**Department of Mechanical Engineering**

# Advancing design criteria for energy and environmental performance of buildings

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**Nusrat Jung**

Aalto University

DOCTORAL DISSERTATIONS

Aalto University publication series
**DOCTORAL DISSERTATIONS** 142/2018
**VTT SCIENCE 182**

# Advancing design criteria for energy and environmental performance of buildings

**Nusrat Jung**

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at Otakaari 1, lecture hall E on the 10th of August 2018 at 12:15.

**Aalto University**
**School of Engineering**
**Department of Mechanical Engineering**
**Energy technology**

**Supervising professor**
Professor Risto Lahdelma, Aalto University, Finland

**Thesis advisor**
Dr. Miimu Airaksinen, President and CEO, Finnish Association of Civil Engineers, Finland

**Preliminary examiners**
Dr. Francesco Pomponi, Vice Chancellor's Research Fellow, Institute for Sustainable Construction, Edinburgh Napier University, Edinburgh, United Kingdom

Dr. Steven Firth, Building Energy Research Group, School of Architecture, Building and Civil Engineering, Loughborough University, United Kingdom

**Opponent**
Professor Kalle Kähkönen, Tampere University of Technology, Finland

Aalto University publication series
**DOCTORAL DISSERTATIONS** 142/2018

**VTT SCIENCE 182**

ISBN 978-952-60-8108-3 (printed)
ISBN 978-952-60-8109-0 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-60-8109-0

ISBN 978-951-38-8660-8 (printed)
ISBN 978-951-38-8659-2 (pdf)
ISSN 2242-119X (printed)
ISSN 2242-1203 (pdf)
http://urn.fi/URN:ISBN:978-951-38-8659-2

Unigrafia Oy
Helsinki 2018

Finland

Publication orders (printed book):
nusrat.jung@vtt.fi

NORDIC ECOLABEL
441 697
Printed matter

**Author**
Nusrat Jung

**Name of the doctoral dissertation**
Advancing design criteria for energy and environmental performance of buildings

**Publisher** School of Engineering

**Unit** Department of Mechanical Engineering

**Series** Aalto University publication series DOCTORAL DISSERTATIONS 142/2018

**Field of research** Energy technology

**Manuscript submitted** 22 April 2018 **Date of the defence** 10 August 2018

**Permission to publish granted (date)** 18 June 2018 **Language** English

☐ **Monograph** ☒ **Article dissertation** ☐ **Essay dissertation**

**Abstract**

Globally, buildings are responsible for 18% of greenhouse gas (GHG) emissions and 40% of energy consumption. The European Union's climate and energy policy framework for 2020 to 2030 requires reducing GHG emissions by 40%, increasing the level of energy savings by 25%, and increasing the share of renewable energy by at least 30% relative to 1990.

The environmental and energy performance criteria for buildings will continually evolve to meet the aforementioned decarbonisation goals. Consequently, buildings will have an increased number of variables and alternatives that are to be evaluated for their performance, indicating increased complexity for building designers. The prospect of evaluating multiple building performance criteria necessitates integrated designing and planning tools, such as the use of Building Information Models (BIM), Building Performance Simulations (BPS), and methodologies for comparing and optimizing alternative design options.

This dissertation presents new insights on advancing the design criteria for the energy and environmental performance of commercial and residential buildings. Specifically, the four associated journal publications demonstrate how building designers and the Architecture, Engineering, and Construction (AEC) industry can integrate embodied GHG analysis, comprehensive BIM tools in conjunction with BPS analyses, and stochastic assessment of public perceptions to work towards buildings that are more energy-efficient, generate energy on-site, and have a smaller carbon footprint. Through comprehensive literature reviews, this dissertation outlines future research directions for BIM-based, iterative multi-criteria assessment for energy and environmental performance of buildings.

**Keywords** Energy performance, Building performance simulation, Environmental performance, Embodied GHG, BIM, Design, Renewable energy technologies, Social acceptance

**ISBN (printed)** 978-952-60-8108-3 **ISBN (pdf)** 978-952-60-8109-0

**ISSN (printed)** 1799-4934 **ISSN (pdf)** 1799-4942

**Location of publisher** Helsinki **Location of printing** Helsinki **Year** 2018

**Pages** 135 **urn** http://urn.fi/URN:ISBN:978-952-60-8109-0

## Acknowledgements

I am writing this while enjoying a cup of tea in the garden of Shamba Lodge at Kitwe, Zambia. Birds are chirping, the sun is shining, and I am preparing to deliver the second series of lectures as part of the UN 10YFP programme on building energy simulations to the fourth year students in the Department of Built Environment at Copperbelt University.

Thank you, Professor Risto Lahdelma for taking me on this journey, you have been my aggregated model: flexible, efficient, and exceptionally accurate to interact with in the optimization of a doctoral dissertation; your wisdom is genuinely inspirational. Dr. Miimu Airaksinen, you filled the gaps in my power grid during the intermittent supply of renewable energy needed to realize my dissertation. Dr. Tarja Häkkinen, you inculcated the honesty and the scientific excellence during the design phase of my humble beginnings, you encouraged me to define the target value, standard value, quantified value and specific value during the life cycle of this work. To the three of you, thank you for sharing every bit of joy and sorrow, I am forever in debt.

I am grateful to all the funding agencies as acknowledged in individual publications including the Academy of Finland, Aalto University, the Finnish Funding Agency for Innovation (Tekes/Business Finland) and the European Union. Dr. Francesco Pomponi and Dr. Steven Firth, I would like to thank you for being a vital part of my dissertation, your critical review, kind words and commendations further inspire me to continue my scientific journey.

Thank you, Mr. Jari Shemeikka for being a robust role model for me; after all, it is worth every simulation run. Thank you Dr. Satu Paiho for all the encouragement and positive energy you provided me with during the work and for sharing the joy of accomplishments thereafter, you are an inspiration. Thank you, Mr. Jyri Nieminen, for trusting me with the ability to carry out the work when I lacked experience, you are the project lead to wish for. Thank you Dr. Jyrki Kesti for being supportive throughout our publication phases. Thank you, Dr. Matti Kuittinen and Ms. Mirka Rekola for your instrumental contribution from the very conception phase to the final publication. Thank you, Dr. Munjur E. Moula and Dr. Mohamed Hamdy for bringing your knowledge and expertise to our publication and thank you, Dr. Tingting Fang, for conducting the field survey together with me. Thank you, Mr. Teemu Vesanen for lending intellect throughout my simulation cycle, I am very grateful. Thank you, Dr. Ala Hasan, for being my critic and for guiding me with your expertise – it has been a thrill to learn from you. Thank you, Dr. Sami Kazi and Dr. Pekka Tuomaala for inspiring me along the way.

I treasure my friends who stood firm with me throughout my dissertation journey. Ms. Päivi Jäväjä, you radiate positive energy, I am so lucky to have met you. From guiding me towards my M.Sc. and then becoming a friend and gradually my family, your contribution is immeasurable, thank you. Thank you Ms. Hannele Ahvenniemi, I am touched beyond words. Ms. Maaria Laukkanen, thank you for sharing the passion and enthusiasm for changing the world. Thank you, Ms. Akanksha Sharma, for the love and kindness.

Ms. Judith Kirschbaum and Mr. Aapo Huovila, thank you for all those endless teatime discussions that led to the page-by-page making of this dissertation summary. Thank you, Ms. Elina Vaara, Dr. Elizabeth Cole-Kodikara, Dr. Vigneshwari Subramaniam and Mr. Jaakko Jääskeläinen for sharing the joy of scientific writing.

I am very blessed to have a love of family; you are at the core of my strength. I owe gratitude to my father Mr. Anis Jung for giving me the wings to fly, to my mother Ms. Salma Begum – your prayers can move mountains. My two siblings Architect Bushra Jung and Mr. Yawar Jung, you fill my life with love beyond measure. I owe gratitude to my in-laws Mr. Brian Boor and Ms. Lila Boor for the love and support you continue to bestow upon us. To my husband Dr. Brandon Boor, you are the epitome of love, kindness, respect and integrity – thank you for your support and for sharing your passion for excellence in science. My two children Gustave H Jung Boor and Frederick Henrik Jung Boor, thank you for occasionally lending a paw.

Yours sincerely,
Nusrat Jung

Kitwe, Zambia
21 June 2018

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Appendix D: Publication IV (with supporting information): Social Acceptance of Renewable Energy Technologies for Buildings in the Helsinki Metropolitan Area of Finland

## List of Publications

This dissertation consists of four journal publications that are referred to by roman numerals as indicated below.

**I.** Nusrat Jung*, Tarja Häkkinen, Mirkka Rekola. Extending Capabilities of BIM to Support Performance Based Design. *Journal of Information Technology in Construction (ITcon)*, Volume 23, Pages 16-52, 2018b.

**II.** Tarja Häkkinen, Matti Kuittinen, Antti Ruuska, Nusrat Jung*. Reducing Embodied Carbon during the Design Process of Buildings. *Journal of Building Engineering*. Elsevier B.V., Volume 4, Pages 1-13, 2015.

**III.** Nusrat Jung*, Satu Paiho, Jari Shemeikka, Risto Lahdelma, Miimu Airaksinen. Energy Performance Analysis of an Office Building in Three Climate Zones. *Energy and Buildings*. Elsevier B.V., Volume 158, Pages 1023-1035, 2018a.

**IV.** Nusrat Jung*, Munjur E. Moula, Tingting Fang, Mohamed Hamdy, Risto Lahdelma. Social Acceptance of Renewable Energy Technologies for Buildings in the Helsinki Metropolitan Area of Finland. *Renewable Energy*. Elsevier B.V., Volume 99, Pages 813-824, 2016.

**Corresponding author*

## Author's contribution

Nusrat Jung is the primary author of three publications (I, III & IV).

Nusrat Jung is the primary author of Publication I. Investigations carried out in Publication I were part of the European HOLISTEEC project (no. 609138) led by Dr. Tarja Häkkinen at VTT Technical Research Centre of Finland. All three authors participated in research design and compiled the reviews, analyses and discussion presented in the publication. The first author did extensive work especially in searching the literature, planning the methodological approach for the literature review, reviewing the literature, and the analysis of the results.

Dr. Tarja Häkkinen is the principal author of Publication II. The work was done in research project OKRA funded by Tekes and BIMCON funded by the Built Environment Process Re-engineering programme. Dr. Matti Kuittinen and the author participated in the expert interviews. Dr. Antti Ruuska contributed to the case study of a real building and its corresponding GHG emissions. Dr. Matti Kuittinen created the design process framework in line with RIBA design stages with a focus on low carbon design. The author had an important role in the research design, methodology formulation, literature review, and a significant role in the revision cycles of this publication.

Nusrat Jung is the primary author of Publication III. Investigations carried out in this publication were part of the ZEMUSIC (no. RFSR-CT-2011-00032) project led by Dr. Jyrki Kesti from Ruukki Construction. Jyri Nieminen led the project at VTT Technical Research Centre, and the project lead was carried over by Jari Shemeikka who supervised the work carried out during the multiple simulation cycles. Dr. Satu Paiho contributed by adding to the literature review and commenting on the limitations of the publication. All of the simulations were run, conducted, and analysed by the author.

Nusrat Jung is the primary author of Publication IV. Dr. Munjur E. Moula and Dr. Mohamed Hamdy guided the creation of the questionnaire study and participated in the literature section. Dr. Tingting Fang helped with the preliminary field test of the survey and online distribution of the questionnaire. The author executed the study and analysed the results.

## List of Abbreviations

| | |
|---|---|
| AEC | Architectural, engineering and construction |
| AIA | American Institute of Architects |
| AHU | Air handling unit |
| ARK | Arkkitehtisuunnittelun tehtäväluettelo (Architectural design task list) |
| BAU | Building as usual (base case) |
| BIM | Building information modelling |
| BPS | Building performance simulation |
| CEN | European Committee for Standardization |
| CHPR | Combined heat and power generation based on renewable biomass, such as wood chips |
| CHPW | Combined heat and power generation based on community waste |
| $CO_2$ | Carbon dioxide |
| EE | Energy efficient |
| EPBD | Energy Performance of Buildings Directive |
| EU | European Union |
| GHG | Greenhouse gases |
| GSHP | Ground source heat pump |
| HVAC | Heating ventilation and air conditioning |
| IDM | Information delivery manual |
| IEA | International Energy Agency |
| IFC | Industry foundation class |
| ISO | International Organization for Standardization |
| LOD | Level of development |
| MVD | Model view definition |
| nZEB | Nearly zero energy building |
| NZEB | Net zero energy building |
| PoW | Plan of work |
| RCP | Radiant ceiling panel |
| RETs | Renewable energy technologies |
| RFP | Radiant floor panel |
| RIBA | Royal Institute of British Architects |
| SOLAR | Photovoltaic solar electricity |
| SHEAT | Solar heat for space heating and domestic hot water |
| SHEATP | Solar thermal system for combined space heating, domestic hot water and electric power |
| SMAA | Stochastic multicriteria acceptability analysis |
| VAV | Variable air volume |
| WINDS | Small-scale wind turbine |
| WINDR | Roof-mounted small-scale wind turbine |

## Definitions

Design work-stages are described on the basis of the architect's Plan of Work (PoW) from conception to completion of a building project.

Building Information Model (BIM) is a three dimensional model that utilizes Industry Foundation Classes (IFC) as a data exchange format.

Building Performance Simulation (BPS) can be defined as set of tools used to ascertain building performance criteria.

Life cycle of a building is based on the international and European standards (ISO 21931-1, 2010; CEN EN 15978, 2011; CEN EN 15804, 2012); a building's life cycle can be described in four stages as:

(1) Product stage (A1-3): raw material supply, transport, manufacturing,
(2) Construction process stage (A4-5): transport, construction, installation,
(3) Use stage (B1-7): use, maintenance, repair, replacement, refurbishment, operational energy use, operational water use and,
(4) End of life stage (C1-4): deconstruction, demolition transport, waste processing, disposal.

Embodied carbon is in this dissertation defined according to International Energy Agency Annex 57 based on Birgisdottir et al. (2017).

Low carbon design is defined as an approach to design, construction, and maintenance of a building with low GHG emissions or low carbon footprint.

Embodied GHG emissions are the cumulative quantity of material-related GHG produced during the creation of a building, its maintenance, and end of life.

Embodied energy is the cumulative quantity of non-renewable primary energy required for processes related to the creation of a building, its maintenance, and end of life.

Operational energy is the amount of energy required for a building's lighting; heating, ventilation, and air conditioning (HVAC); and appliances. It can be further divided into delivered energy and energy generated from renewables.

Delivered energy is the total energy purchased for a building in relation to its floor area.

nearly Zero Energy Building (nZEB) is a high-performance building as determined by Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby (European Parliament, 2010).

# 1. Introduction

## 1.1. Background

The United Nations Intergovernmental Panel on Climate Change (IPCC), Fifth Assessment Report, has confirmed the urgent need for immediate and sustained action on climate change (IPCC, 2014). Globally, buildings are responsible for 18% of greenhouse gas (GHG) emissions and 40% of energy consumption. The key climate change mitigation strategies suggested by IPCC Workgroup 3 for the building sector include: (1) reducing emissions and final energy by integrating renewable energy technologies (RETs) with buildings; (2) reducing the final energy consumption of a building through use of high-performance heating/cooling systems, lighting, and appliances; (3) lowering the embodied energy/operating energy during a building's lifetime; and (4) use of integrated design processes, low/zero energy buildings, and building automation and control. A holistic approach that considers the entire lifecycle of the building and integrated building design is recommended to achieve the broadest impact possible (IPCC, 2014).

In the European Union (EU), the building and construction sector accounts for 36% of $CO_2$ emissions, 40% of total energy consumption, and 55% of electricity consumption European Commission, 2016a). The Energy Performance of Buildings Directive (EPBD) (European Parliament, 2010) is a legislative instrument aiming to proliferate the EU's longer-term objective demarcated in the climate and energy policy framework from 2020 to 2030. The objectives are set at reducing GHG emissions by 40%, increasing the level of energy savings by 25%, and increasing the share of renewable energy by at least 30% (European Parliament, 2013; European Commission, 2016a). These goals are focused towards the EU 2050 low-carbon economy roadmap aiming to drastically reduce emissions by 80% to 95% relative to 1990. To be cognizant of these long-term goals, it is of vital importance to transform the way buildings are designed, built, operated, and renovated.

In both the scientific and empirical literature, the importance of the early design stages for informed decision making is recognized as decisions made during the design phase of a building have a significant impact on the building's lifecycle and performance. Due to the decarbonization goals mentioned above, there will be an unremitting increase in environmental and energy performance criteria of buildings. Consequently, future buildings will increase in complexity due to the growing number of performance variables to be evaluated. Addressing the environmental performance of a building, for example, includes accounting for embodied GHG emissions based on the lifecycle data of its building products and materials. Similarly, a standard indicator of a building's energy performance is its annual energy consumption as a function of climate, envelope properties, heating, ventilation and air-conditioning (HVAC) systems, and occupant behaviour, among other parameters (IEA ECBCS Annex 53, 2013).

The challenges faced by designers to integrate environmental and energy performance assessment into the design process is an emerging area of research. Many fluid variables are chosen by designers as a rule of thumb during the conception phase of projects. These variables continue to evolve and become fixed during iteration cycles until design completion as explained by Marsh *et al.* (2018). The prospect of evaluating multiple building performance criteria emphasizes the need for designing and planning tools, such as the Building Information Model (BIM), Building Performance Simulations (BPS), and methodologies for comparing and optimizing alternative design options.

Typically, BPS and associated analyses are not started during the early design phases (Bazjanac, 2008, Zapata-Lancaster and Tweed, 2016). This may hinder the design team's ability to elucidate how different design options and material selections affect the environmental and energy performance of the building. If BPS tools are employed during the early design phases, there is an opportunity to administer a multi-iterative design cycle towards finding optimum solutions for building operating systems, materials, and geometry before the construction phase. However, for BPS tools to be able to be employed in the early design phases it is fundamental that they are interoperable with design tools (such as BIM-based models). To ease the integration of BPS during the design process, BIM models created by architects and designers can be used as a foundation to transfer building-specific data to the BPS tools. However, there are multiple BPS tools with a variety of capabilities, and they may or may not be interoperable with BIM models. Publication I "*investigates the potential of BIM-based models at the core of providing input data required for performance-based simulations to enable iterative multi-criteria assessment towards high-performance buildings*" Jung *et al.* (2018b).

In addition to increasing the energy performance of buildings through the reduction of energy use during the building's operation phase, there is also a need to reduce the relative contribution of embodied energy and embodied GHGs (Andresen, 2017; Ruuska, 2018). Embodied GHGs (also called embodied carbon) account for $CO_2$ emissions from the energy consumed during the production of the material. Embodied energy is the cumulative quantity of non-renewable primary energy required for processes related to the creation of a building, its maintenance, and end of life. Embodied GHGs and embodied energy of a building are interrelated – therefore, focusing solely on operational impacts (energy performance) is an incomplete strategy (Dahmen et al., 2018). Wiik *et al.* (2018) suggest that the reduction of embodied GHGs for zero energy buildings (ZEBs) should focus on material selection and use in the early design and construction phases. However, approaches, methodologies, and ways to integrate such assessment during the early design phases are scarce. Therefore, Publication II proposes a clear stepwise methodology for architects and planners to account for embodied GHGs during the specific work stages of the design process.

Another major challenge in BPS is the accuracy of the predicted building performance when compared to measured data after the building is built (Piette et al., 2001; Scofield, 2002). The simplified modelling approach leads to miscalculations and inaccurate predictions of a building's actual performance (Coakley et al., 2014). Office buildings are the second largest category of non-residential building stock, yet there is still a general lack of data available compared to residential buildings (Economidou et al., 2011). To provide new data on the energy demand profiles of an office building, Publication III (Jung et al., 2018a) presents an exhaustive full-scale model to obtain robust and diversified energy efficient solutions for large buildings.

These solutions are investigated to reduce the amount of delivered energy or net energy supplied to a building in the three different climate zones of Northern Europe, Central Europe, and South-Eastern Europe.

The European Commission recognized the central role of consumers in propagating the growth of the energy market and proposed a package of measures with the three main goals of: "*energy efficiency first, global leadership in renewable energy and provision of a fair deal for the consumers*" (European Commission, 2016b). It is irrefutably critical to not only inform consumers but to involve and actively empower them as they determine the future of energy consumption and supply for buildings. There is a scarcity of scientific research on the public perception of integrating RETs in buildings in the Nordic region. To direct the private sector and governmental organizations towards steering the policy framework needed to achieve the EU's 2050 decarbonization goals, Publication IV investigates the public perceptions of RETs for buildings (Jung et al., 2016). This will inform the definition of design criteria for selecting RETs for residential buildings, as well as small- and large-scale apartment/office buildings. Stochastic Multicriteria Acceptability Analysis (SMAA) was applied to ascertain various RET options that may be acceptable to the public.

