristics* of the two activity systems of building design & construction and building operation and identifying important *actions* that support data utilization and exchange with regard to LCC throughout the projects' lifetime in two paradigmatic social housing projects.

Through the analysis of the activities of building design & construction and building operation, it is observed that there are three actions where LCC related data are exchanged between the two activity systems. The first action is observed in the tendering processes of new building projects, where LCC requirements are included in the tendering documents and LCC related data are transferred from the activity system of building operation to the activity system of building design & construction through a novel *model maintenance plan* (MMP). The model maintenance plan includes yearly expected expenditures expressed in monetary value for eighteen (18) maintenance activities for the first 30 years of operation, providing valuable information of operating building to the new building design. The second action is *the transfer of LCC related data* during the design processes, where LCC related data are transferred between the two activity systems through several meetings and LCC calculations. Through the meetings, the activity system of building operation provides knowledge and experience from operating existing buildings while the activity system of building design provides results of LCC calculation of different solutions. The third action is *the provision of an O&M guide* delivered at handover of a building project, where an O&M guide is provided from building design & construction to building operation. The O&M guide includes, among else, LCC related data like expected lifetimes of building components and expected O&M activities and intervals, providing useful information to building operation.

Despite the identified actions, the exchanged LCC related data creates disturbances in the activity systems rather than attempts to create a *shared objective* towards LCC. The research pinpointed a number of misalignments between the mediating elements of the two activity systems that obstruct the collaboration and data utilization towards LCC. Specifically, misalignments are identified between tools, division of labour and tools due to different classification systems, limited collaboration through the project execution and lack of commonly defined rules. In conclusion, resolving the misalignments are essential to transform the two activity systems and create a shared objective towards LCC.

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SUMMARY

Life-cycle costing (LCC) is gaining increased attention in the architecture, engineering, construction, and operations industry as a vital methodology for assessing the economic sustainability throughout the lifetime of building projects. LCC has recently became part of procurement policies, certification schemes, and national regulations. Despite the increased attention, the concept faces limited adoption in the design practices due to various challenges of implementation. The Industrial PhD research aims to understand and explain the current practices regarding LCC and provide new insights into the challenges and opportunities of integrating LCC in building design.

This is an article-based PhD thesis written by Maria Saridaki. The PhD research was conducted in an Industrial PhD program that is partially funded by the Danish architectural company Vandkunsten Architects (www.vandkunsten.com) and the Innovation Fund Denmark.

ISSN (online): 2446-1636
ISBN (online): 978-87-7573-817-5

AALBORG UNIVERSITY PRESS