Collectively, the research presented in this dissertation aid to advance design criteria for the energy and environmental performance of commercial and residential buildings. Specifically, the four associated journal publications demonstrate how building designers and the Architecture, Engineering and Construction (AEC) industry can integrate embodied GHG analysis, comprehensive BIM tools in conjunction with BPS analyses, and stochastic assessment of public perceptions to work towards buildings that are more energy efficient, generate energy on site, and have a smaller carbon footprint.

## 1.2. Research questions

In order to meet the requirements for high-performance building design, this dissertation examines the ways by which we can reduce the energy and environmental impact of buildings during the design phase. It also explores the public perception of various RETs available on the market. The research questions are:

(1) What is the potential of BIM-based tools to be used in conjunction with BPS tools for high-performance building design?
(2) How to calculate embodied carbon during the design process?
(3) What are the optimal solutions for large buildings that can be applied to achieve nZEB?
(4) What are the public perceptions of renewable energy technologies for buildings?

## 1.3. Structure of the dissertation

This dissertation is a compendium of four peer-reviewed journal publications as illustrated in Figure 1 and described in Table 1. Publication I discussed the data exchange issues between the BIM-based tools and BPS-based tools/methods applied during the design phases. Publication II provides a framework that can be applied during the design phase to enable low-carbon building design. Publication III goes a step further in providing diversified energy efficient solutions with the goal of reducing the energy consumption of buildings. The requirement for all new buildings to be nearly zero energy buildings (nZEBs) in turn requires that the majority of energy demand is met by RETs. Publication IV focuses on the public perception of multiple RETs that are applied to buildings for energy generation.

Figure 1. Compendium of four journal publications

Table 1 Summary of publications and their role in this dissertation

| Publication | Research question | Research method | Region of relevance | Outcome |
|---|---|---|---|---|
| **Publication I**<br>Extending Capabilities of BIM to Support Performance Based Design<br>(Jung et al., 2018b) | What is the potential of BIM based tools to be used in conjunction with BPS tools towards high performance buildings? | (a) Extensive literature review<br>(b) Expert interviews | Worldwide | Future directions for using BIM-based tools in conjunction with BPS-tools |
| **Publication II**<br>Reducing Embodied Carbon during the Design Process of Buildings<br>(Häkkinen et al., 2015) | How to calculate embodied carbon during design phases? | (a) Literature review<br>(b) Building case study<br>(c) Expert Interviews | Worldwide | Methodology to calculate embodied carbon during design phases |
| **Publication III**<br>Energy Performance Analysis of an Office Building in Three Climate Zones<br>(Jung et al., 2018a) | What are the optimal solutions for large buildings that can be applied to achieve nZEB? | (a) Dynamic simulation of an office building<br>(b) Number of studied zones:160<br>(c) Software: IDA ICE | Northern Europe, Central Europe and South-eastern Europe | Recommends optimal solutions to achieve nZEB in three climate zones of Europe |
| **Publication IV**<br>Social Acceptance of Renewable Energy Technologies for Buildings in the Helsinki Metropolitan Area of Finland (Jung et al., 2016) | What are the public perceptions of renewable energy technologies? | (a) Web-based questionnaire<br>(b) Stochastic multi-criteria analysis | Finland | Public perceptions of residents of Helsinki region on renewable energy technologies |

## 1.4. Novelty of the dissertation

This dissertation provides new perspectives on the use of building information modelling (BIM)-based tools in tandem with building performance simulation-based tools towards holistic building performance assessment. The main novelty of the study conducted in publication I is to develop an understanding of the potential for BIM-based tools for multi-criteria performance-based assessment, based on a thorough literature review (*n*=249 documents). This enables the application of performance-based design principles, considering factors such as indoor air quality, thermal comfort, acoustics, lighting, and energy and environmental performance.

Sustainable building design process to account for the environmental performance of buildings with a focus on design for low embodied carbon (GHG emissions) was investigated in Publication II. The novelty is the proposed framework of a gradual assessment process developed corresponding to the Finnish architects' PoW (Arkkitehtisuunnittelun tehtäväluettelo, 2013) and the British architects' PoW (Royal Institute of British Architects, 2013) for the particular design stages.

Energy performance of a large-scale office building in three different climate zones of Europe was examined in Publication III. A comprehensive full-scale dynamic simulations of an office building with 160 zones fulfilled a critical gap by (1) providing a thorough evaluation of an office building and (2) guiding the application of diversified nearly Zero Energy Building solutions that can perform in three different climate zones of Europe.

The social acceptance of building integrated renewable energy technologies (RETs) was evaluated in Publication IV for the Helsinki Metropolitan area of Finland. Stochastic Multicriteria Acceptability Analysis (SMAA) using a numerical Monte Carlo simulation was applied to compute the uncertainty in the results obtained from a questionnaire study (*n*=246 respondents). Since it was impossible to form a consensus due to the large data set, a novel two-phase sampling technique was created and applied to the ordinal criteria to develop the ranking of technologies. In addition to the above, this dissertation also provides novel insights into the the most acceptable RET solutions for homeowners.

# 2. Rationale and Methods

## 2.1. The design process

The design process is the most critical stage in determining the fate of a building. The design process can be described as a progression spanning the duration of a building project, where the design variables are gradually realized to eliminate uncertainty progressively (Marsh, 2016). The decisions made during the design process have indirect or direct impacts at many levels throughout a building's life cycle. Building regulations and country-specific building commissioning codes provide the basis for any building design. However, they only prescribe the 'minimum criteria' of what must be fulfilled to obtain a building permit. So what constitutes a good building? The International Organization for Standardization (ISO) presents building performance criteria based on a set of 14 aspects, such as emissions to air, consumption of non-renewable resources, energy performance, environmental performance, indoor air quality, lighting, and acoustics (ISO 21929-1, 2011). The early design phase is the best time to ascertain and consider these multiple performance criteria. The impact of decision making at an early stage during the design process has been very widely acknowledged (Brahme et al., 2001; Bragança et al., 2014; Lin & Gerber, 2014; Mavromatidis et al., 2014; Oliveira et al., 2017).

In general, design stages can be described as a rational stepwise process where multiple decisions are made by all stakeholders to realize the fate of a building, from the architect's plan on paper to actual walls and windows on the ground. Based on the architect's PoW (American Institute Of Architects, 2012; Arkkitehtisuunnittelun tehtäväluettelo, 2013; Royal Institute of British Architects, 2013) the ten design stages are presented in Table 2. They include: project briefing, pre-design, concept design, developed design, technical design, construction documents, building permission, construction/commissioning, and handover and close out. The specific design work stages and their impact on decision making are discussed in Publication I and Publication II.

Table 2. Work stages based on ARK12, RIBA and AIA architects' PoW (Publication I and II). Original figure: Appendix A, Publication I, Figure 1, p. 18.

| Plan of Work | Corresponding work stages of the design process (0-9) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Finnish Architects Plan of Work (ARK12, 2013) | 0<br>Briefing | 1<br>Preparation | 2<br>Concept design<br>3<br>Generic design | 4<br>Building permission tasks | 5<br>Technical design<br>6<br>Preparation for construction | 7<br>Construction | 8<br>In use | 9<br>Warranty period during use |
| Royal Institute of British Architects Plan of Work (RIBA, 2013) | 0<br>Strategic definition | 1<br>Preparation | 2<br>Concept design | 3<br>Developed design | 4<br>Technical design | 5<br>Construction | 6<br>Handover and close out | 7<br>In use |
| The American Institute of Architects Plan of Work (AIA, 2012) | 0<br>Project brief | 1<br>Concept design | 2<br>Schematic design | 3<br>Design development | 4<br>Construction documents<br>5<br>Bidding | 6<br>Construction | 7<br>Commissioning | 8<br>Occupancy |

The three most crucial work stages where the key design decisions are made include *concept design, developed design, and technical design* as stated by Häkkinen *et al.* (2015). These stages, being the most crucial, also provide a unique window of opportunity for various stakeholders for evaluating building performance criteria. During these work stages, the use of simulation-based tools to evaluate building performance is essential. It is during the technical design stage (work stage 4) that the critical exchange of data between the BIM model and a designated building performance aspect occurs. Publication I "*investigates the potential of BIM-based models at the core of providing input data required for performance-based simulations (BPS) to enable iterative multi-criteria assessment towards high-performance buildings*" (Jung et al., 2018b).

## 2.2. Performance-based design

*Performance-based design* is a process where the targeted solution is based on its required performance (CIB Report publication 64, 1982). As mentioned previously, the ISO presents building performance criteria based on a set of 14 aspects, such as emissions to air, consumption of non-renewable resources, energy performance, environmental performance, indoor air quality, lighting, and acoustics (ISO 21929-1, 2011). Accordingly, an optimally functioning building that fulfils the need of the end-user (Gursel et al., 2009) and is designed in an environmentally consciously manner necessitates the use of multiple criteria assessment (Jung et al., 2018b).

A *high-performance building* is a building that integrates and optimizes major building attributes, including energy efficiency, durability, life-cycle performance, and occupant productivity (National Institute of Building Sciences, 2008). During the process of achieving a high-performance building it becomes imperative to set quantifiable targets, to identify and apply diverse methods and tools to be able to quantify the set targets, and to activate unified collaboration between all stakeholders during the various design work stages (Publication II). To ensure unified collaboration during a project, adoption of BIM is becoming a popular practice in the architectural, engineering and construction (AEC) industry. Multiple national and global BIM standards, BIM handbooks, BIM implementation guides, BIM measurement tools, BIM execution plans, and BIM maturity guidelines have been introduced worldwide (Smith, 2014; Sacks et al., 2016).

Past and current AEC industry trends have focused on the potential of BIM to streamline construction and delivery processes. With the wide implementation and adoption of BIM-based tools it is natural to utilize BIM-based models as a knowledge database and a source of input parameters for building performance simulations. Nevertheless, the more we advance in terms of building technology, the more complicated our buildings become, leading to the creation of very complex BIM-based models presenting a variety of parameters. Even though simulation tools have the potential to steer the design, designers, and architectural firms are struggling to incorporate simulation tools in the design process (Zapata-Lancaster & Tweed, 2016). BPS tools vary greatly in terms of their variety, complexity, non-linearity, discreteness, accuracy, capacity, the quality of required input data, data usability in different situations, phases of design, and validity. Additionally, interoperability between various BPS tools is an everyday problem when dealing with multiple building performance criteria.

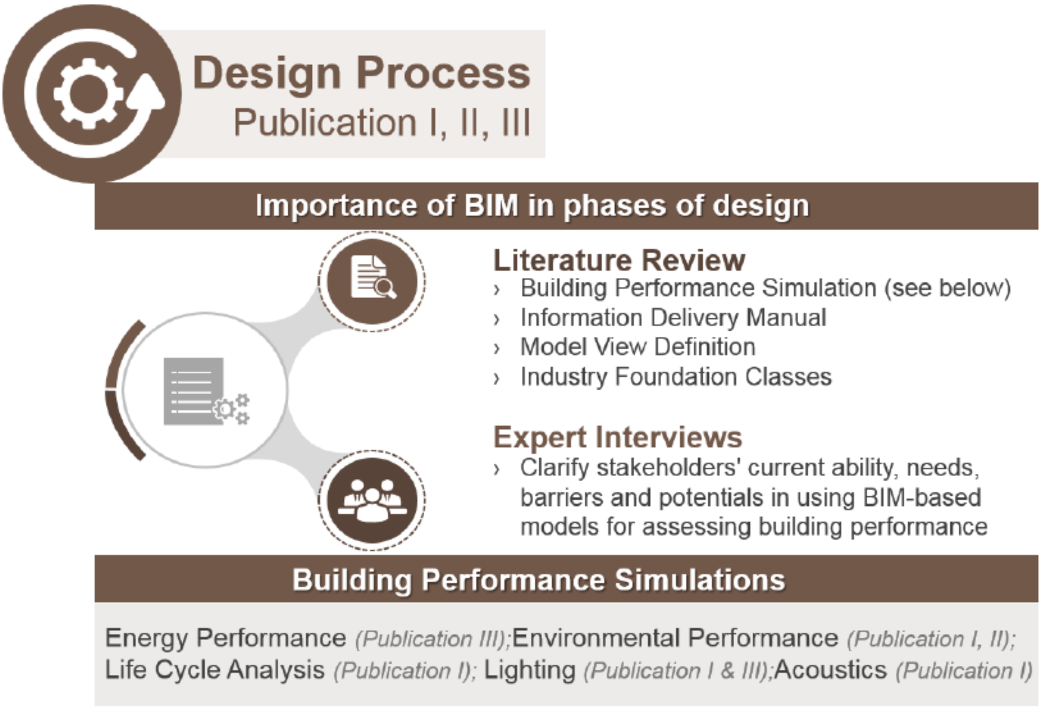

Figure 2. Scope of research questions for publication II on extending the capabilities of BIM to support performance-based design.

Publication I evaluates the capability of BIM-based models to be used in conjunction with BPS-based tools to enable iterative multi-criteria assessment towards high-performance building design. Figure 2 presents the scope of the study conducted in Publication II and shows the interrelation with other publications discussed in this dissertation. Utilising building performance simulations during the design phases are further investigated and applied in Publication III. The specific research objectives of Publication II were:

(1) To study the current capability and highlight the issues of data exchange between BIM-based and BPS-based tools/methods (based on a comprehensive literature review of 249 documents).
(2) To explain and clarify stakeholders' current ability, needs, barriers and potential in using BIM-based models for assessing building performance (based on expert interviews).
(3) To identify what additional methods or procedures are needed in research (based on literature review) and industry (based on expert interviews) in order to ascertain building performance criteria. The results of this investigation are presented in Section 3.1 and Publication II.

## 2.3. Assessment of embodied carbon during the design phase

As the building is designed, commissioned, and constructed on a given site, a significant share of the total carbon footprint of the building is established and cannot be reverted. The typical definition of a building's life cycle currently does not include the design phase, which has a significant impact on a building's embodied GHG emissions, embodied energy, and operational energy. Based on international and European standards (ISO 21931-1, 2010; CEN EN 15978, 2011; CEN EN 15804, 2012), a building's life cycle can be described in four stages as: (1) Product stage (A1-3): raw material supply, transport, manufacturing; (2) Construction process stage (A4-5): transport, construction, installation; (3) Use stage (B1-7): use, maintenance, repair, replacement, refurbishment, operational energy use, operational water use; and (4) End of life stage (C1-4): deconstruction, demolition transport, waste processing, disposal.

In this dissertation, the definition of embodied carbon is based on IEA Annex 57 (Birgisdottir et al., 2017) and Publications I, and II. Low carbon design (Publication II) can be defined as an approach to the design, construction and maintenance of a building with low GHG emissions or low carbon footprint. Embodied GHG emissions are the cumulative quantity of material-related GHGs produced during the creation of a building, its maintenance, and end of life. Embodied energy is the cumulative quantity of non-renewable primary energy required for processes related to the creation of a building, its maintenance and end of life (IEA Annex 57, Part 1, 2016)

The reduction of operational energy continues to receive significant attention due to EU 2020 targets (European Parliament, 2010). Accounting for embodied GHG emissions and embodied energy is therefore becoming increasingly important because the proportion of embodied impacts increases as the operational energy of a building decreases (Iddon & Firth, 2013; Dahmen et al., 2018). The embodied energy of a conventional building can easily account for 2-38% of the total life cycle energy, as reported by Sartori and Hestnes (2007). The same study reports that for a building that consumes a lower amount of operational energy (e.g. an energy efficient building) embodied energy may account for up to 46% of total energy consumed during its life cycle. In a nZEB, materials used in the building envelope can contribute, on average, 65% of total embodied GHG emissions, whereas the production and replacement of materials can account for 55–87% of total embodied GHG emissions during the life cycle, and operational energy can account for 14–42% of total embodied GHG emissions (Wiik et al., 2018). Another study from Ireland on residential nZEBs suggests that embodied GHGs can account for up to 44% of total embodied GHG emissions and embodied energy up to 100% of total energy consumed during the building's life cycle as stated by Moran *et al.* (2017). The above indicates that reduced operational energy consumption alone as a building performance criterion does not cover all environmental criteria during the building's life cycle embodied GHGs and embodied energy must also be accounted for.

In an ideal scenario, the embodied GHGs and embodied energy of a building should be taken into account during the early design phase of the building. There are many reasons why it is not standard practice to calculate the carbon footprint. First and foremost is the lack of a legal requirement to calculate it; for example, building energy certifications do not require carbon footprint calculation as described by Kuittinen (2015). Secondly, the Life cycle assessment methods are available cradle to gate, but approaches for calculating embodied GHGs and embodied energy during the design work stages are not clearly established, as investigated in Publication I and Publication II. This is further confirmed by an industry-academia collaboration project in which three consultants were asked to account for the whole-life embodied carbon of five projects. The results reveal that the consultants had a profound influence on the numerical outcome, which varied greatly despite being provided with the same building project data, such as bill of quantities and technical drawings (Pomponi et al., 2018). This revealed the architects', designers', and consultants' lack of knowledge on the potential impact they can have towards reducing the environmental burden of a building during the inception phases of design. While the importance of decision making in the early stages of design has been widely studied and acknowledged, there is scant research on how to account for embodied carbon while a building is in its design stages. Publication II fulfils this knowledge gap in the literature and provides a stepwise framework as a recommendation to account for embodied GHG during various stages of the design process for various stakeholders.

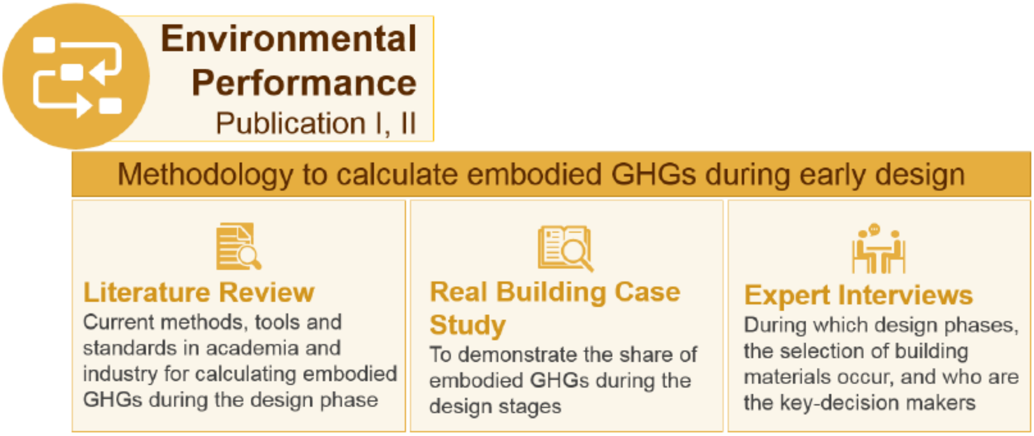

Figure 3. Scope for evaluating the environmental performance of buildings

Part of Publication I focused on the required input data for environmental performance and whether the design tools are compatible with life cycle assessment tools. The inquiries made in Publication II were specifically designed to identify: (1) the potential and drawbacks of the current methods, standards, and tools in aiding the design of low-carbon buildings; and (2) the significance of different design phases with respect to accounting for embodied carbon. To meet these research objectives, a three-directional methodology was pursued as shown in Figure 3. The first step was to identify the current state of the art by means of a comprehensive literature review focused on the current methods, tools and standards in academia and industry which aid in accounting for embodied carbon during the design phase of buildings. The second step included utilizing a real case building and calculating the share of embodied carbon (respective GHG emissions) corresponding to each design stage. The design stages were based on an architects' PoW as shown in Table 2 and as described by Häkkinen *et al.* (2015) . The embodied carbon assessment of the case-building was done utilizing the bill of quantities containing material specification obtained from an architect's BIM-based model in a previous study conducted by Ruuska & Häkkinen (2015). The LIPASTO and ILMARI carbon accounting tools were used to estimate the carbon footprint, which is expressed as $CO_2$ equivalents over the product's life cycle (VTT Technical Research Centre of Finland, 2017).

The third step included conducting semi-structured interviews of seven principal architects from twelve leading design firms in Finland (see Appendix B, Publication II, Table 1, p. 3). Each interviewee was asked to choose their most recently completed design projects as the basis for answering a pre-designed questionnaire, leading to a follow up discussion based on their questionnaire choices. The architects' own experiences of specific projects thus served as the primary source of data on what choices regarding building materials, structures, etc. are made and during which design phase. The second most pressing question was to identify which stakeholders has the most significant role in decision making among the owner, architect, element planner, etc. This three-directional methodology encompassing a literature review, real case building analysis, and expert interviews led to developing a deeper understanding of when (which design stage) and how to (which tools) account for embodied carbon in buildings. The findings and results of this investigation are presented in Section 3.2 and are discussed in Publication II.

## 2.4. Energy performance evaluation of buildings

In the EU, the building sector accounts for 40% of total energy consumption, and this percentage is set to increase. Interest in energy saving potential and reduced emissions has proliferated under the EU's Energy Performance of Buildings Directive (EPBD), which requires all new buildings occupied and owned by public authorities to be nZEB by 2019 and all new buildings to be nearly zero energy from 2021 onwards (European Parliament, 2010). The EPBD defines a nZEB as a building with very high energy performance, where a significant amount of the energy required by the building is covered by renewables. It is also noted that the building should be designed from the outset to consume the least amount of energy possible and should be cost-optimal before installing renewable energy systems.

The annual amount of energy consumed by office buildings in the EU is 40% greater than the equivalent value for residential buildings. Over the last 20 years, the amount of electricity consumed by non-residential buildings has increased by 74%. In addition, office buildings account for 26% of total energy use, making them the most energy-intensive non-residential buildings as noted by Economidou et al. (2011). Of the commercial buildings, office buildings are the least investigated, and there is a lack of data for energy performance comparison when compared to the residential buildings. To ensure that all member states can deliver equivalent outcomes with regard to the EPBD recast, we need to create robust and diversified solutions that can be applied in multiple climate zones.

In addition to the above, there is an ever-increasing need to understand the relative energy performance of buildings to account for the energy consumption patterns during the design phase. If energy-conscious choices based on detailed simulations are made in the early design, it is possible to set measurable targets and accordingly improve building performance significantly. Building performance simulation (BPS)-based tools are utilized to evaluate and set building performance criteria, as discussed in Publication I. The majority of conventional simulation studies of multi-storey buildings use simplified models to reduce complexity, leading to the calibration of a 'select-few zones' in a building to predict whole building performance. This step is justified in the early design phases when the required building data is incomplete; however, in the technical design work stage, most of this data is available. Simplified models lead to design discrepancies as significant as 100% between predicted performance and actual building performance (Coakley et al., 2014). The average error increases with decreasing modelling detail (Simson et al., 2017) and the results obtained from a simplified model fail to see the interactions of energy flow, leading to increased uncertainty in building simulations.

Deeper problems of data discrepancies and interoperability issues between an architects' BIM-authoring model and BPS simulation are described in Publication I (see subsection 3.2.1 energy performance assessment in Jung *et al.*, 2018b, p. 28, Appendix I). The average accuracy of the simulations increases if the data generated during the developed design and technical design phases [specific work stages 4-5 for ARK 12, work stages 3-4 for RIBA and AIA] is integrated into the simplified model leading to gradual development of the simulation model. Simplified methods are not able to accurately distinguish the differences in power needs, leaving a gap in understanding of the delivered energy requirement of a building. Progressively more intermittent renewable energies are being supplied to the energy networks, creating the need for more accurate predictive simulation for reliable demand side management (Jung et al., 2018b). The detailed BPS modelling and system-level parameters suggested in Publication III can be applied to achieve a more accurate assessment of the energy performance analysis towards nZEBs.

Based on the above rationale, the investigations made in Publication III were focused on obtaining robust and diversified energy efficient solutions for large office buildings that can: (1) be applied to reduce the amount of delivered energy or net energy supplied to an office building and (2) be conveniently designed to perform in the three different climate zones of Northern Europe, Central Europe and South-Eastern Europe. Figure 4 summarizes the scope of Publication III, while Figure 5 presents the methodology used to meet its objectives. Annual dynamic simulations (8760 hours) using IDA ICE simulation software (see section 3 Building model description on p. 1026, Appendix C) were conducted to ensure greater confidence in the model accuracy, as suggested by Royapoor and Roskilly (2015), for a large scale six-storey office buildings with a total floor area of 9775 m$^2$. For calibration of the simulation model, a total of 160 zones (see supporting information in Appendix C) were created and mapped using the IDA ICE simulation software to import functionalities of IFC based on the architects' BIM-based model. The author used the mixed model method (manual and automated) to calibrate a precise simulation model in order to mirror the actual building design using the architects' BIM-based model to avoid any discrepancies due to using a simplified modelling approach. The real building is located in Jyväskylä, Finland, and is combined with a novel chamber flooring system housing mechanical, electrical and plumbing features (as shown in abstract figure of publication III available in the online version) which can adapt to the implementation of alternative heating and cooling technologies.

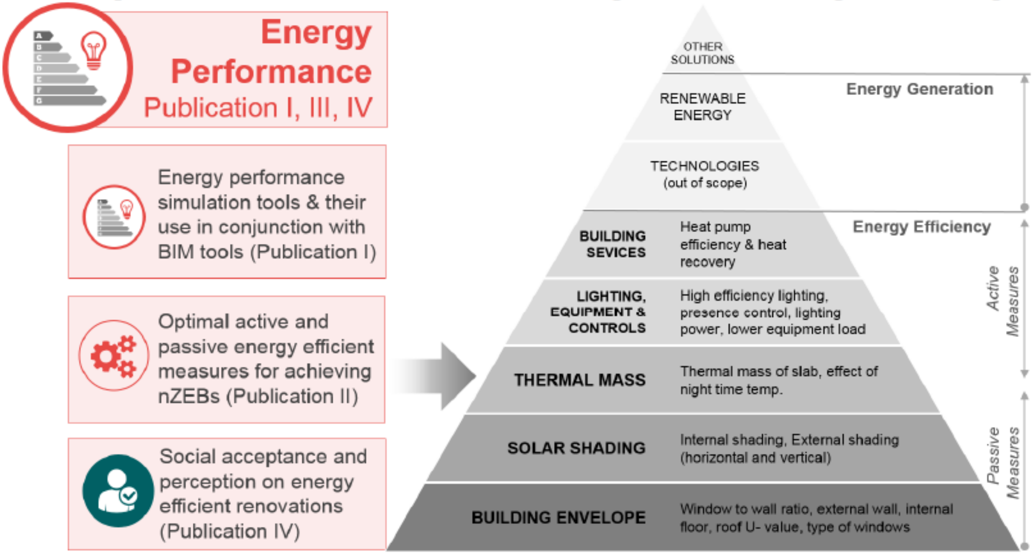

Figure 4. Scope of research questions for publication III on the energy performance analysis of an office building in three climate zones. Hierarchy triangle adapted from Botti (2015).

A building as usual case (reference case), energy efficient case, and nZEB case were each created in the three cities of Helsinki (Finland) London (UK) and Bucharest (Romania). These three cities were selected to represent the climate zones of Northern Europe, Central Europe, and South-Eastern Europe. Multiple parameters were considered to reduce the delivered energy demand of the building as presented in publication III (p.1026, Appendix C). Two phases of simulation as presented in the simulation plan were carried out for fifteen cases. As shown in Figure 5, the first phase of simulations focused on creating the building as usual (BAU), energy efficient (EE), and nearly zero energy (nZEB) cases for all three climate zones. Before the first phase of simulation, a detailed parametric analysis was conducted which is not discussed in this dissertation (see Jung et al., 2013). As presented in Figure 5, the first phase of the simulation focused on energy performance analysis and the second phase on alternative heating and cooling technologies of a radiant floor panel (RFP) system and radiant ceiling panel (RCP) system for all three climate zones.

The results of the above simulations are presented in Publication III and Section 3.3, Appendix C. The results suggest a set of optimal solutions that can be applied to reduce the delivered energy demand of large office buildings. The above investigation presents choices for alternative heating and cooling systems, suggesting the specific system-level parameters, considerations, and definition that are required or needed to achieve a nZEB office building that are applicable in multiple climate zones of Europe.

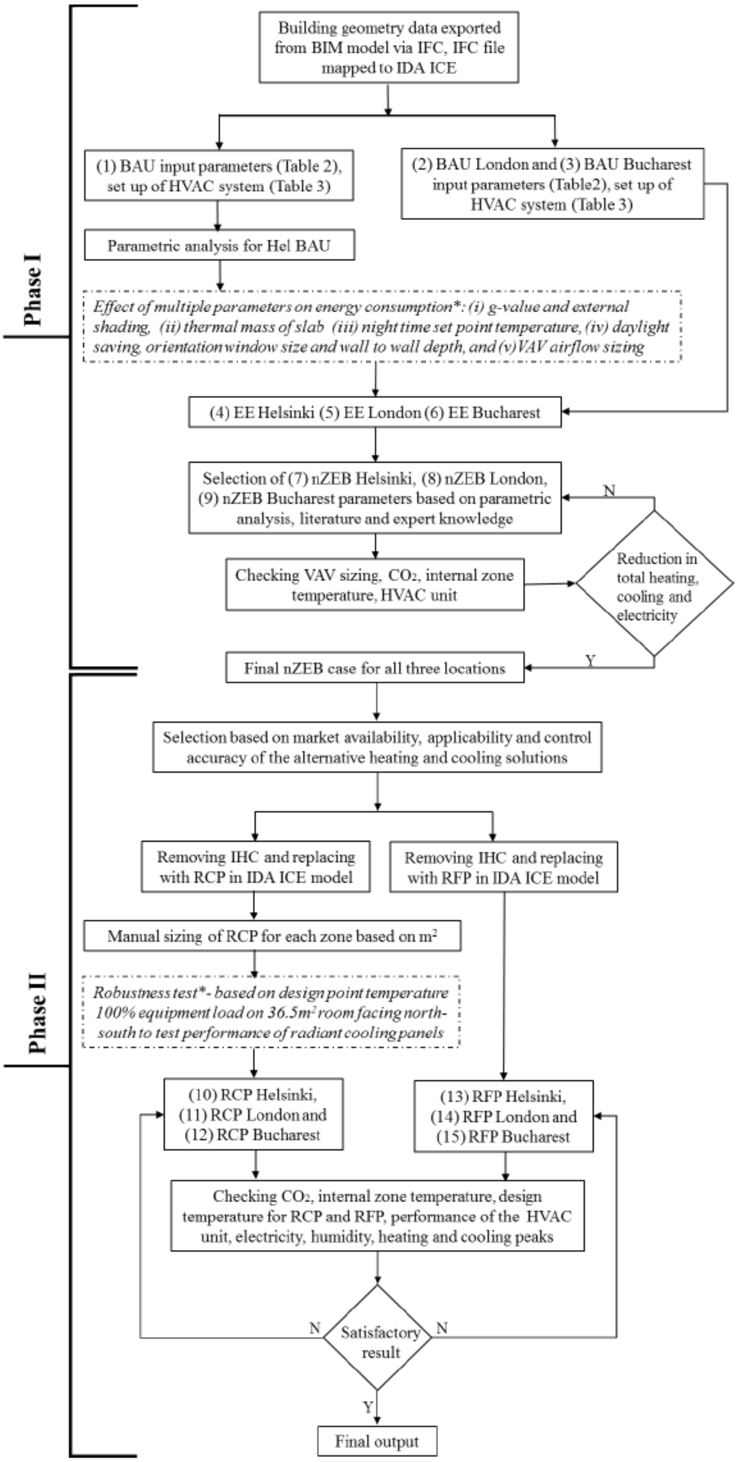

Figure 5. Simulation methodology. Original figure: Appendix C, Publication III, Figure 1, p. 1025. *Dotted lines represent the parametric analysis separately published in Jung (2013) and the robustness test, which are not discussed in this dissertation.

## 2.5. Renewable energy technologies and associated public perceptions

The EPBD recast has been the principal policy instrument towards achieving EU energy and climate objectives for both the existing and future building stock. At the brink of 2021, by which all new buildings should be nZEBs, it is difficult to say how increasing the number of nZEBs will trickle down, in practice, to society. Ultimately, building owners and users are the most critical groups of stakeholders when it comes to foreseeing the implementation of nZEBs in practice. This makes it essential to understand the fundamental factors that influence societal acceptance of RETs. However, multiple barriers have been identified in the EU that may prevent the implementation of RETs, such as education in and information on the technologies, high investment cost, bureaucracy, regulation and legal issues, high level of private ownership, trust in RETs, social factors, payback time, and return on investment (Heimonen et al., 2012; Ahvenniemi et al., 2013; Risholt, Time and Hestnes, 2013; Sepponen and Heimonen, 2016).

Europe has an old building stock, 40% of which was built before 1960 and 90% before 1990, and many buildings are in need of renovation (European Parliament, 2016). Based on the age profile of buildings in the EU, there is an enormous renovation potential that could be tapped to reduce the environmental burden of buildings. In Finland, residential buildings account for half of all renovation activity, and their share is expected to increase (stock built in 1960-1970). According to Statistics Finland, the renovation investments for residential buildings in 2016 was 6.6 billion euros, which is 15.2% more compared to the year 2013 (Statistics Finland, 2017). This means that all of the existing building stock in Finland will be renovated once by 2040–2050 as stated by Tuominen (2015), presenting an opportunity for applying energy saving strategies and implementing nZEBs criteria.

Very few scientific studies in the Nordic region present the key factors detrimental to the implementation of RETs. Our first investigation on social acceptance of RETs (*n=50*) reported that residents in Finland expect the public sector to be the forerunner in domestic renewable energy generation (Moula et al., 2013). The overall results suggested that: (1) willingness to pay for RETs is high, (2) 43% of interviewees would like to take practical steps to install RETs, (3) many were not aware of the RETs available for individual buildings, (4) the concept of payback time was not clear, (5) mixed opinions were received about local renewable energy generation, and (6) the general public had dissimilar views on RETs. We decided to further investigate the questions raised, by introducing specific RETs to identify the corresponding viewpoints of the interviewees. The specific research objectives of Publication IV were:

1) To identify the status of public perceptions of building-related RETs in the capital region of Finland.
2) To identify the associated influencing factors, such as: perceived reliability of RETs, investment cost, payback time, and national incentives based on housing type.

This study was conducted in the capital region of Finland. The Helsinki metropolitan area includes four areas: Helsinki city, Vantaa, Kaunianen, and Espoo. The web-based questionnaire study was prepared in the following three stages: (1) working group meetings, including researchers from technology and social science fields; (2) field test survey in Helsinki (*n*=24);

and (3) distribution of the developed questionnaire using social media in both English and Finnish from autumn 2014 to spring 2015.

Our first study (Moula et al., 2013) used a typical means of analysing the results of the dataset. To better understand the ranking of the RETs of the respondents, Stochastic Multicriteria Acceptability Analysis (SMAA) using a numerical Monte Carlo simulation was applied to compute the uncertainty in the results obtained from the questionnaire survey (*n*=246 respondents). Computing results based only on a mean or standard deviation does not specify the reliability or robustness of the obtained results. "*For example, respondents who prefer technology A may systematically also prefer technology B and disfavour technology C. In general, such multi-dimensional and potentially nonlinear dependencies can be considered in the statistical analysis only by using a simulation approach also clarified in Figure 6 (p. 820, Appendix D"* (Jung et al., 2016).

**Social Acceptance**
Publication IV

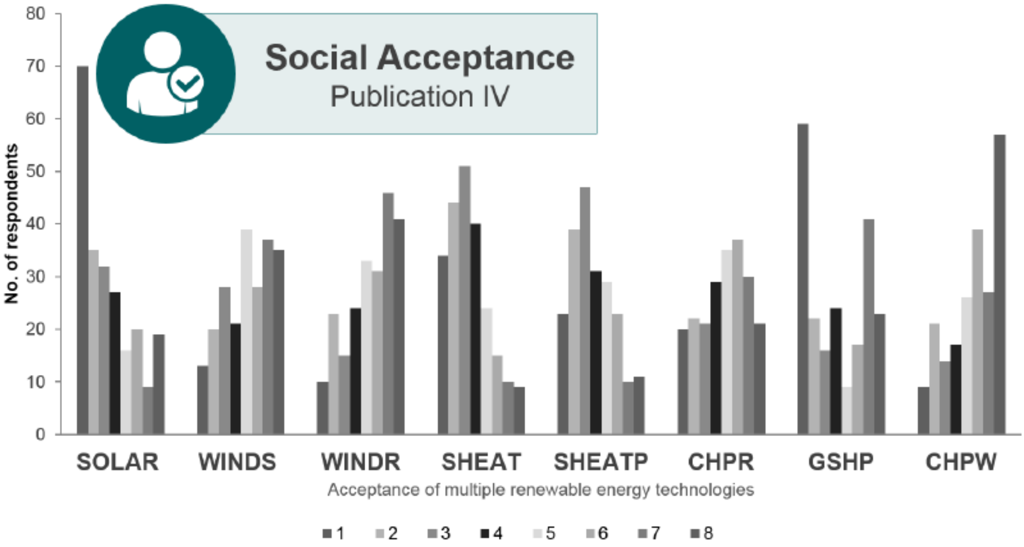

Figure 6. Ranking of the RETs before application of SMAA. Preference was ranked as most favoured and least favoured technology on a scale of 1 to 8.

Due to the large dataset, it was impossible (as explained in Appendix D, section 2.2, p.816, Jung *et al.* (2016)) to form a consensus ranking; thus a novel two-phase sampling technique in SMAA was created and applied to the ordinal criteria to develop the ranking of technologies. "*In the first phase, a random respondent from the group is selected. In the second phase, the traditional SMAA mapping technique is applied to convert the selected respondent's ranking into a cardinal value*" Jung *et al.* (2016).

In total, public perceptions of eight popular RETs that can be integrated with buildings were evaluated, including: (1) Solar electricity through photovoltaics (SOLAR), (2) Ground source heat pump (GSHP), (3) Solar heat for space heating and domestic hot water (SHEAT), (4) Solar thermal system for combined space heating, domestic hot water, and electric power (SHEATP),

(5) Combined heat and power generation based on renewable biomass, such as wood chips (CHPR), (6) Small-scale wind turbine (WINDS), (7) Combined heat and power generation based on community waste (CHPW), and (8) Roof-mounted small-scale turbine (WINDR). The respondents were grouped into five stakeholder categories: (G1) Industry representative, (G2) Energy company representative, (G3) Researcher/scientist, (G4) Real estate developer, and (G5) General public. The results of the investigation are presented in Section 3.4 and Publication IV.

# 3. Results

## 3.1. Extending the capabilities of BIM to support performance-based design

Publication I evaluated the capability of BIM-based models to be used in conjunction with BPS-based tools to enable iterative multi-criteria assessment of the future of high-performance buildings. A comprehensive literature review of *n*=249 documents as well as expert industry interviews were conducted to examine the current capabilities, barriers, needs and potential of BIM-based models to be used as a data source for BPS. With a focus on performance-based design, five building performance criteria were evaluated: energy performance, environmental performance, indoor air quality, lighting, and acoustics. In terms of interoperability between BIM-based models and BPS-based tools, the study focused on the following data exchange criteria: Industry Foundation Classes (IFCs), Level Of Detail (LOD), level of development, Model View Definition (MVD), Information Delivery Manual (IDM), and the international framework for dictionaries and BIM tools and platforms for integrated assessment.

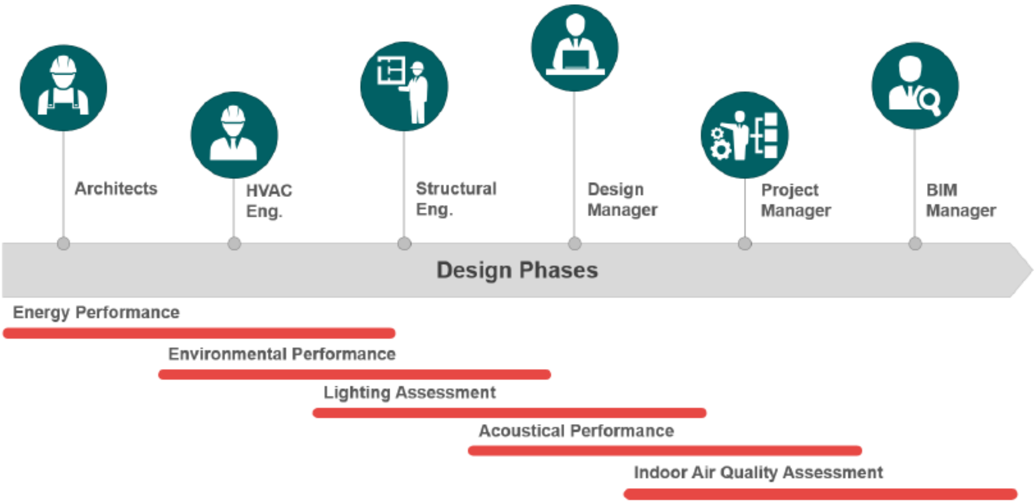

Figure 7. Roles of expert interviewees and the evaluated building performance criteria. See more on quantitative and qualitative results of the interviews in Appendix A, Publication I, Jung *et al.* (2018b), p. 31-34.

The results of this investigation suggest that considering multiple building performance criteria is an incredibly complex task that is further intensified by problems of interoperability between various BIM-based and BPS-based software. '*Data exchange and data extraction were found to be the two key processes associated with interoperability among BIM and BPS-based applications*' Jung *et al.* (2018b). The IFCs do not yet support seamless data exchange, and 'ifcPropertySets' needs to be further developed to account for thermal comfort and indoor air quality; currently they lack semantic information on building performance. To ensure that the BIM-based models are equipped with the data required for BPS, it is necessary to highlight the 'Level of Detail' that can be seen as a BIM-based model input. Level of Development (LOD) is essentially the model output that is required to specify how much detail a model should have; however, based on the expert interviews, how LOD is to be applied in real projects is unclear. The LOD should therefore be further '*developed and defined corresponding to the stages of design to support iterative design process and the use of simulation tools throughout*' (Jung et al., 2018). Currently, there are no certified tools using IDM/MVDs for BPS, and this should be further developed to propogate its use in practice. The current potential of utilizing BIM-based data in conjunction with BPS tools for:

(1) Energy performance assessment is very high
(2) Environmental performance assessment is high in regard to the availability of tools, but still far from becoming an industry practice
(3) Indoor air quality assessment is very low
(4) Lighting assessment is low
(5) Acoustic performance is low

The ratings (very high, high, low and very low) were based on the number of publications found during the literature review based on line of inquiry and their subsequent assessment. The expert interviewees (Figure 7) recognized the need for BIM compatible tools that can assist BPS for development of multi-criteria assessment supportive of iterative design processes. There is a rapid uptake of multi-criteria evaluation in the design and construction of nZEBs. Energy performance, being a central criterion for achieving high energy efficiency targets, should be assessed simultaneously with other building performance aspects. Indoor air quality, thermal comfort, and acoustics as performance criteria were highly valued by all BIM-managers. However, the literature highlighted a lack of tools for evaluating indoor air quality and acoustics during the design work stages, and no studies were found integrating BIM-based models with BPS tools for evaluating either criterion. Specifically for lighting, only one tool was found capable of exchanging information using IFC.

From an AEC industry point of view, cooperation between the various stakeholders dealing with building performance assessment starts too late, and it is often not possible to make radical changes in design if the design work stage is surpassed. In addition, '*if the level of detail is too high, this demands too much work and makes the use of the model complicated and thus the overall usefulness decreases*' (Jung et al., 2018b). All of the interviewees acknowledged the need for solutions and iterative approaches where they can work with the building engineers to ensure sustainable building design and comprehensive consideration of multiple performance criteria during the design work stages. The interviewees also all called for 'iterative building performance methods' that can be applied in various work stages of design as the details begin to develop, as currently most BPS work is done isolation. BIM data was also considered essential for the building operation stage, especially for subsequent renovation cycles. Overall, there is a need for both technical and process standardization and for the roles of each stakeholder in the design and construction to be defined from the beginning of the process regarding data management in order to aid and ascertain the criteria for building performance assessment.

## 3.2. Reducing embodied carbon during the design process

Publication II investigated opportunities for reducing embodied carbon emissions during the design phase of buildings, as described in Section 2.2. The chosen three-directional methodology applied was successful in capturing the barriers to designing low-carbon buildings by means of a thorough literature review, a real building case study, and expert interviews on: (1) embodied GHGs compared to total GHGs induced by buildings, (2) the importance of early design stages in evaluating embodied GHGs, (3) assessing alternative approaches such as practical guidelines, sustainable building rating systems, life cycle assessment tools, simplified tools, BIM compatible tools, (4) the availability of data for low-carbon design, and (5) the lack of process descriptions.

The results of the literature review suggest that there is an apparent lack of ‘explicit’ process descriptions of the ‘need to calculate’ and ‘how to calculate’ the associated GHG emissions during the early design phase of buildings (e.g. ARK 12, RIBA, AIA). Sophisticated and simplified Life Cycle Assessment (LCA) and Life Cycle Inventory (LCI) tools are not integrated with the architects’ design software (typically BIM authoring) and do not support taking into account low-carbon design in the early design work stages (see Appendix B, Publication II, p. 5-6). Sustainable rating systems (LEED, CASBEE, GBC, Green Star, BREEAM) should be used in the very early phases of design for target setting, even though detailed information on building components are lacking.

Seven expert interviewees (mainly principal architects) discussed the relative importance of decision making during the design work stages. The discussions were guided by semi-structured interviews based on their experiences of twelve actual building design projects won through national design competitions. The results indicated that the project type greatly affects the decision making process. For example, design-build projects implemented by large construction companies have a pre-defined structure, standardized construction processes, and a fixed material type, which cannot be easily altered to take into account low carbon design. Decision making was found to be relatively easier with smaller size construction companies as, due to their flexible approaches, many changes can be made during later phases of design. During the early phases of design the primary stakeholders including architects, engineers, and building owners were found to have the vital role and impact on decision making.

The quantified impact of decision making during the design phases on total embodied (material-related) GHG emissions was calculated for a block of flats located in the city of Tampere, Finland, for fifty years of its life. The decisions made during the preparation phase (specific work stage 0-1 for ARK 12, work stage 0-1 for RIBA and work stage 0 for AIA) accounted for approximately 15% of total life cycle material-related GHG emissions. During the concept design and developed design (specific work stages 2-5 for ARK 12, work stages 2-4 for RIBA and work stages 1-3 for AIA), structural components of buildings, such as the building frame, foundations, etc., can account for 50% of total GHGs emissions excluding operational energy during the use phase. The block of flats under study is not augmented with any RETs, and its building service systems account for only 2% of GHG emissions. The addition of photovoltaics on the building's roof can easily account for 15% of total life cycle material-related GHG emissions (Alwan & Jones, 2014). If the planned renovations for the case building are considered, the decisions made during the technical design phase (specific work stage 5 for ARK 12, work stage 4 for RIBA and work stage 3 for AIA) will account for 15% of materialrelated GHG emissions. The three-directional methodology applied (Section 2.3) informed the development of a 'gradual assessment process' (see Appendix B, publication II, Table 9, p. 10) that should be applied during the design phases. Table 3 presents the gradual assessment process for carbon footprint calculation, from the target values set in the early design phase to the specified values in the later design phase, where the:

(1) Target value: is intended for the preparation work stage, where benchmark values can be set based on *(a) Reference data* accounting for the building framework, e.g., the effect of excavations, foundations and yard structures.
(2) Standard value: is assessed during the conceptual and developed design work stages. It can be accounted for by using information on standard structures and *(b) Generic data*, e.g. material used for columns, beams, base floor, intermediate floors, roof structure, walls, windows, and doors.
(3) Quantified value: is assessed during the technical design phase using more detailed information, such as HVAC unit and system type, using life cycle inventory databases, e.g. (Thinkstep GaBi, 2018)
(4) Specified value: is assessed during the construction phase as it will include the final information on surface finishes. During this phase *(c) Product-specific data* such as Environment Product Declarations (EPDs) should be applied.

Table 3. Proposal for gradual assessment of carbon integrated with design process descriptions

| **Proposal for gradual assessment** | **Target Value** | **Standard Value** | **Quantified Value** | **Specified Value** |
|---|---|---|---|---|
| Design process descriptions | Preparation | Conceptual and developed design | Technical design | Construction |
| ARK 12 (Arkkitehtisuunnittelun tehtäväluettelo 2013) | work-stage 0-1 | work-stage 2-5 | work-stage 5 | work-stage 6-7 |
| RIBA (Royal Institute of British Architects 2013) | work-stage 0-1 | work-stage 2-4 | work-stage 4 | work-stage 5 |
| AIA (The American Institute Of Architects 2012) | work-stage 0 | work-stage 1-3 | work-stage 3 | work-stage 4-6 |

The above-described process requires the 'data source' to be compatible with the subsequent processes. Status, coverage, and accuracy can be distinguished by the data type required for the carbon footprint assessment and should be categorized as:
(a) Reference data (based on structure type) and benchmarking data (based on building type using generic data)
(b) Generic data (based on average or typical data)
(c) Product-specific data (derived from EPDs)

These definitions can be standardized as ‘process descriptions’ to create much-needed clarity on how to gradually account for material-related GHG emissions and make informed decisions during the design process. The milestones of the above process during each design work stage are described in more detail in Publication II using the RIBA PoW, which can be universally replicated, for example, the PoW of ARK12 and AIA.

## 3.3. Strategies to reduce the delivered energy demand of buildings

Publication III presented full-scale (160 zones) dynamic simulations providing an energy performance analysis of an office building in the three climate zones of Helsinki, London, and Bucharest. Both active and passive building performance measures were applied, as described in Section 2.4 and Figure 4. The objective of the investigation was to reduce the delivered energy demand in three climate zones for a building to achieve very high-performance to meet nZEB criteria, which can be further augmented with RETs. In total, fifteen cases were simulated using the IDA ICE software (see description on Appendix C, publication III, p. 1028, Jung (2018a)), resulting in five cases for each geographical location. The results were achieved by using various combinations of energy saving parameters, from building envelope properties, building operational parameters, and HVAC system controls. The parameters were incrementally improved from a building as usual (BAU) case to an energy efficient (EE) case, and lastly to a nZEB case for all three locations. Furthermore, radiant floor panels (RFP) and radiant ceiling panels (RCP) were applied in the final nZEB cases as alternative heating and cooling methods by testing them as replacements for conventional (ideal) heating and cooling systems.

As presented in Figure 8, for the northern European climate zone (Helsinki, Finland) space heating can be reduced by 86% from BAU 73.2 kWh/m$^2$/year to nZEB 10.2 kWh/m$^2$/year. Total cooling demand is very low for northern climate zones, the reductions achieved are also low from BAU 3.9 kWh/m$^2$/year to nZEB 1.1 kWh/m$^2$/year. Total electricity demand can be reduced 32% from BAU 64.2 kWh/m$^2$/year to nZEB 43.7 kWh/m$^2$/year. For northern climate zones, the average U-value recommended for a nZEB office building is 0.1931 W/m$^2$K with building envelope properties suggested in Table 1, Table 2, Table 3 (Appendix C, publication III p. 1026, Jung et al. 2018a). For heating-dominated climates around 80% ventilation heat recovery efficiency is recommended.

For the central European climate zone (London, United Kingdom), space heating can be reduced by 95% from BAU 88.7 kWh/m$^2$/year to nZEB 4.1 kWh/m$^2$/year. Total cooling is slightly increased due to the variation in load distribution between space cooling (BAU 3.40 kWh/m$^2$/year to nZEB 0.29 kWh/m$^2$/year) and AHU cooling (BAU 7.61 kWh/m$^2$/year to nZEB 11.62 kWh/m$^2$/year). Total electricity demand can be decreased by 33% from BAU 62.5 kWh/m$^2$/year to nZEB 41.8 kWh/m$^2$/year. For the central European climate zone, the average U-value recommended for a nZEB office building is 0.1998 W/m$^2$K.

For the south-eastern climate zone of Europe (Bucharest, Romania), space heating can be reduced by 92% from BAU 153 kWh/m$^2$/year to nZEB 12.5 kWh/m$^2$/year. Total cooling demand can be reduced by 60% from BAU 18.2 kWh/m$^2$/year to nZEB 11 kWh/m$^2$/year.

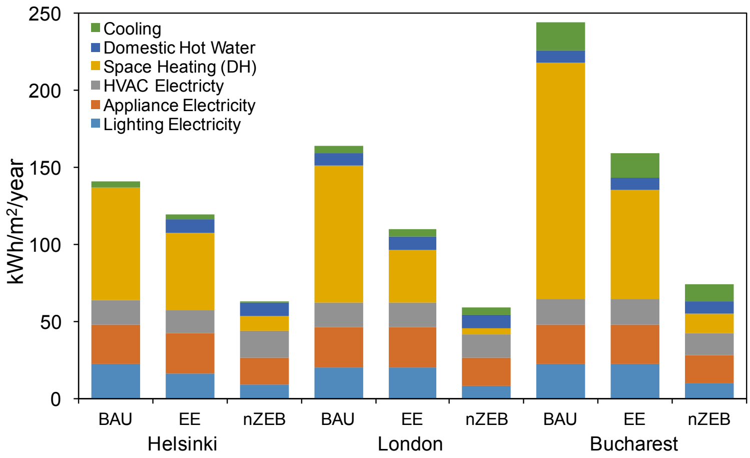

Figure 8. Delivered energy demand for BAU, EE and nZEB for three climate zones. Original figure: Appendix C, Publication III, Figure 4, p. 1029.

The variation in load distribution between space cooling (BAU 18.57 kWh/m$^2$/year to nZEB 0.64 kWh/m$^2$/year) and AHU cooling remained largely unchanged (BAU 27 kWh/m$^2$/year and nZEB 26.93 kWh/m$^2$/year). Total electricity demand can be reduced by 34% from BAU 64.8 kWh/m$^2$/year to nZEB 42.5 kWh/m$^2$/year. For cooling-dominated climate zones around 75% ventilation heat recovery is recommended.

The nearly zero energy cases were further investigated for all climate zones with two alternative heating and cooling solutions. Heating and cooling in all nZEBs were simulated using radiators (categorized as ideal heaters and coolers in IDA ICE), which were replaced with RFP and RCP. Additionally, all nZEB cases were augmented with demand control ventilation (VAV+$CO_2$+temp). For RFP and RCP simulation, IDA ICE's control algorithm first used the HVAC unit to regulate heating and cooling and offset the set point temperature of the alternative heating and cooling room units by 2 °C. Total heating requirement was almost identical in all IHC (17.6 kWh/m$^2$/year) RCP and RFP (18 kWh/m$^2$/year) cases. Total cooling for the northern climate zone was for nZEB IHC 0.4 kWh/m$^2$/year; for nZEB RFP 0.6 kWh/m$^2$/year; and for nZEB RCP 2.5 kWh/m$^2$/year. For the London nZEBs, total cooling was for IHC 3.9 kWh/m$^2$/year; for RFP 3.7 kWh/m$^2$/year; and for RCP 7.3 kWh/m$^2$/year. For the Bucharest nZEBs, total cooling was for IHC 11.2 kWh/m$^2$/year; for RFP 8.8 kWh/m$^2$/year; and for RCP 8.9 kWh/m$^2$/year.

Radiant floor panels cover a larger surface area (m$^2$) in comparison with RCP's for heating and cooling and can supply heating at a low temperature and cooling at high temperature. However, during the humid season supporting air-based cooling is needed. Radiant ceiling panels cover a smaller surface area (m$^2$) in comparison to RFPs due to beam structure of the case building, limiting the surface area (m$^2$) for temperature exchange. This requires an increase in airflow to supply cooling at a lower temperature for the same load. It is recommended for RCPs to be fitted with CAV system where cooling peaks can be supported by the HVAC system.

Based on the above results, low-temperature heating is recommended for all three climate zones as it enables higher heat pump efficiency. High-temperature cooling enables use of a higher fraction of harvested energy if the building is augmented by RETs, such as geothermal energy piles. Generally, nZEBs tend to have long time constants, and with intermittent operation from the building systems point of view, RFP for heating and cooling cannot be recommended. The cooling peaks can be supported via ventilation unit for all nZEBs; based on this study, 7/12 °C is recommended considering dehumidification during hot and humid seasons. In addition, heating set-back and cooling set-up during unoccupied hours should be carefully chosen depending on the RET installed in the building to avoid the morning peaks, otherwise, the benefit might be lost.

## 3.4. Preferred renewable energy technologies in Finland

Publication IV presented the public perceptions of preferred RETs in the Helsinki metropolitan area of Finland and used SMAA to examine the robustness of the survey results. In total $n$=246 respondents answered the survey and their responses were grouped into five categories (G1-G5), as described in Section 2.5. These categories were deliberately set to identify the weight of opinions, which were treated as a 'criterion' in the SMAA of each group. Since it was complicated and, in fact, impossible to form a consensus due to high standard deviation (1.2-2.8) in the results obtained, a novel approach was developed to treat the ranking information by converting the responses into ordinal criteria. The applied method was proven effective, as it provided balanced weight to all respondents, resulting in reduced uncertainty in analysis and improved interpretation of the data.

The overall results of the survey demonstrate a dissimilarity in public preferences for RETs. About two thirds of the respondents were willing to invest in the selected RETs as a means to reduce their carbon footprint. Overall, almost all (except eight) respondents were open to the possibility of installing or investing in RETs regardless of their employment status, indicating that the 'not in my backyard' attitude is not prevalent in Finland. About 68% of respondents with an active employment status are willing to invest more than 1000€, and one third are ready to invest more than 6000€ in their preferred renewable energy generation technology. Regarding improving the energy performance of a building also investigated in Publication III, 54% of the respondents opted for overhauling HVAC systems and installing efficient windows to improve the energy performance of their current home. A common issue throughout the study was the current housing type of the respondent, for example, respondents willing to invest were unclear about the feasibility of installing photovoltaics on the roof of an apartment building. Such decisions are mainly related to the type of ownership, especially when renting. Also, decisions regarding apartment building renovations are made collectively in Finland. Investment in energy efficient renovation was considered the best option by 54% of the interviewees and 58% favoured producing their own renewable energy.

Based on the results received, residents in Finland are environmentally conscious and keen to invest, and would appreciate the availability of governmental incentives such as tax-deductible

RETs (61%), investment grants (47%) and, possibly, feed-in tariffs (34%). Payback time for the initial investment was chosen liberally by the respondents with 36.5% choosing five years, 36% ten years and 13.9% even choosing 15 years. Based on the results of this study, a policy implication could be the introduction of instruments such as owner-based subsidies for rapid implementation of RETs.

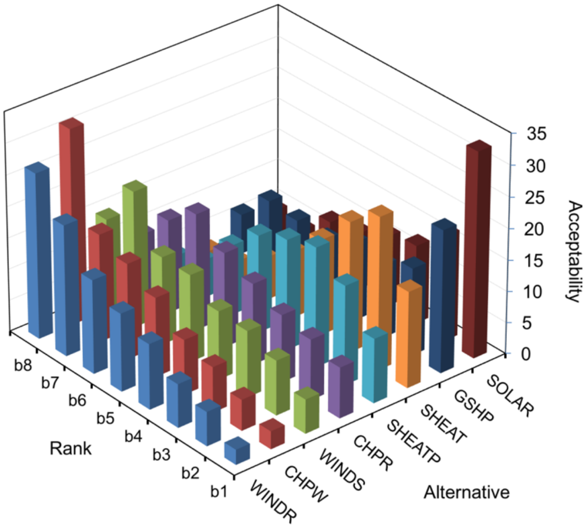

Figure 9. Acceptability ranking indices for the RET alternatives, showing the variety of possible preferences and their acceptability ranking. Original figure: Appendix D, Publication IV, Figure 6, p. 820.

Photovoltaic solar electricity generation and ground source heat pumps were chosen as the most reliable RETs. Both of these technologies are popular in Finland, with homeowners alone investing 500 million euros per year in heat pumps (Finnish Heat Pump Association SULPU, 2018). However, given the climate condition, solar technology is not a complete solution and should be augmented with other RETs to cover the significant delivered energy demand. As shown in Figure 9, after SOLAR and GSHP, the ranking was followed by SHEAT, SHEATP, CHPR, WINDS, CHPW and WINDR, revealing that most of the RETs were considered acceptable, although CHPR, WINDS, CHPW and WINDR were least popular, indicating that people are most interested in building-integrated technologies.

# 4. Discussion

## 4.1. Limitations

The process of design is dynamic and varies based on the project type. Many factors influence the design of a building, and not every project carries out the design strictly as presented in the architects' PoW, as represented by ARK12 (2013), RIBA (2013), and AIA (2012). With this in mind, the results of Publication I and Publication II should be applied to real building design in accordance with the process followed by each particular project. Publication I focused on performance-based design, and only five building performance criteria were studied: energy, environmental performance, indoor air quality, lighting, and acoustics. A selected number of tools were investigated for each performance aspect and these, of course, do not cover the entire domain of each aspect. For assessing environmental performance criteria, commercial tools were not investigated; instead, the focus was placed on research-based tools, which provide a better capability to exchange data using Industry Foundation Classes.

The expert interviews conducted for Publication I (*n*=19) and Publication II (*7 architectural and design companies, 12 real building projects*) were carried out in Finland. The results of both publications are of interest to the AEC industry worldwide, as practices and process around the world overlap. For Publication II, building rating systems (LEED, BREEAM) were not the focus. The focus was on methods that can help architects and engineers to attain targets such as low-carbon design and high-performance buildings.

When conducting the energy performance simulations of an office building in three climate zones, the delivered energy (end-use energy) approach was used instead of the primary energy approach in Publication III. This was done to allow comparison of how a building performs in different climate zones with similar energy performance criteria. The comparative analysis of heating and cooling demand is not affected by country or region-specific primary energy factors. For the heating choices, district heating was used as it was found to be prevalent in all the countries investigated. However, this might not be the case for all European countries. The results should be carefully extrapolated to match the end use heating demand depending on the type of supply.

When understanding the public perception of RETs, it is important to provide many choices for renewable heating and cooling solutions. In Publication IV the "*questionnaire excluded advanced heat pump solutions for combined district heating and cooling systems, options of investment potential in community-based RETs, and other off-site energy generation approaches (e.g. hydroelectric, nuclear)*" Jung *et al.* (2016). Additionally, the questionnaire did not include if the respondent had already invested in RETs, which led to the exclusion of those who have already invested. Therefore, for future investigations we suggest including specific questions that address informed consumers. SMAA was applied only to eight RETs, and thus, social perceptions of other sources of renewable energy are considered out of scope and were not evaluated.

## 4.2. Discussion of the results

For building performance simulation (BPS) tools to be used with confidence, it is necessary that the created model closely represents the actual building to reduce discrepancies between predicted and actual measured building performance (Coakley et al., 2014). This can be better achieved by utilizing BIM-based models at the core to provide input data for BPS simulations, as discussed in Sections 2.2 and 3.1. Based on the literature review conducted in Publication I, no certified tools were found for model view definition (MVD) performance assessment which is an essential element when utilising BIM-based models in conjunction with BPS tools during design stages. Recent work by Pinheiro et al. (2018) presented an approach to facilitate the transfer of BIM-based data to both conventional and advanced BPS tools. Since Publication I was recently published, much of the discussions are presented in the publication itself, and more reflections are presented in Section 5.2 as recommendations for future research.

Publication II provided a framework for designing buildings with a low carbon footprint. Since its publication, much work has been done towards the integration of calculating embodied energy and embodied GHGs in assessment methodologies. Olsson et al. (2016) have presented a tool for decision support during early phases of design that can provide rough estimations of operational energy use, GHG emissions (due to operational energy use) and embodied GHG emissions from the production of building materials. Marsh et al. (2018) provided a simplified approach (LCA profile tool) for environmental assessment that can be applied during the early phases of design. When compared to detailed LCA tools, only a 5-10% margin of error was observed suggesting that use of simplified geometric models in early design phases is a valid approach. Similar to that, Meex et al. (2018) reported that limitation of the ‘level of detail’ of building elements could be fulfilled by using default values in the early design phases, as also suggested in Publication II. Subtask 4 of the IEA Annex 57 provided much needed clarity on the evaluation of embodied energy and $CO_2$eq for building construction based on 80 case studies, multiple methodologies, and recommendations for uniform definitions and templates for the description of system boundaries when calculating embodied energy and embodied GHGs (Lützkendorf et al., 2015; Birgisdottir et al., 2017; Marsh et al., 2018).

With the strengthening of building codes, the energy performance analysis of new buildings should always be carried out using full-scale models as presented in Publication III to assess the delivered energy requirements more accurately. Publication III focused on applying active and passive measures to a detailed multi-zone model to achieve the best building properties leading to reduced delivered energy demand. It also provides new data on the demand profile of an office building. Moran et al., (2017) also confirmed that to achieve nZEBs, it is necessary to design and construct very well insulated buildings to achieve minimum heating requirements and to implement heating systems with low environmental impact. During the simulation cycles it was noted that an improved building envelope with better thermal properties showed a certain degree of energy saving potential. However, due to the colder climate, building insulation in Helsinki is rather good compared to London and Bucharest building codes. This implies that active measures to reduce delivered energy demand, such as building controls (lighting and equipment) and building services (heat pump efficiency and heat recovery), would be more common and profitable in the long term. Also, active energy efficiency measures can better participate in the demand side management.

In Finland, building permits are granted based on the energy efficiency reference value (E-value), which "*represents a building annual consumption of purchased energy, according to the net heated interior space* (*kWh/*$m^2$*a*) *and is also based on the standard use of the building type and weighted coefficients of the energy forms used*" (Green Building Council Finland, 2018). The new building code of Finland (Ministry of the Environment, 2018) requires the E-value of nZEB office buildings not to exceed 100 kWh/$m^2$/year (previously 170 kWh/$m^2$/year based on 2012 national building code D3, i.e. a decrease of 41.18%). This study contributes to predicting the delivered energy demand of office buildings in three distinct climate zones of Finland, London, and Bucharest and adds new knowledge on the growing need of predicting building energy performance. The overall recommendations for achieving nZEBs that can be applied to different climate zones are presented in Appendix C, publication III, Table 7, p. 1027.

To further the work of Publication III towards net zero energy buildings (NZEBs) with an annual energy balance of 0 kWh/$m^2$, boreholes for ground source heat can be drilled to facilitate the use of ground source heat pumps and free cooling. Regarding the application of RETs, solar collectors can be installed to satisfy hot water demand. Concerning alternate heating and cooling systems, heat pumps can be seen as a viable option to support the AHU and to deliver hot water needed for radiant panel heating, whereas, an AHU-based chiller can be used for radiant panel cooling. In addition, an auxiliary electric heater can be added if the solar collectors and heat pump are unable to fulfil the demand. Thermal storage is also central to balancing RET production with the variable demand for heating, hot water, and cooling.

Based on multicriteria analysis using SMAA in Publication IV, several different RETs can be considered suitable for mitigating the climate impact of buildings. The best technologies depend on which specific criteria are emphasized. It is therefore not possible to produce a precise order of ranking for the alternative technologies. This finding also implies that multiple RETs are preferred by the public, and thus, from the policy point of view, the city of Helsinki should have a diverse set of schemes supporting the implementation of multiple renewable technologies. The public seems to be most in favour of financial incentives such as tax deductions, investment grants, and subsidies. Another step forward regarding understanding the market uptake of RETs is better quantification of the intention-behaviour gap to specifically understand the negligible rate of adoption (Hai et al., 2015).

Since Publication IV, a few noteworthy studies have forwarded the research on acceptance of RETs in Finland. Commercialization of RETs in Finland was studied by Shakeel et al. (2017) suggesting a ladder approach of government subsidies and support schemes to increase the market uptake of RETs. The same study also reports the impact of policy on technology providers; for example, if the government decides to reform its policy (e.g. on wind power), this can lead to an unfavourable outcome for the technology provider, hindering RET market penetration. In general, subsidies should always be carefully introduced and defined for a fixed time limit to encourage uptake of RETs. In 2017, the Finnish Ministry of Economic Affairs and Employment published a draft proposal for a 'premium scheme' targeting 2 TWh of additional electricity generation using renewables and requiring a power plant to be of a specific size with minimum and maximum power output level. The scheme, which is yet to come into effect, is thus not focused on individual homeowners.

Meijer et al.'s (2009) policy overview of eight countries, including Finland, revealed a lack quantitative data on policy effects. This has been amended in part by Dahal et al. (2018), who showed that the current energy production and energy utilization policies in Finland are focused on switching to cleaner fuels (biofuels, natural gas, etc.) with incentives such as a feed-in-tariff for bio-energy and wind. The WINDR and WINDS RETs were not viewed enthusiastically by the respondents, as reported in Publication IV. The use of combined heat and power production based on community waste (CHPW), also studied in Publication IV, is still under consideration by the city of Helsinki but remains unimplemented in practice. The study noted that while many RETs are available, the achievement of carbon neutrality goals is dependent on political commitment and administrative cooperation between cities (Dahal et al., 2018).

# 5. Conclusions

## 5.1. Concluding remarks

Energy performance seems to be the most evaluated building performance criterion. Multiple approaches, such as combined models, central models, and distributed model methods (Negendahl, 2016) are at an experimental stage and are being applied to reduce the energy consumed by buildings. Tools for the environmental assessment of buildings have been developed, but there is a lack of defined approaches for how to apply them. Regarding the assessment of indoor air quality, thermal comfort and acoustics, there is a clear lack of evidence of Building Performance Simulation tools that are compatible with BIM-based models. This presents several opportunities for future work towards multi-criteria assessment of whole building performance.

The embodied energy and embodied GHGs of buildings can only be reduced if the 'already existing knowledge' on the 'choice of buildings components' is applied during the early design phases. The literature reviews conducted in Publication I and II indicate a lack of both design integrated tools and process descriptions for low carbon design. A gradual approach to achieving low-carbon design was presented in this dissertation, indicating that the highest level of precision is not required to inform decision making during the early designs stages. Designing a low carbon building essentially requires a gradual assessment process, in which high environmental and energy performance is envisioned.

The energy performance analysis of buildings requires design tools to be better integrated with building performance simulation tools. This dissertation utilized a building information model to conduct thorough building performance simulations of an office building in three climate zones. The findings suggest that it is easier to minimize the heating and cooling demand of office buildings by using active and passive measures than to reduce electricity demand. This is not necessarily negative, as energy can be generated by coupling renewable energy technologies with the building to supplement delivered energy.

Viewpoints of the public can inform the policy makers to introduce instruments and methods leading to the application of renewable energy technologies (RETs) that can be implemented in practice to reduce the environmental burden of buildings. The quantitative findings of this dissertation suggest that the public in Finland is keen on investing in multiple RETs, implying that a spectrum of acceptable options would be the top choice for consumers. The public viewpoints also indicated the need for developing government mechanisms, such as tax incentives to support the application of renewables for individual buildings.

## 5.2. Recommendations for future research

New methodologies and simplified tools are needed to better estimate the optimal indoor air quality, thermal comfort, and acoustics during the design phase. Also, much more attention should be diverted to enhancing interoperability between design tools and building performance simulation (BPS) tools. If data discrepancies continue to occur, it will become increasingly difficult to translate simulation results into actual designs. Publication I detail the BPS tools required to calculate hourly and sub-hourly forecasts of integrated RETs that can be applied during the design phase.

The current capabilities of BPS are focused on reducing energy use through energy efficiency measures (Salom et al., 2014). Increasingly, we need to work towards seamless integration between design tools and building performance assessment tools towards multi-iterative building performance criteria assessment (Publication I). With an increase in the application of building-integrated RETs, it is also important to study the interaction (data exchange) between BPS tools and building system-level tools (e.g., TRNSYS) that are focused on predicting power generation through RETs. The energy generated by RETs is intermittent, being dependent on natural energy sources (sun, wind, etc.). Increased deployment of RETs will result in a fluctuating energy supply, as the electrical grid has insufficient storage capacity. This will require BPS tools to provide more accurate prediction through detailed model calibration (as shown in Publication III) and the respective generation capacity for load matching.

To capture the impact of a building on the environment, calculating the operational energy is only a partial strategy. Embodied energy and embodied GHGs should be part of mainstream calculations (Publication II) as buildings are increasingly designed to integrate more RETs. The effect of local RET solutions on GHGs, considering both operational and embodied impacts on buildings, should be investigated for nZEBs. Environmental Product Declarations (EPD) (CEN EN 15804, 2012) data is typically used for subsequent assessment leading to no change in GHG emissions of already designed and built buildings, and there are certain requirements for how LCAs should be performed in order to be used as a basis for an EPD (Del Borghi, 2013). To support the calculation of GHG emissions, data on GHG emissions of building materials must be available and comparable. EPDs are essentially based on LCAs standardized by the ISO (ISO 14040, 2006) and developed according to pre-defined product category rules (PCR) at noted by Minkov *et al.,* (2015). Future work should be carried out on EPDs to enable identical PCRs for comparability of products between different producers to better support the calculation of LCA and associated GHG emissions. Overall, there is a need for both technical and process standardization and for the roles of each stakeholder in the design and construction of new and renovated buildings. The roles should be defined from the beginning of the design process regarding data management to aid and ascertain the criteria for building performance assessment. Increasingly, we need to reinforce and inculcate the idea of considering whole life cycle of buildings during early stages of design to reap maximum benefit of the design process while reducing the environmental burden of buildings.

Nearly Zero Energy Building (nZEB) definitions and methodologies are under discussion in all European countries, with a focus on the energy efficiency of buildings. These discussions often overlook the crucial fact that decisions made during the design process of a building affect, directly or indirectly, on the overall performance of the building once it is in use. The development towards nZEBs has not been integrated with the design process of a new building.

Future work should be conducted on creating guidelines for building designers, architects and engineers that can be applied during the planning stages of the building.

Future studies on user preferences and public perceptions should provide numerical assessments of the RET alternatives to better capture the consumers’ willingness to invest. It was found to be difficult to obtain quantitative data on energy technology-based funding mechanisms specific to homeowners and their impact on the current scenario in Finland. It is thus recommended to conduct future research specifically on public policies available for building-integrated and community-level RETs to understand what is needed from the policy point of view for increasing the market uptake of RETs.

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# Appendix A: Publication I

Nusrat Jung*, Tarja Häkkinen, Mirkka Rekola. Extending Capabilities of BIM to Support Performance Based Design. *Journal of Information Technology in Construction (ITcon)*, Volume 23, Pages 16-52, 2018b.

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

# EXTENDING CAPABILITIES OF BIM TO SUPPORT PERFORMANCE BASED DESIGN

SUBMITTED: January 2017
REVISED: October 2017
PUBLISHED: February 2018 at https://www.itcon.org/2018/2
EDITOR: Amor R.

***Nusrat Jung, M.Sc.,**** 
***VTT Technical Research Centre of Finland and Department of Mechanical Engineering, Aalto University,***
***Nusrat.jung@vtt.fi; nusrat.jung@aalto.fi***

***Tarja Häkkinen, PhD.,***
***VTT Technical Research Centre of Finland***
***Tarja.hakkinen@vtt.fi***

***Mirkka Rekola, M.Sc.,***
***Senate Properties***
***Mirkka.rekola@senaatti.fi***

***SUMMARY:*** *As we advance towards high-performance buildings, it is becoming necessary to reinforce and extend the role of building information modelling (BIM) to better support performance-based design. To achieve an optimally functioning building that fulfils the need of the end-user and is designed in an environmentally conscious manner necessitates considering energy performance, environmental performance, indoor air quality, lighting, and acoustics. To consider these multiple criteria, use of computer-based modelling tools and comprehensive simulation methods becomes essential. These criteria are typically assessed after the main phases of architectural design of the building, and the knowledge is passed on to the engineers for development of the technical design. During the technical design process, the exchange of data between the design model and a selected building performance aspect may occur. This paper investigates the potential of BIM-based models at the core of providing input data required for performance-based simulations (BPS) to enable iterative multi-criteria assessment towards high performance buildings. A comprehensive literature review of 249 documents was conducted to identify the current state of knowledge and provide future directions for design and simulation tools to better quantify and evaluate the performance aspects. Furthermore, it explains and clarifies stakeholders' current ability, needs, barriers, and potentials in using BIM for assessing building performance through nineteen expert interviews of key BIM stakeholders in Finland.*

***KEYWORDS:*** *BIM, Performance-based design, Energy performance, Environmental performance, Indoor air quality, Lighting, Acoustics.*

***REFERENCE:*** *Nusrat Jung, Tarja Häkkinen, Mirkka Rekola (2018). Extending capabilities of BIM to support performance based design. Journal of Information Technology in Construction (ITcon), Vol. 23, pg. 16-52, http://www.itcon.org/2018/2*

# 1. INTRODUCTION

As described by the International Organization for Standardization (ISO), the building performance requirement is the minimum acceptable level of a critical property (ISO 6707-1, 2014). Performance-based design can be defined as a process where the targeted solution is described with the help of its required performance (CIB Report publication 64, 1982). Kalay (1999) defines performance-based design as an approach focused on a holistic view where functions and aesthetics are not compromised and at the same time ensuring the ecological and environmental performance of a building. Lützkendorf et al. (2005) describe building performance as a major concept divided into categories: functional, technical, environmental, economic, social and process performance. According to Sexton and Barrett (2005) and Eriksson and Westerberg (2001), performance-based and qualitative requirements give the best basis for innovative design solutions.

Achieving an optimally functioning building that fulfils the need of the end-user necessitates identifying and quantifying the performance (Gursel *et al.*, 2009), setting measurable targets which can be monitored during different phases of design and implementation (Koskela, 2000), and considering multiple criteria. There have been many attempts to outline the overall building performance and describe various performance aspects with the help of indicators which can be used for requirement setting (Alwaer and Clements-Croome, 2010; Augenbroe and Park, 2005; Frandsen *et al.*, 2010; Loomans *et al.*, 2011; Prior and Szigeti, 2003). Also, ISO (ISO 21929-1, 2011) presents indicators of a sustainable building with fourteen aspects, such as emissions to air, the consumption of non-renewable resources, indoor conditions (including lighting and acoustics) and air quality, etc. For example, a standard indicator of building energy efficiency is annual energy consumption (kWh/m$^2$) as a function of climate, envelope design, heating ventilation and air-conditioning (HVAC) systems, and occupant behaviour, among other parameters (IEA ECBCS Annex 53, 2013). Similarly, for environmental performance, embodied impacts (e.g., greenhouse gas emissions) of a building are assessed based on life cycle data of building products. Indoor air quality includes assessment of the dynamics of gaseous and particulate pollutants and human exposure to these contaminants. Lighting of interior and exterior spaces in a building includes such factors as illuminance, luminance, daylight, and glare probability. Acoustical performance of indoor spaces is calculated based on reverberation time, sound intensity level, noise, and other factors that are important to be considered during design phases.

To achieve an optimally functioning building that fulfils the need of the end-user also necessitates assessing the building performance indicators with simulation methods by applying an iterative design process (Oduyemi and Okoroh, 2016). The simulation of different design aspects requires information from the design model such as that of quantities of products, performance characteristics of products, building elements and their surfaces, dimensions of spaces, etc. Iterative design towards required performance requires the availability of methods and tools that can be easily used by designers and that cover the selected performance criteria (Hopfe, 2009). The methods and tools used to carry out the assessment vary regarding complexity and accuracy, capacity, the quality of required input data, usability in different situations and phases of design, and validity. Negendhal (2015) categorized the method of integrating the design tools with BPS in three ways: (a) combined model method, which have simulation packages such as IESVE (IESVE, 2013), (b) central model method, which includes using shared data schema such as that of BIM, and (c) distributed model method where a middleware software is used to move data bi-directionally between building geometry model and BPS software. A major challenge in the application of simulation tools is how to deal with difficulties through a large variety of parameters and complexity of factors such as non-linearity, discreteness, and uncertainty (Hopfe and Hensen, 2011).

BIM-based models prepared by architects and designers (eg. structural, HVAC, mechanical electrical, plumbing) may have the potential to ease the management of input data significantly, to make BPS in different phases of design less time consuming, while considering performance criteria simultaneously. However, this may require that BIM-based and BPS-based methods are compatible to be deployed effectively along the design process to optimize multiple performance aspects in various phases of design. BIM as defined by the National Institute of Building Sciences (2016) is a digital representation of physical and functional characteristics of a facility. BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition (National Institute of Building Sciences, 2016). It contains interoperable information allowing it to be exchanged based on open standards, such as Industry Foundation Classes (IFC) widely used for data transfer.

The need, value, and usefulness of BIM is well established in the architectural, engineering and construction industry and facilities management (AEC/FM) and has been discussed by several studies. According to Yalcinkaya and Singh (2015) implementation and adoption of BIM has been the most important principal area in BIM research. However, when evaluating the need, value and usefulness of BIM, the AEC industry has focused on its potential to streamline the construction and delivery processes of a project. Past and current research trends have been riveted on studying the capability of BIM as a process management tool and its ability to help evaluate selected performance criteria as presented in section 3.1 and 3.2. This study investigates the potential of BIM-based models at the core of providing input data required for BPS to enable iterative multi-criteria assessment towards the future of high performance buildings. The specific objectives are:

(1) To study the current capability and highlight the issues of data exchange between BIM-based and BPS-based tools/methods through a literature review.

(2) To explain and clarify stakeholders' current ability, needs, barriers and potentials in using BIM-based models for assessing building performance through expert interviews.

(3) Identify what kind of additional methods/procedures research (literature) and industry (expert interviews) calls for to ascertain building performance criteria.

## 1.1 Organisation of this study

The purpose of Section 1 (Introduction) is to position this study and explain the essential terms related to the scope of this study. Section 2 presents the method for the literature review (2.1) and the method used for the expert interviews (2.2). Section 3 is dedicated to the literature review of 249 documents organised in two parts, where 3.1 explains the generic benefits of using BIM and Section 3.2 links availability of BIM-based models to BPS methods for selected performance aspects. Section 4 is organized in two parts where, Section 4.1 discusses the qualitative results of the nineteen expert interviews, and Section 4.2 presents the quantitative results of the expert interviews. The qualitative results of expert interviews are designed in accordance with the architect's Plan of Work as presented in (Häkkinen *et al.*, 2015) and in this study structured as (i) Briefing, Preparation, Concept design, Developed design phases; (ii) Technical design and Construction phases; (iii) Building In-use and Warranty period phase. Section 5 is devoted to discussions focused on future need for performance-based design simulations using BIM-based models (Section 5.1) and Section 5.2 discusses the challenges in interoperability and information processes based on the literature review and the expert interviews followed by conclusions.

# 2. METHODS AND LIMITATIONS

## 2.1 Method for the literature review

A study of literature was conducted to summarise the current availability and capability of BIM compatible BPS tools and methods for designers and the scope of topics covered in the literature review are outlined in Figure 1. To fulfil objective 1, we concentrated on (1a) what information is needed as input variables to the simulation tools from the BIM model, (1b) can this information be brought from architects and designers' BIM model to the simulation model with the help of open standards such as Industry Foundation Classes (IFC). IFC is an international data exchange standard for building information developed by BuildingSMART formerly known as the International Alliance for Interoperability.

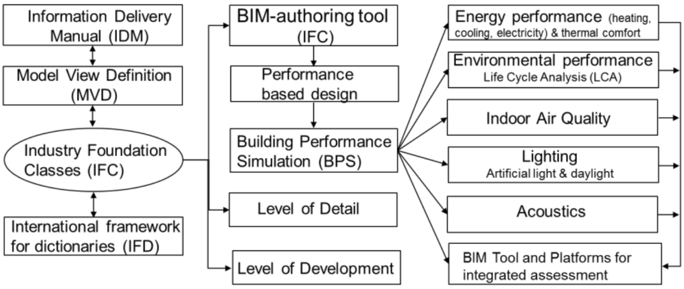

*Figure 1. Scope of this study*

There are different kinds of approaches for utilizing BIM for simulating building performance. This article focuses on approaches where the use of open standards such as IFC (ISO 16739, 2013) for data transfer is applicable. By BIM compatible tools, this study refers to widely used commercial tools/software that can exchange data via IFC. By 'modelling' this study relates to the creation and the authoring of the building information model in software such as Graphisoft ArchiCAD (ArchiCAD, 2017) and Autodesk Revit (Autodesk Revit, 2017) which are IFC compatible. This approach was selected because the open standard exchange enables any tool of any developer to utilise produced information but is restricted to the limited data properties of the standard. The limited data properties of IFC can be overcome by extending the property sets, to capture proprietary BIM content if agreed upon between the users. The resulting IFC exported files containing IFC objects with their properties can be used for sustainable building assessment (Fies, 2012). In addition, ISO 16739:2013 specifies a conceptual data schema and an exchange file format for BIM data (ISO 16739, 2013).

The building performance aspects assessed in this study are presented in section 3.2, and they were selected based on ISO standard 21929-1 Sustainability in building construction – sustainability indicators Part 1 (ISO 21929-1, 2011). Namely, five performance aspects studied comprise of energy performance (section 3.2.1); environmental performance (section 3.2.2); indoor air quality (section 3.2.3); lighting (section 3.2.4), and acoustics (section 3.2.5). Relevant articles based on title, abstract, and keywords (BIM, BIM compatible tools, performance, design, environment, energy, indoor air, acoustics, and lighting) were searched by using Scopus and Science Direct. During this process, a wide array of articles in specific journals were found. For the literature review, a total number of 249 documents were investigated including journal publications, conference publications, industry reports, scientific reports, standards, codes, factsheets, user manuals and thesis. Table 1 presents the subject of enquiry and the corresponding number of publications investigated in this study. It should be noted that each building performance aspect considered in this study is a scientific topic in itself. The focus of this study is not to dwell on the details of each performance aspect but on the potential to holistically assess the selected performance aspects. This can be ascertained by understanding capabilities of available BIM-based tools and BPS tools that can exchange data bi-directionally using open standards.

*Table 1: Subject based enquiry and the corresponding list of publications investigated*

| Subject of enquiry | Number of publications investigated |
|---|---|
| Generic BIM | 15 |
| Performance Based Design (PBD) | 18 |
| IDM, MVD, IFC, IFD, Level of Detail, Level of Development | 15 |
| BIM tools and platforms for integrated assessment | 13 |
| **Section 3.2.1 Energy performance assessment** | 32 |
| (1) Required input data for building energy performance simulation | 21 |
| (2) No. of investigated tools/software for energy performance simulation | 7 |
| (3) Linking BIM-based data with BEP-based simulation | 20 |
| **Section 3.2.2 Environmental performance** | 12 |
| (1) Required input data for environmental performance assessment | 3 |
| (2) No. of investigated tools/software for environmental performance assessment | 2 |
| (3) Linking BIM-based data with environmental performance assessment | 3 |
| **Section 3.2.3 Indoor Air Quality** | 9 |
| (1) Required input data for IAQ simulation | 5 |
| (2) No. of investigated tools/software for indoor air quality simulation | 2 |
| (3) Linking BIM-based data with IAQ simulation (*not IFC based*) | 3 |
| **Section 3.2.4 Lighting** | 7 |
| (1) Required input data for lighting simulation | 14 |
| (2) No. of investigated tools/software for lighting simulation | 4 |
| (3) Linking BIM-based data with lighting simulations | 14 |
| **Section 3.2.5 Acoustics** | 7 |
| (1) Required input data for lighting simulation | 16 |
| (2) No. of investigated tools/software for acoustics simulation | 4 |
| (3) Linking BIM-based data with acoustics simulation | 3 |
| **Total** | **249** |

Although the focus is on approaches that use open standards for data transfer, this study briefly mentions two other approaches where (1) the calculation algorithms are embedded in the BIM authoring software or the use of proprietary software-developer-specific file formats or even plug-in tools for design software (for example: (Liu *et al.*, 2015)) and (2) approach based on automatic bi-directional exchange of data, enabling designers to make parametric changes to the BIM-based model and simulate performance-based aspects simultaneously (for example: (Asl *et al.*, 2013)). As a limitation, the literature review focuses on the use of tools during the design process and does not deal with the usefulness of BIM in supporting the certification of sustainable buildings as that has been studied elsewhere, for example (Azhar *et al.*, 2011; Ilhan and Yaman, 2016; Wong and Zhou, 2015).

## 2.2 Method for the interviews

Expert interviews were conducted, to explain and clarify stakeholders' current ability, needs, barriers and potentials in using BIM for assessing building performance. During the discussions, we focused on what are the common practices for conducting simulations and pertaining problems as experienced by the interviewees and if the current simulation methods supports performance-based design (objective 2) and what is needed to improve the current practice (objective 3).

The basis of selection and identification of the expert interviewees for this study required that: (a) all the expert interviewees have more than ten years of experience in application and utilization of BIM in their domain as presented in Table 2. Other than this criterion, the experts were selected with no prior preference or bias of the authors. (b) The expert interviewees were identified by contacting engineering companies and architectural offices, while paying attention to actors that are members of the BuildingSMART Finland (2017). BuildingSMART Finland is a chapter under BuildingSMART International and a forum founded by Finnish AEC industry, large-scale property owners, and software vendors. This forum is meant for disseminating BIM related information and support implementation of BIM-based processes. (c) The authors requested Senate Properties (Senaatti-Kiinteistöt in Finnish) to list designers, architects, and BIM-coordinators that have been involved in their projects. Senate Properties is a government-owned enterprise and the largest building owner in Finland; their building portfolio consists of 9 300 buildings (Senaatti-kiinteistöt, 2017). Application of BIM is mandatory in all of Senate properties significant building projects that exceed the size of one million euro, making it a global forerunner in deploying IFC-based integrated BIM also noted by Gupta et al. (2014).

All expert interviews were conducted either face-to-face or by a teleconference between the interviewer and the interviewee. The duration of each interview lasted between 1-2 hours with nineteen respondents. To gain in-depth knowledge and enhance discussion, the interviews were semi-structured, so that the expert could add detailed background information or discuss the questions in addition to the questionnaire. A questionnaire was prepared and shared with the interviewees before conducting the interview. Each respondent was provided with a document of twelve open-ended and multiple-choice questions. During the interview, the importance of raised issues in the context of this study was assessed by all interviewees. Later, the interviewees were requested to further explain and reason their responses.

To capture the level of experience of the respondents, we asked them to explain their role in the design process based on their respective position in the company (see Table 2), their main motivation, and driver for exploiting BIM, and the most significant benefits of using BIM (see appendix 1 for the questionnaire). Table 2 lists the designation of the interviewees, role and features of the company in AEC industry to provide context to the readers. Consistent with extending the use of BIM in performance-based design, we asked the interviewees about: setting and monitoring of quantitative targets; the most important performance criteria that need or would need BIM compatible tools; the use of simulations tools available at present for building performance assessment; suitability of simulation tools in different phases of design; need for simultaneous consideration of various performance criteria; need for holistic design methodology; a comprehensive approach to support performance management; multi-criteria design and optimization of different performance criteria.

The limitation of our study include that the interviews were conducted solely in Finland. However, the outcomes of this study may have broader interest as Finland has been cited as one of the forerunners in the use of BIM (Finne, 2012; Rahman *et al.*, 2013; RIBA Enterprises Ltd, 2016). Additionally, the performance aspects and potential of BIM in performance-based design discussed in this study are of universal interest to the AEC/FM industry.

*Table 2: List of Interviewees*

| | Designation in the company | Role of the company in AEC industry | Name and features of the company |
|---|---|---|---|
| 1 | Architect | Architectural design | Architects firm (In Finnish:Arkkitehtitoimisto) Lylykangas Kimmo |
| 2 | Architect | Architectural design | Architects (In Finnish: Arkkitehdit) Davidsson and Tarkela |
| 3 | Architect | Architectural design | Architects firm (In Finnish:Arkkitehtitoimisto) Lasse Kosunen |
| 4 | Architect | Architectural design | Architects firm (In Finnish: Arkkitehtitoimisto) Brunow and Maunula |
| 5 | Architect | Architectural design | JKMM Architects (In Finnish:Arkkitehdit) |
| 6 | Architect | Architectural design | L Architects (In Finnish: Arkkitehdit) |
| 7 | Architect | Architectural design | Parviainen Architects (In Finnish: Arkkitehdit) |
| 8 | HVAC engineer, BIM expert | Design, engineering, and consultancy | Ramboll Finland is leading engineering, design and consultancy company founded in Denmark |
| 9 | HVAC engineer, BIM manager | HVAC design | Granlund in Finland is one of the leading experts in Energy efficiency design, consultancy and software services |
| 10 | Structural engineer | Structural engineering | IdeaStructura is based on structural and physical engineering competence and used data modelling in reconstruction |
| 11 | Structural engineer | Engineering | Sweco Finland is a set of European engineering consultancy companies focused on construction, architecture, and environmental engineering |
| 12 | Project manager | Engineering | A-Insinöörit as a company is specialized in construction and design |
| 13 | Design coordinator | Contractor | YIT Finland (in Finnish:Yleinen Insinööritoimisto), is the largest residential construction company in Finland |
| 14 | Design Manager | Contractor | Skanska is a multinational construction and development company based in Sweden |
| 15 | Design Manager | Property owner | Finavia is a limited corporation fully owned by the Finnish state. Finavia is responsible for maintaining and developing 21 airports in Finland |
| 16 | Project manager | Property owner | City of Espoo (in Finnish: Espoon Kaupunki) has its own municipality, which is the second largest city in Finland, sharing borders with Helsinki and Vantaa regions |
| 17 | Project manager | Property owner | HUS kiinteistöt provides Facility management and services and is fully owned by the Hospital district of Helsinki and greater Helsinki (Uusimaa) area |
| 18 | BIM expert, architect | Property owner | Senate Properties (in Finnish: Senaatti-kiinteistöt), is a Finnish unincorporated, fully state-owned enterprise, under the Finnish Ministry of Finance |
| 19 | BIM Coordinator | BIM consultancy | Gravicon is an IT consultant and developer for building industry specialized in BIM consulting services. |

# 3. POTENTIAL OF BIM IN PERFORMANCE BASED DESIGN

## 3.1 Generic benefits of BIM in design process

The generic benefits of BIM have been discussed and evaluated by several studies. Barlish and Sullivan (2012) compared non-BIM and BIM projects and made preliminary estimates of overall savings and benefits. According to them the most important benefits of BIM concern scheduling, sequencing coordination, rework, visualization, productivity, project cost, communication, design/engineering, physical conflicts, labour, and quality and simulation.

BIM models generated digitally can provide design models together with accurate and fundamental information for decision making through a standard method of storing this information, thereby facilitating sharing of information, visualization and improving collaboration (Eastman *et al.*, 2011; Rancane, 2014). As presented in Table 3, improvement in visualization and coordination is especially emphasized by the NBS National BIM report (RIBA Enterprises Ltd, 2014) and the Finnish BIM survey (Finne *et al.*, 2013). Quite consistent with this, Bryde et al. (2013) reported that cost reduction through the project life cycle, time reduction, communication improvement, coordination improvement, quality increase, negative risk reduction and scope clarification (listed in the order of importance) are the most important success criterion of using BIM resulting in positive benefits. Many studies emphasize the benefits of BIM in promoting collaboration of team members from different design disciplines and interaction (Eadie *et al.*, 2013; Elmualim and Gilder, 2013; Porwal and Hewage, 2013; Saini and Mhaske, 2013).

In the UK, the use of BIM has been defined as BIM Maturity levels and categorized as a maturity index in four (0-3) levels. At level three, BIM would support cost estimation, thermal properties analysis, operational applications, and lifecycle management as part of the process. Level three 'intends to use open process and data integration through web services which are compliant with the emerging IFC/IFD (International Framework for Dictionaries) standards' (BIM Industry Working Group, 2011). Malleson (2014), stated that the level of use is moderately good in Britain, but there is still much to do before the overall building performance is managed in different project phases with the help of BIM. Becerik-Gerber and Rice (2010) presented that the lack of proper experience in the use of BIM hinders the determination of the value of BIM.

*Table 3: Benefits of BIM based on NBS National BIM report 2014 and Finnish BIM survey 2013.*

| Claimed benefits | Percentage of respondents that agreed with the claims in the survey conducted in NBS National BIM report *(n=1000)* | Percentage of respondents that agreed with the claim in the Finnish BIM survey *(n= 400)* |
|---|---|---|
| Visualization | 83 | 85 |
| Coordination of construction documents | 77 | 39 |
| Data management | *not assessed individually* | 77 |
| Cost savings | 61 | 24 |
| Speed of delivery | 52 | 22 |
| Profitability | 45 | 27 |
| Use of COBie* in projects | 23 | 8 |

* Construction Operations Building information exchange (COBie)

Kreider et al. (2010) have studied the use frequency and benefits of applying BIM on projects with the help of a survey. Among the perceived benefits and use frequency of 3D modelling, design reviews, and design authoring was assessed most positively among other BIM uses. The survey results reveal that, BIM has the potential for energy analysis, sustainability analysis, mechanical analysis and lighting analysis although the use frequency of BIM is moderately low. Even though BIM can support the assessment of many performance-based criteria of the building, the AEC industry doesn't have a streamlined process to achieve desired results as it depends greatly on the interoperability of the software used to conduct the analysis. Also, Bynum et al. (2013) highlighted the interoperability problems that hinder the use of BIM in different kinds of building performance analyses. In summary, the results of the above surveys and corresponding studies reinforce that BIM is very successful in terms of managing the performance of the project.

## 3.2 BIM support for building performance simulation (BPS) and assessment methods

Building performance simulations are typically done separately and independently of each other in different design phases (Cho et al., 2009). There are still large challenges in implementing BIM-based sustainability analyses because of the lack of process models and practical strategies for integration of information (Lim, 2015). This section intends to focus on BIM-based and BPS-based aspects of the tools. We also assume that, the presented BPS tools (Table 4) are known to the architects and other representatives of design disciplines being wide spread in academia and AEC industry. This section gives an overview of the status of different simulation tools, their ability to exchange information with BIM and the ability of BIM to support BPS (objective 1). The focus is on widely used commercial tools that support the simulation of energy performance (section 3.2.1); environmental performance (section 3.2.2); indoor air quality (section 3.2.3); lighting (section 3.2.4), and acoustics (section 3.2.5). Approaches such as that of 'tools and platforms' for integrated design assessment are discussed in section 3.2.6. Table 4 summarizes the results of the literature review linking the BIM-based model with BPS-based tools/software.

### 3.2.1 Energy performance assessment

Energy performance assessment and simulation have become increasingly popular research topics in BIM research (Yalcinkaya and Singh, 2015). A high number of BPS tools with a range of capabilities are available. The choice of tools depends on the ability to perform the needed assessment. When aiming to obtain accurate assessment results, sophisticated dynamic energy simulation methods must be used, like those applied in, e.g., Energy Plus (Crawley *et al.*, 2008) or the IDA ICE program (Sahlin, 1996). These tools require the modelling of the whole building considering the characteristics, such as volume, form, orientation, window sizes, heat-insulation, dynamic environmental conditions, and HVAC components. This information can be brought to the simulation tool from the BIM-based design model by using directly or indirectly IFC compatible tools, for example (Bazjanac, 2008). Until now, the AEC industry has not found an absolute solution to derive a coherent process for efficient use of BIM information for energy optimization purposes (Asmi *et al.*, 2015; Robert *et al.*, 2012) and there are in fact many studies presenting semi-automated approaches such as that of (Barnes and Castro-Lacouture, 2009; Bazjanac, 2008; Cemesova *et al.*, 2015; Cormier *et al.*, 2011; Geyer, 2012). Also, Ahn et al. (2014) pointed out that IFC is not ready to include all needed information for the simulation. The details of mechanical systems applied to dynamic simulation tools are still unstructured in the IFC format, and it is difficult to accurately convert IFC to a well-structured simulation information model. Some part of the needed information should be captured in external sources (e.g., weather data), and some could be linked to the BIM-based model by using a standard approach (e.g., product data).

Although many simulation tools can utilize IFC, the generation of an building energy performance (BEP) simulation model from BIM-based model is still time-consuming because it may include unnecessary information and on the other hand may lack the needed information (Kim *et al.*, 2015). Data extraction and data exchange are two key processes associated with the interoperability among BIM applications. Also noted by Lu et al. (2017), to support the required performance analyses, BIM data requires many modifications which weakens the design benefits. Significant time savings can be achieved when there is no need to create the building geometry in energy simulation model but there is a high risk for missing, misplaced, or deformed building elements during a BIM data exchange process, also reported by Oh et al. (2015) and Senave and Boeykens (2015). An object-based approach in which the geometry and material information needed to build an energy input file able  to collect data from a model authoring software parsed for energy simulation may yield higher accuracy (Kim *et al.*, 2015).

'BIM-based model extension can be achieved by extending data through subclass like IFC property sets' (BuildingSMART International, 2007) but the extended IFC model is deficient in semantic information. Though, the most recent version of IFC4 also 'does not allow the specification of all elements required to express HVAC systems'(Asmi *et al.*, 2015) and BIM-based specification is rather poorly addressed (Robert *et al.*, 2012). Thermal comfort is very often evaluated together with the energy performance assessment of buildings. Some property sets in IFC exist only as a notion of thermal comfort linked with the HVAC design parameters (air temperature, mean radiant temperature, air velocity, and relative humidity) and the thermal environment caused by the choice of building components eg: PsetSpaceThermalPHistory, SpaceThermalRequirements etc. (Huovila *et al.*, 2014). Accounting for the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) is also acknowledged by ISO 7730 (2005). Most of the commercial BEP software, such as IDA ICE, accounts for PMV and PPD. However, as noted by Soubra et al. (2012) IFC schema doesn't contain specific Psets to include thermal comfort specifically as it is considered as a building 'use phase' parameter, and should be introduced.

BuildingSMART alliance developed the Information Delivery Manual (IDM) approach to identify the processes and information flow during the life cycle of a facility (buildingSMART International, 2017a). The objective of IDM has been to provide a method to capture and specify the semantically rich information required by the IFC schema. Model view definition (MVD) or IFC View definition is a mechanism proposed by the standardisation organisation buildingSMART for defining the subset of the IFC data model that is necessary to support a specific data exchange, such as energy simulation (buildingSMART International, 2017b). It is intended to overcome the complexity and large size of IFC data models (buildingSMART International, 2017a), but from perspective of BEP, MVDs have been specified only for energy and structural analysis. Liu et al. (2013) introduced an IDM approach to identify information requirements for performance analysis of HVAC systems, where they had to make changes to the original IDM approach. The official certification is currently available only for IFC Coordination view (buildingSMART International, 2017c), so exact information of software implementing these MVDs is not easy to achieve. Moreover, as presented in Table 4 none of the BPS analysis and simulation software's listed in buildingSMART application category with IFC compatibilty are MVD supported (buildingSMART, 2017).

Another challenge lies in exporting the results of the best BEP solution back to the design BIM model solutions after the simulations are conducted. Even if the design and simulation tool is directly or indirectly IFC compatible, none can export information back to the BIM model even through an "intermediary" as explained in detail by Bazjanac (2005) and Soubra el al. (2012). Thus, the BIM model has to be manually updated after simulations if the design needs to be altered after the energy simulations. This unidirectional approach of information exchange is unable to inform building design in a streamlined manner. Approaches based on automatic bi-directional exchange of data workflows, enable designers and architects to make parametric changes to the BIM model and simulate the energy performance or other performance aspects simultaneously for example: Asl et al. (2013) and Turrin et al. (2011). Even though at an experimental stage, such approaches have paved the path for enhanced decision-making capability, and it remains curious if we see the influence of this trend applied in AEC practice at large.

### 3.2.2 Environmental performance

The assessment of embodied environmental impacts (all impacts related to materials and products such as impact because of extraction of raw materials, manufacturing, transportation, installation etc.) happens by combining the information about material types and quantities with the data of the environmental impacts of these materials (Alwan and Jones, 2014; Wang *et al.*, 2011). BIM supports the assessment of embodied impacts by offering the rapid assessment of material quantities (Jalaei and Jrade 2014). Also, Matthews and Capper (2012) and Kulahcioglu et al. (2012) suggest that the consideration of embodied impacts can be done by combining environmental data about materials and products with model-based information about quantities based on the model using IFC as a data sharing format. The external data can be taken from product libraries with the help of IFC-based implementation (Soubra *et al.*, 2012). IFCs also incorporate a mechanism called Property Sets. As explained earlier, this allows the information provider to allocate new properties to an object in a BIM model and consider different kinds of embodied impacts. ILMARI (VTT Technical Research Centre of Finland, 2017) and ELODIE (CSTB, 2017) are examples of publicly available tools for BIM-based environmental assessment. ILMARI combines IFC-based quantity take-off data from design software with generic carbon footprint data of products saved in ILMARI software. ELODIE combines external Environmental Performance Data (EPD) with quantities of building elements defined with the help of a model viewer. This allows the selection of the building parts to be included in the Life cycle assessment.

Jalaei and Jrade (2014) suggest BIM compatible plug-in tool which supports product suppliers' web pages by cataloging green components and their environmental characteristics. Basbagill et al. (2012) recommend considering embodied impacts already in early phases of design; material quantity formulas and embodied GHG emission factors can be embedded in the BIM authoring tool. Also, Diaz and Anton (2014) and Anton and Diaz (2014) compare the benefits of two alternative approaches. First, when the assessment is done with the help of a separate assessment tool by importing the model-based quantity information via IFC, there is no need for manual data transfer. However, the effects of any changes in the design can only be evaluated by going back to the model and re-importing the quantity data back to the assessment software. Second approach is to include LCA information in the BIM objects instead of using external databases that could better support designers' understanding of environmental issues in early design phases (Antón and Díaz, 2014). However, the use of external databases offers more flexibility to use various sources and easier maintainability of environmental data.

Tsikos et al. (2017) propose a method that consists of an integrated dynamic model. In this approach, Revit is used with an external material life Cycle Inventory (LCI) database in connection with the visual programming language Dynamo. There is a permanent link with unique material IDs from Revit to an external database that includes life cycle inventory-based environmental information for materials per a specific functional unit ($m^3$ or $m^2$). The material take-off and environmental information are collected in the same script and finally exported in a new excel sheet which generates necessary graphs and charts. Similarly, Abanda el al. (2017) also address the problem of material IDs, where they manually edited 57 concepts in Revit material database to use as input in their proposed system. To apply British New Rules of Measurement 1 (NRM), they used Naviswork as an intermediary to avoid the loss of information about structures while following the NRM methodology. NRM ontology was mapped to XML codes loaded in Navisworks and were then exported to a spreadsheet using Revit as an interface. The environmental information based on Bath Inventory of Carbon and Energy was structured accordingly.

Several solutions have been presented for the linkage of quantity data and environmental data in BIM-based environmental assessment procedures, but none of them are generic. The problem of linking environmental data becomes more complicated when different environmental data sources are required to be used during the assessment process. During concept, developed and technical phases of design (see Table 3) generic data is needed as the specific manufacturers and their specific products have not yet been selected. Nonetheless, during the construction phase, the environmental impact should be calculated based on as-built information, and correspondingly specific data should be used available in environmental product declarations (EPDs).

### 3.2.3 Indoor air quality assessment

Indoor air quality plays an intrinsic role in occupant comfort, and should be evaluated as a key building performance evaluation criterion. Indoor air quality modelling categories include, statistical models eg., SHAPE (Ott, 1984), material/mass balance models eg, RISK (Sparks, 1996) and CONTAM, and Computational Fluid Dynamics (CFD) models (Sparks, 2003). The Multizone Airflow and Contaminant Transport Analysis Software (CONTAM) is suitable for assessing indoor air quality (IAQ) in multi-zone buildings for e.g., with multiple rooms and floors (National Institute of Standards and Technology (NIST), 2017). A number of studies have integrated multi-zone indoor air quality and fluid dynamics computation with energy simulation software, such as TRNSYS and EnergyPlus, to evaluate the relationship between IAQ and building energy consumption (Deru *et al.*, 2011; Dols *et al.*, 2016; Drogemuller, 2006; Laine *et al.*, 2000; McDowell *et al.*, 2003; Ng *et al.*, 2012, 2015, 2018). Chen et al. (2015) describes an integrated simulation environment for energy efficiency and IAQ analysis with the help of EnergyPlus and an enhanced CHAMPS-Multizone model. It enables the simulation of combined heat, air, moisture, pollutant transport and daylighting for a whole building. Salis et al. (2017) describes the complexity of assessing IAQ in low-energy buildings and proposed four IAQ indices as part of IEA EBC Annex 68 to provide a quantitative measure. In the same study, they also reported that there is too limited data on the level of indoor air pollutants in low-energy residential buildings. Availability of limited data further deepens the challenge of providing reference values to compare the obtained IAQ simulation results (Ng *et al.*, 2012).

Input data required for the simple modelling of IAQ can be broadly categorized under physical condition (location or building), chemical contaminants (indoor/outdoor), biological contaminants (indoor/outdoor), etc. Depending on the type of analysis required, contaminate transport analysis can be performed for e.g. $CO_2$, Ozone, particulates less than 2.5 μm and generic volatile organic compounds (Hussein and Kulmala, 2008). IAQ assessment requires information about indoor pollutants as input data and much of this data is dependent on the activities carried out in the building during occupancy is difficult to be captured in BIM-based model. Recent research efforts have focused on proposing extensions to IFC data set for IAQ properties, such as including the concentration of $CO_2$ during occupancy and formaldehyde concentrations (Huovila *et al.*, 2014). However, IAQ is very complex due to a plethora of chemical compounds in the indoor air, and the information needed to fully comply with perceived air quality measures are too detailed to be captured by an IFC model on one particular dynamic calculation tool. Research efforts are needed in this direction, as IAQ should not be over looked to be applied only during the buildings 'use phase', similar to that of thermal comfort as discussed by Huovila et al. (2014). The part of the input data required for the IAQ assessment during the early phases of design such as a type of the building, expected occupancy, and details of the HVAC from the technical design phase can be obtained through external product libraries which could be linked to BIM.

### 3.2.4 Lighting assessment

Factors such as in-depth illuminance, luminance, and daylight glare probability are calculated by specific software solutions such as DIALux (DIALux, 2017a), Radiance (Berkeley Lab, 2017), ReluxSuite (Relux Informatik AG, 2017) and others (Acosta *et al.*, 2015). In April 2017, DIALux became the first lighting specific software to release IFC import functionalities allowing the import of BIM-based models (DIALux, 2017b). Even though, it support import of only few objects, and export functionalities are underdevelopment and are expected to be released in 2018 (based on e-mail communication). Lighting simulations such as Radiance use three-dimensional geometrical description of a scene and physical properties of materials as input data. It is possible to store the information about the properties of a lighting fixture and its photometric data in the BIM-based model and this data can be transferred to simulation in theory, though external databases of photometric data are used for example by DIALux and Relux (Ochoa *et al.*, 2012). There are also several examples of semi-automated and computation approaches where energy simulation has been integrated with in-depth lighting studies (Mavromatidis, 2015; Mavromatidis *et al.*, 2014; Tagliabue *et al.*, 2012). BIM does not have all the information that is necessary for creating the simulation input files for Radiance but it provides options to incorporate the required information. Kota et al. (2014) presented a method to enable direct integration of BIM with daylighting simulation tools. The same study identified that the representations of some elements are not identical between Revit and Radiance; for example, a glass pane represented with a thickness in Revit has to be represented as a surface without a thickness in Radiance. Their prototype creates input files from Revit models to Radiance and DAYSIM simulation tool through automated steps with high accuracy.

There seem to be two kinds of approaches for lighting simulations, the first where the calculation algorithms are embedded in the BIM authoring software and second, where the assessment uses proprietary software-developer-specific file formats for design software. For example, Liu et al. (2015) introduce the use of Ecotect Analysis BIM software produced by Autodesk in lighting performance and thermal performance simulations, however, Ecotect Analysis is now discontinued (ECOTECT, 2015).

### 3.2.5 Acoustical performance

The acoustic simulation process consists of fundamental steps of collecting necessary data about acoustic qualities of the architecture, simulating sound propagation, modifying a sound sample with the simulation results, and listening to simulated sound (known as auralisation) and inspecting the sound characteristics both numerically and graphically (Wu and Clayton, 2013). Four sets of input data are needed when performing an acoustic simulation of an indoor space: the geometry of the room, finish materials of the room with the absorption characteristics at various frequencies, sound source, and audience (Wu and Clayton, 2013). An approach of developing IFC assembler program that would both read and write to the IFC file refer to the construction database to populate IFC file with corresponding acoustical properties (Vedvik and Mooney, 2011). BIM has the potential to deliver information of room geometry and its material characteristics. For example from Citherlet and Hand (2002, p. 849), “an office room might be modelled as a single thermal zone for the energy performance analysis. In this case, the acoustic zone boundaries correspond to the thermal zone boundaries and the volume used to assess the reverberation time is equal to the volume delimited by the thermal zone’’. Mapping essential parameters such as sound intensity level, reverberation, absorption coefficient and transmission losses can be directly extracted from BIM-authoring software. There is evidence from construction industry manufactures who released their acoustic slabs as BIM objects (Paroc Group Oyj, 2014) and produces their own EPD’s with third party certification (Paroc Group Oyj, 2016), but the commonly used acoustic software’s are not interoperable with IFC.

There are many commercial software applications for acoustic simulations such as (CATT-Acoustic, 2011; EASE, 2017; Odeon, 2017; RAMSETE, 2007; SoundPlan, 2017) among others. For prediction and evaluation of noise barrier performance, tools such as that of CadnaA noise prediction software (DataKustik GmbH, 2017a), CadnaR-calculation and Assessment of Interior Sound (DataKustik GmbH, 2017b), Bastian-building acoustics planning system (DataKustik GmbH, 2017), LimaA (Softnoise GmbH, 2017) environmental noise projects, Immi, MicroBruit are used. For the computation of noise at building projects such as that of airport, cityscapes ECAC Doc. 29-Interim, Predictor 8.11 is commonly used (Sari *et al.*, 2014) .Some of these applications allow the import of geometry representations produced by CAD programs and permit the user to assign absorption coefficients to each face (Wu and Clayton, 2013). Although these applications require additional work to assign acoustic properties to each face, some of them are proven to be excellent in accuracy (Bradley and Wang, 2007; Vorlander, 2010). However, there is greater risk of input uncertainty, model uncertainty and uncertainty in assignment of noise level (Shilton, 2017).

Possibilities for BIM integrated acoustical analysis are presented by, e.g. Lepage (2010) and Sunvoung *et al.* (2013), but neither represent an IFC-based approach. Deng et al. (2016) achieved BIM and 3D GIS noise mapping by developing a data integration engine to allow bidirectional conversion between major data schemas in BIM and GIS in a virtual design and construction (VDC) process using Italian C.N.R. model. The trend of virtual reality in AEC industry is already catching up with acoustics engineering. For example, Cundall Virtual Acoustic Reality (VAR) links a 3D graphics program,-Unity, with the CATT Acoustic software which allows the stakeholders to immersive audio visual experience in a virtual building environment (Cundall, 2016).

To summarise, two kinds of approaches have been presented in research for utilising BIM: the first retrieves only geometry information from BIM and adds acoustical characteristics of spaces using an acoustical database (Vedvik and Mooney, 2011); in the second approach, BIM is first "enriched" by inputting acoustical characteristic parameters into the model and then all of the data is extracted from BIM to the simulation engine (Wu and Clayton, 2013).

During the literature search, the authors exhausted a broad range of keywords, and in fact could not find publications integrating BIM and Acoustic simulations. This study reconfirms that there is no scientific evidence of the current commercial software to the knowledge of authors that can use “enriched" BIM that includes acoustic data. From the viewpoint of simulation tools, BIM files are complex and include unnecessary information. Typically, BIM data will have complex textural information and metadata. The inclusion of this data for room acoustic prediction requires much simplification together with a rendering strategy that presents the most subjectively important features of the soundscape while preserving validity as stated by Drumm and O'Hare (2015).

### 3.2.6 Tools and platforms for integrated design assessment and enriching BIM

There is not yet a single way to comprehensively utilise BIM-based model data for assessing several performance aspects of a building. The research on integrated BIM tools (BIM platforms, BIM servers, collaboration tools, project data management tools) focuses especially on data storage and sharing, communication, and workflow management related features (Jaradat *et al.*, 2013; Singh and Gu, 2012). Also, Chen et al. (2015) claim that there is a general lack of studies on BIM interoperability among different BIM software. However, some research has been conducted on tools which would integrate multiple assessments to one platform unifying design and calculation tool (Aouad *et al.*, 2005; Negendahl, 2015), offer an integrated framework for BIM-based performance optimisation (Jalaei and Jrade, 2014), or provide processing of BIM models so that multiple assessments can be run with them (Sanguinetti *et al.*, 2012). According to Charalambous et al. (2012), the potential of BIM combined with online collaboration platforms, provides an opportunity for addressing many building industry obstacles such as fragmentation and adversarial relationships.

nD-modelling (where 'n' is the number of dimensions 'D' which can be interpreted as parameters) tool prototype presented by Aouad et al. (2005) aims at aiding an integrated design. The target is to integrate some design dimensions into a holistic model, which would encourage and support the project team to systematically assess and compare the strengths and weaknesses of different design scenarios. The greatest benefit of this approach was the capture of knowledge without losing data. However, they reported that interoperability should be considerably developed to enable 'what-if' analyses of buildings.

Pinheiro et al. (2015) proposed a BIM-based life-cycle performance evaluation framework to improve building performance analysis. The paper describes an IDM/MVD mechanism that provides a structured framework for the definition and exchange of building data for building performance analysis by gathering all information from heterogeneous sources and by converting it to a common data format. The result is an IFC compliant framework for the assessment of buildings. However, the authors found out that technical documentation for the MVD is still missing.

Investigation by Sanguinetti et al. (2012) offered a post-processing approach for BIM models to run multiple analyses based on a single BIM model without the designer having to prepare the model separately for each analysis. The presented examples include space program validation, circulation validation (requirement of user-specific access to specific parts of the building), cost estimation and energy analysis. A tool was generated to extract data from BIM and embed domain-specific requirements for different analysis tools. Similarly, Bakis et al. (2007) discussed the need for such intervening tools.

One of the draw-backs in IFC-based interoperability is that whenever the model is updated (and new IFC file is generated) the linkage of the input data from BIM and other analysis specific input data has to be started over. Improved functionality should be developed to retrieve the changes in IFC file to ease the update process regarding simulation parameters (Vedvik and Mooney, 2011). Another general challenge is the possibility to export results of the best-developed solutions back to the design BIM model. Currently, the bi-directional dataflow solutions are at an experimental phase thus not generic enough to be applied.

The BIM model has to be manually updated after BPS requiring design to be altered according to the obtained results. Based on the above findings from the literature review, it is clear that even though we have made progress within the scientific community on utilizing and enriching BIM, we are still struggling with the implementation of exploiting the availability of the BIM-based data for BPS-based assessment in real building projects. The following section focuses on the current challenges faced by the AEC industry. Table 4 presents the summary of the literature review linking BIM-based models to BPS tools.

*Table 4: Literature review linking BIM-based models to BPS tools*

| **Tools for assessing performance based design** | **Name of the tool and origin** | **Capability** | **Import/Export via IFC 2X3 compatibility corresponding to the tool** | **Examples of required input data in BPS tools** | **Linking BIM-based data with BPS-based simulation*** |
|---|---|---|---|---|---|
| **3.2.1 Energy performance** (Heating energy, cooling energy, HVAC systems and thermal comfort) | IDA ICE, EQUA Simulation AB, Sweden | Energy simulation | Import (buildingSMART International, 2017d; EQUA Simulation AB, 2011) | Ahmed et al. (2015); Hilliaho et al. (2015); Jung et al. (2018); Soleimani-Mohseni et al. (2016) | Giannakis et al. (2015); Jung et al. (2018); Nageler et al. (2017) |
| | RIUSKA, Granlund Oy, Finland | Comfort and energy simulation. Software based on DOE-2 | Import and Export (buidlingSMART International, 2017a) | Mitchell et al. (2007);<br>Pietaril, (2013) | Gupta et al. (2014); Laine and Karola (2007); Lilis et al. (2017);<br>Maile et al. (2007) |
| | Simergy, LBNL, USA | Building Energy Modeling (BEM) front end to DOE EnergyPlus simulation engine | Import (buidlingSMART International, 2017b); Export (Lawrence Berkeley National Laboratory, 2017) | Cao et al. (2014); Lawrence Berkeley National Laboratory (2017) | Chen et al. (2017); Remmen et al. (2015) |
| | OpenStudio, NREL/U.S. DOE, USA | BEM using EnergyPlus and advance daylighting using radiance | Import (buidlingSMART International, 2017c) | Bazjanac et al. (2011); Cho et al. (2009); Tagliabue et al. (2012) | Lee et al. (2015); Parker et al. (2017) |
| | IESVE, offices worldwide | Integrated Environmental Solutions (IES) Virtual Environment (VE), Multiple integrated application | Import (buidlingSMART International, 2017d); interoperable with Revit, Sketch up, DXF, gbXML and Vectorworks (Integrated Environmental Solutions Ltd., 2017) | Cho et al. (2009); Micono and Zanzottera (2015); Mostafavi et al. (2015) | Habibi (2017) |
| | Energy Plus U.S. DOE, USA | Energy simulation console-based program | Indirectly interoperable with IFC. (1) can translate IFC file to Energy plus using GST and BimServer (a native IFC database) OpenStudio plug-in for example Senave and Boeykens (2015); (2) can be linked to co-simulation programme by using- one to one coupling, middleware coupling and via Functional Mock Ups (FMUs) as presented by Nouidui *et al.* (2014); U.S. Department of Energy (2017) | Cho et al. (2009); Gunay et al. (2016); Garcia and Zhu, (2015); Mateus et al. (2014); Pereira et al. (2014); Yang et al. (2015) | Asl et al. (2013, 2014);<br>Choi et al. (2016);<br>Asl et al. (2015) |
| | TRNSYS, University of Wisconsin, USA | Transient system simulation tool | Not interoperable with IFC. Modular and expansible simulation environment. | Mateus et al. (2014) and many other studies | Boukara and Naamane (2015); Cormier et al. (2011); CSTB Logiciels (2017); Giannakis et al. (2015) |

| **Tools for assessing performance based design** | **Name of the tool and origin** | **Capability** | **Import/Export via IFC 2X3 compatibility corresponding to the tool** | **Examples of required input data in BPS tools** | **Linking BIM-based data with BPS-based simulation*** |
|---|---|---|---|---|---|
| **3.2.2 Environmental performance** (Life Cycle Analysis) | ILMARI, VTT Finland | Life cycle analysis | Import, the tool can import .xls based quantity take off data generated from BIM authoring software to be used as import to ILMARI | Häkkinen et al. (2015); Ruuska and Häkkinen (2015) | Jalaei and Jrade (2014); S. Lee et al. (2015); Shadram et al. (2016) |
|  | ELODIE, CSTB, France | Life cycle ELODIE uses Environmental Product Declarations (EPD) provided by manufacturers and made available through the INIES (www.inies.fr) database (Gantner *et al.*, 2012) | Import, the tool recommends to first apply FDES-French equivalent to EPDs on the BIM authoring software to embed data on IFC, which can be exported as an .xls to be used as an import to ELODIE | Chevalier et al. (2010);<br>CSTB (2017) | - |
| **3.2.3 Indoor air quality** | CONTAM, NIST, USA | Contaminant transport analysis | Not interoperable with IFC. | Salis et al. (2017);<br>Ng et al. (2015, 2018) | Altaf (2011); Y. Chen et al. (2015); Li (2013) |
|  | COMIS | Multi-zone Air Flow Modelling (COMIS) | Not interoperable with IFC. However, Energy plus V2.0 onwards include links to multi-zone air flow engine COMIS and SPARK (Maile *et al.*, 2007) | Hussein and Kulmala (2008);<br>Warren (2000) |  |
| **3.2.4 Lighting** | DIALux, DIAL GmbH, Germany | Simulation software to design, calculate and visualize lighting | IFC import available in version DIALux evo 7.0 released April 2017(DIALux, 2017b); IFC export capabilities expected in 2018 (based on email correspondence with DIALux) | Acosta et al. (2015); Jayashri and Arvind (2013); Kovacic and Zoller (2015) | Mavromatidis (2015);<br>Mavromatidis et al. (2014);<br>Tagliabue et al. (2012) |
|  | ReluxSuite, Relux Informatik AG, Switzerland | Simulation software for artificial light and daylight | Not interoperable with IFC. For input, gbXML can be used to import 3D geometry, ReluxCAD available as an add-on to Autodesk Revit for specific lighting tasks, exports results in DWG/DXF (based on email correspondence with Relux) | Acosta et al. (2015); Ochoa et al. (2012); Shailesh and Raikar (2010); Yu et al. (2014) | - |
|  | Radiance, Berkeley Lab, USA | Suite of programs for the analysis and visualization of lighting in design | Not interoperable with IFC. | Naboni (2013); Torres and Sakamoto (2007);<br>Ward (1994) | Kota et al. (2014); Manzan and Pinto (2009); Santos et al. (2017); Welle et al. (2012); Yi and Kim (2015) |
|  | DAYSIM | Simulation engine with plug in capabilities, based on RADIANCE | Not interoperable with IFC. Can import raw input files in 3D model (.obj, .dxf), plug in capabilities: Sketchup & Rhinoceros | Acosta et al. (2015); Flodberg (2012); Flodberg et al. (2012); Reinhart and Wienold (2011) | Caldas and Santos (2016);<br>Gadelhak and Lang (2016);<br>Kota et al. (2014) |

| Tools for assessing performance based design | Name of the tool and origin | Capability | Import/Export via IFC 2X3 compatibility corresponding to the tool | Examples of required input data in BPS tools | Linking BIM-based data with BPS-based simulation* |
|---|---|---|---|---|---|
| **3.2.5 Acoustical performance** (Geometry of the room, sound propagation, auralisation). | ODEON A/S | Simulating and measuring the interior acoustics of buildings | Not interoperable with IFC. Import of DXF (Drawing Exchange Format) and 3DS format files from CAD software such as: AutoCAD®, Microstation®, 3DS max, IntelliCAD®, Google-Sketchup and Rhino | Gul and Caliskan (2013); Naylor (1993); Passero and Zannin (2010); Rindel (2000, 2002); Zhu et al. (2015) | (1) IFC as schema for BIM, & City Geography Markup Language (CityGML) used to present 3D GIS schema (Deng et al., 2016)<br>(2) Robust Acoustical Templates (RAT) integrated with IFC assembler program (Vedvik and Mooney, 2011)<br>(3) A software porotype using Autodesk Revit, the Revit API, the DirectX toolkit, and C# programming in Visual Studio (Wu and Clayton, 2013) |
| | CATT-Acoustic | For room acoustics prediction and auralization | Not interoperable with IFC. Support AutoCAD or other CAD plugins, can export VRML 2.0 export. File conversion utilities available for MATLAB .MAT, MLSSA .TIM, .WAV, Lake .SIM, | Alvarez-Morales and Martellotta (2015); Sequeira and Cortínez (2016); Sunyoung et al. (2013) | |
| | CadnaA, CadnaR, Bastian, Datakustik GmbH | Environmental noise, psychoacoustic parameters for workplace noise and airborne and impact sound transmission between rooms in buildings | Not interoperable with IFC. CadnaA, linked to GIS, support many BMP bitmap-file formats (PSD, DWF, IFF etc.); Bastian can import sketch files (BMP/JPG), noise emission spectra from CadnaA. | Hao and Kang (2014); Margaritis and Kang (2016); Silva et al. (2014) | |
| | SoundPLAN GmbH | Modular design: Geo-database, road, railway, industrial noise indoor, noise maps, aircraft noise, etc. | Not interoperable with IFC. Interface available for DXF, ASCII sources, LIMA BNA file, ESRIU Shape file, QSI, DBF, ASCII elevation grid, TNM etc. | Bunn and Zannin (2016); Magrini and Lisot (2015); Ozkurt et al. (2014, 2015) | |

## 4. RESULTS OF THE INTERVIEWS

This section presents results of the interviews by explaining different viewpoints to highlight the common practices for conducting simulations and the pertaining problems as experienced by the interviewees (objective 2), if the current simulation methods support performance-based design (objectives 1), and what is needed to improve the current practice (objective 3). This section is split into the qualitative (section 4.1) and the quantitative (section 4.2) results of the expert interviews.

Architects and designers go through several phases of design during the design process of a building; 'Plan of Work' provides the description and guidelines for the design process. Accordingly, Finnish plan of work ARK12 (2013), RIBA plan of work (2013), and the American Institute of Architects (2012) used by architects was set as a podium to align the results of the interviews with the design process. This was prepared to gain understanding of the respondents opinion, in terms of which phase of design use of BIM performance-based assessment is implemented. Table 5 presents the importance of BIM utilization is different phases of design. Correspondingly, Section 4.1 is structured as (i) Briefing, Preparation, Concept design, Developed design phases; (ii) Technical design and Construction phases; (iii) Building In-use and warranty period phase.

Table 5: Phases of design in accordance with RIBA/ARK/AIA plan of work and the number of interviewees who pointed out the importance of BIM in different phases of design.

| **Plan of Work** | **Corresponding design phases of Finnish, British and American Architects Plan of Work** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Arkkitehtisuunnittelun tehtäväluettelo (ARK) Plan of Work 2012 (ARK12, 2013) | 0<br>Briefing | 1<br>Preparation | 2<br>Concept design | 3<br>Generic design | 4<br>Building permission task<br>5<br>Technical design | 6<br>Preparation for construction<br>7<br>Construction | 8<br>In use<br>9<br>Warranty period during use | |
| Royal Institute of British Architects (RIBA) Plan of work 2013 (Royal Institute of British Architects, 2013) | 0<br>Strategic definition | 1<br>Preparation | 2<br>Concept design | 3<br>Developed design | 4<br>Technical design | 5<br>Construction | 6<br>Handover and close out | 7<br>In-use |
| The American Institute of Architects (AIA) (The American Institute Of Architects, 2012) | 0<br>Project brief | 1<br>Pre-design/ concept | 2<br>Schematic | 3<br>Design development | 4<br>Construction documents | 5<br>Bidding<br>6<br>Construction | 7<br>Commissioning<br>8<br>Occupancy | |
| Importance of BIM in different phases of design | 6 | | 13 | 14 | 14 | 8 | 1 | 1 |

## 4.1 Qualitative results of the interviews

(i) Briefing, Preparation, Concept design, and Developed design phases: Architectural modelling typically starts in the concept design phase but the aim is to utilize BIM already in early design phase starting from the briefing phase. The main phases of BIM utilization are developed design phase and technical design phase (Table 5). Usually, the first purpose of the BIM-based model is to study the massing (sometimes also energy performance), landscape and urban setting of a building. The interviewees noted that, in Finland, architects seldom use energy performance assessment tools (like EcoDesigner included in the architectural modelling software ArchiCAD). Their reasons include the assumed complexity, unwillingness to model the required details and uncertainty of the validity of results. Some interviewees expressed that the use of calculation tools is very time consuming and simulations should mainly be conducted by the engineers specialized in that particular assessment. Interviewees reinforced that the iterative approach is important in designing for high-performance buildings and thus simulation tools are especially needed in collaboration with the engineers. On the other hand, some interviewees addressed that tools are useful only if they do not give too self-evident results (like "decrease windows to improve energy-efficiency"). Only a few interviewees said that alternative models are created in projects to find the best options for low energy design and sustainable buildings. They emphasised lack of data and the need to develop better access to different kinds of external data (such as product data, geographical data, etc.) needed in the performance assessment. At present, especially the lack of product data or the lack of access to product data hinders the management of certain performance criteria such as service life and maintainability. The interviewees said that much better compatibility of building models and geographical information systems (GIS) models should be developed. Data transfer between computer aided design (CAD) model and GIS model is difficult. However, GIS-data is very useful for many design issues such as consideration of windiness and solar radiation.

Modelling authoring process: The interviewees addressed that the cooperation between different designers, architects and engineers typically starts too late. Every time a new discipline is introduced to the design, changes typically take place. A lot of rework is caused, and at worst case, the design schedule does not allow one to make all changes that would be needed to make the design optimal. Compromises are made between project schedule and performance assessment and design. The interviewees also pointed out that the accuracy and the Level of Detail (LOD) of the model is an essential issue to determine its usefulness. If the level of detail is too high, this demands too much work and makes the use of the model complicated and thus the overall usefulness decreases. If the level of detail of the model is not high enough, the possibility to use it as the basis for assessments is impaired. Thus, the information creation process and its flow are not yet matured and need development. The interviewees also said that tools to assess design in different levels of development are needed. According to interviewees, BIM is still weak in supporting cost-efficient design and construction. There is a need for BIM compatible tools that actually support monitoring and iteration of cost in different phases.

(ii) Technical design and Construction phases: Structural engineers use BIM-based models mainly in the developed and technical design stage but sometimes already in early stages of design. HVAC engineers use BIM in developed design stage mainly for defining space requirements. Actual HVAC modelling is done in the technical design phase and onwards. Tools like IDA ICE and the Finnish RIUSKA can retrieve IFC-based data from the model (Gupta *et al.*, 2014; Harish and Kumar, 2016). Typically, HVAC engineers conduct energy performance assessment in concept and developed design phases and use architects' 3D model. Nevertheless, for this purpose, HVAC designers create a separate specific energy model due to inappropriate or incomplete data required in terms of conducting energy performance assessment. During the design process, a lot of calculations and simulations are conducted by the experts with separate tools and often without any linkage to BIM-based models as input data. Many interviewees spoke about the data contents and the related lack of data. One HVAC designer pointed out that the design models include types of information which is not required during the operation phase. In the opinion of the interviewees, both data content and processes (including the maintenance and updating responsibilities of information) should be developed to better utilise BIM during facility management.

Contractors use BIM in the construction phase for production scheduling. Visualization benefits a lot in planning timetables and scheduling work. Large-scale building contractors in Finland develop their skills in using BIM to effectively lead the construction projects. Whereas the interviewees noted that very seldom contractors are seen utilizing BIM during the design phase for steering design and assessing options, although this is largely dependent on the type of the delivery model and the role of the contractor in a specific building project.

(iii) Building In-use and Warranty period phases: property owners addressed that models are used for better communication through the design process between the client, users, and designers. Seldom owners or their consultants are seen to use BIM in steering the design and assessing options in the design phase. The interviewees did not refer to any systematic way to use pre-existing BIM models during the use phase of the building. The most urgent task on the basis of the interviews is to enable utilisation of modelled data during building operation. The maintenance guidance should be linked to the model. In addition, the BIM objects could carry useful information about products and their care and maintenance needs, and the information could be searched and visualised in the model (for example "show all rooms with the same flooring type"). It was noted that, often the building does not perform as designed, needs system overhauls and later during the use stage care and maintenance of systems is needed. This would become an easier task if pre-existing BIM data were available to support the multiple renovation cycles during a lifetime of a building.

## 4.2 Quantitative results of the interviews

It was found that the main motivation of utilizing BIM by the interviewees is either the client requirement or actors own experience of BIM bringing abundance of benefits by streamlining the design and construction process. Most of the interviewees emphasized both of these criteria. Benefits of utilizing BIM in projects addressed by interviewees are presented in Figure 2. For data analysis and to understand the opinions of interviewees better, they were divided into two groups. Group 1 includes architects, designers, structural and HVAC engineers who are more focused on the design activities. Group 2 represents the project and design managers and BIM coordinators who are focused on the time and scope management of the project and coordination of design and modelling work.

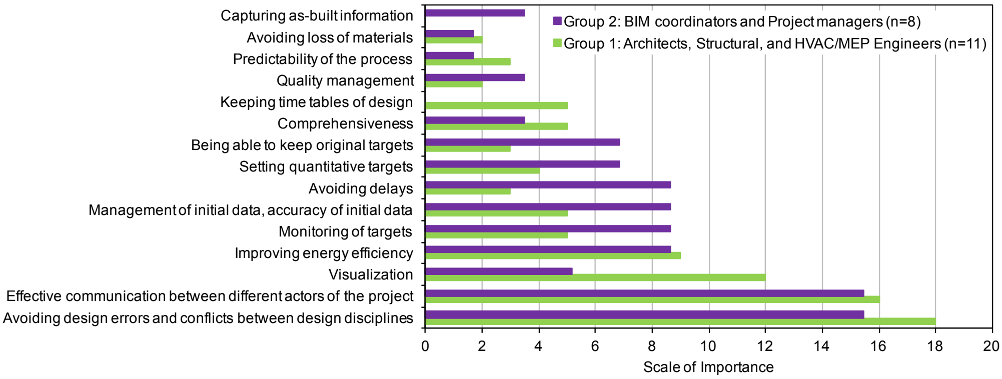

*Figure 2: Benefits of utilizing BIM in projects. The responses of group 1 (11 interviewees) were proportioned by multiplying with a size ratio of the group to eliminate the effect of the difference in the number of respondents in group 2 (8 interviewees).*

As shown in Figure 3 all interviewees were asked to give zero, 1 or 2 points where zero point denotes the least important and 2 points as the most important benefit observed by them based on their experience (x-axis). The choices presented in y-axis were based upon already established benefits of BIM obtained through literature study before preparing the questionnaire.

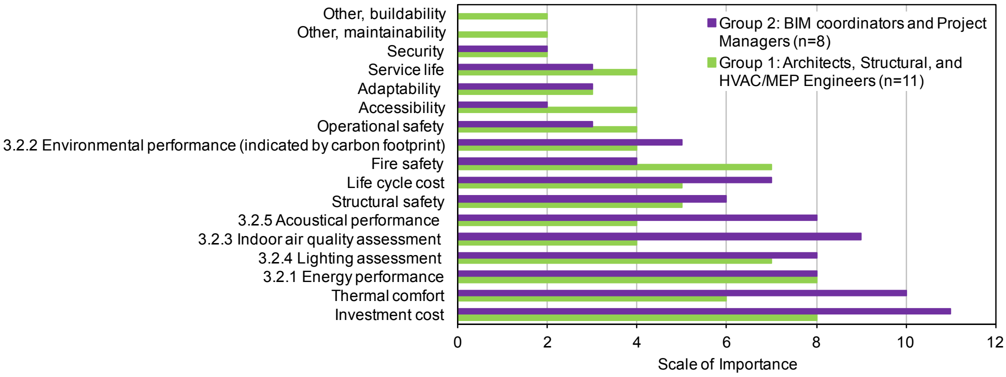

*Figure 3: Performance aspects that should be assessed with BIM compatible tools during the design process. All interviewees were asked to denote zero, 1 or 2 points for each aspect based on the importance of the performance aspect in ascending order*

BIM supports all actors both within one discipline (like architects to design for better accessibility and flexibility) and across design disciplines, enhancing the communication between the client and designers. Designers and other interviewees were found to have slightly different answers. Managers believe that BIM adds control (e.g., keep targets, monitor targets, avoid delays) while modellers (architects and engineers) value the visualisation. Communication and avoidance of design errors were seen important by all interviewees. HVAC designers addressed that an important motivation is the possibility to utilize the model data for different kinds of simulations. At present, BIM-based data is used for the assessment of energy performance, bill of quantities and costs, and sometimes for the assessment of carbon footprint and barrier-free design. These building performance and Life cycle aspects are evaluated with the help of tools that use BIM-based data.

As presented in Section 4.1 (qualitative) and Table 6 interviewees were asked to freely describe the current use of BIM and address needs for development to improve the performance-based design. The issues seen most important by the interviewees focused on (1) need to develop iterative approaches in sustainable building design, (2) need of support for multi-criteria performance analyses and comprehensive consideration of different performance aspects in collaboration with different designers and other stakeholders, and (3) integration of information, which is needed during operation and in use phases, where pre-existing BIM data can be used after the project is completed. Almost all of the aspects presented in Table 6 were seen as possible through a holistic BIM-based design approach to facilitate and support comprehensive performance assessment of a building by all stakeholders. Table 6 presents the aspects addressed by the interviews in the left column, and the right column presents the number of interviewees who address the same aspect as others. This information was post-processed by the authors to simplify readability and understanding.

*Table 6: Current way of using BIM and development needs related to BIM and performance based design addressed by the interviewees*

| **Current way of using BIM** | | No. of interviewees who addressed this issue |
|---|---|---|
| BIM and design phases | The main phases of the use of BIM are developed design phase and technical design phase | 14 |
| BIM and simulation tools and comparison of alternative models | Architects seldom use energy performance assessment tools | 5 |
| | The use of calculation tools is very time consuming and simulations should mainly be done by engineering specialists | 2 |
| | A lot of simulations are done by experts with separate tools and often without linkage to BIM as input data | 2 |
| | Alternative models are created seldom to find the best options for low energy design and sustainable building | 3 |
| Cooperation and communication during modelling | Cooperation between different designers typically starts too late | 3 |
| | Models are used for better communication (between the client, users, and designers) in the developed design stage | 3 |
| **Development needs** | | No. of interviewees who addressed this need |
| Better version control, saving of models for later use and rational design flow | | 6 |
| Solutions to avoid incompatibility issues among different software | | 6 |
| Solutions for iterative approach in sustainable building design in collaboration with engineers | | 9 |
| Better compatibility of BIM models with geographic information systems models and the neighbourhood information models | | 3 |
| More BIM-compatible simulation tools (for example for energy and cost assessment) that can be used in early phases of design | | 3 |
| Possibility to provide the pre-existing BIM data for the use of maintenance processes after the construction project is completed | | 6 |
| BIM compatible tools for service life design | | 6 |
| Support for multi-criteria performance analyses and comprehensive consideration of different performance aspects in collaboration with different designers and other stakeholders | | 7 |
| Easy-to-use BIM compatible tools for the assessment of carbon footprint and other simulations | | 4 |
| Better support for life-cycle cost assessment and design | | 5 |
| Better linkage to external product data to support environmental design, service life design, or any other performance aspects which require product specific data as input parameters | | 4 |
| Easy-to-use BIM compatible tools for lighting simulation | | 3 |
| Visualization of the simulation results with the help of the model | | 3 |

# 5. DISCUSSION

## 5.1 Future need for performance-based design simulations using BIM-based models

The current potential of BIM for *energy performance assessment* is very high, based on our literature analysis and results obtained through the expert interviews. The main motivation and driver has been the ever-increasing regulations BPIE (2015); European Commission (2012); European Parliament (2010). From the 'availability of tools' point of view, multiple methods and tools exist as presented in the literature review (section 3.1) and capabilities are improving tremendously for example coverage of information retrieved from the model with the help of IFC is high about the requirements of energy simulations. However, high accuracy is needed from the modeller. At present, energy simulations are often done without a linkage for a BIM model. Establishing bi-directional sharing between the IFC data model and the simulation model is one of the limitations that will form the basis for future developments in renewable energy simulation methods (Gupta *et al.*, 2014).

At present, clients' requirements for energy performance are often moderate and can be reached with standard solutions and thus iteration is seldom done. However, the willingness of clients and designers for iterative design process varies, and this may be a strengthening trend especially when requirements for net-zero energy building and plus-energy building has become stronger. The interviewees acknowledged the need for BIM compatible tools for multi-criteria assessment and iterative design processes. Multi-criteria assessment, simultaneous visualization of multiple aspects and optimization are all valid goals. The first actual need for multi-criteria assessment might be the design of zero-energy buildings (ZEBs) in the future. In the design for ZEBs, the energy efficiency must be assessed simultaneously with designing and assessing other performance aspects. The managers (Group 2) valued the indoor environment (IAQ, Acoustics and Thermal comfort) much higher than the designers (Group 1). This could be because BIM managers are in continuous communication with the building owners during the project commissioning, who value the quality of the indoor environment as occupants.

The current potential of BIM for *environmental performance assessment* is high regarding the ease and clarity of approaches based on our literature analysis. BIM supports environmental analyses because the needed information about quantities can be exported from the BIM authoring software with the help of IFC and can be further linked with environmental data of building elements or building materials. The coverage of information retrieved from the model with the help of IFC is good regarding quantities, but it may require further manual handling. The main challenge is to find a good solution for dealing with material IDs. The environmental impact should be calculated based on as-built information, and correspondingly specific data available in environmental product declarations (EPDs) should be used. Different kinds of solutions are available but none of those are generic. However, the potential in practice is still moderately low from the viewpoint of willingness to perform environmental analyses in ordinary design projects. Environmental analyses are typically done in significant construction projects, which aim at sustainability certification. Especially, North American researchers have paid much attention to the potential of BIM to support sustainability (green) certification analyses. However, many European countries are now increasingly emphasizing the meaning of embodied impacts - besides operational environmental impacts - and this is also becoming an issue of building regulations (Bionova, 2017). A probable increase in the willingness to use simulation tools that assess embodied carbon footprint and other environmental impacts by combining BIM-based quantity information with EPDs is expected.

The current potential of BIM for *IAQ assessment* is rated as very low based on our literature analysis and results obtained through the expert interviews. Standards depend on the performance of the HVAC system to provide adequate ventilation to maintain an acceptable ventilation rate per person (L/s-person, see ASHRAE Standards 62.1, 62.2). Some HVAC systems modulate ventilation rates based on indoor $CO_2$ (human bio-effluent) concentrations, however, such systems do not account for the vast spectrum of particulate and gaseous air pollutants of indoor and outdoor origin that occupants are exposed too. A large proportion of pollutants that affect IAQ during the operational phase originates from indoor sources which are not modelled in BIM. Similarly, HVAC filtration and portable air purification equipment have not been modelled to be stored in BIM-based model. Working on the software specific to contaminant transport (CONTAM) and mass balance analysis (CFD) requires an IAQ expert to be part of the design team, which has not been found to be the case in any published studies to the knowledge of the authors.

Based on the expert interviews, BIM coordinators and project managers (Group 2) rated IAQ as one of the most important aspects to be assessed by using BIM. This reinforces that we need to provide designers with easy to use tools to assess IAQ at early design stages beyond fulfilling the standard requirements. There are very few studies which have integrated occupational IAQ exposure with BIM and GIS, for example: Altaf (2011) and Li (2013). The IAQ of space is affected by the usage and function of the space. This is why it is important to consider IAQ not only during the design stage but also during the building operation phase. In our hypothesis, IAQ is going to become one of the forthcoming challenges of high-performance buildings. Among many reasons, a few are, that we are moving towards tighter building envelopes by reducing infiltration and using minimum ventilation rates to reduce the electricity usage of the HVAC system. The BIM model itself has a 3D representation of all the spaces, and it can be effectively used to monitor IAQ if systems such as Wang et al., (2010) and Chen et al. (2014) and low-cost IAQ sensing networks are incorporated, eg. Saad et al.(2015).

The current potential of BIM for *lighting assessment* and *acoustical performance* is low, based on our literature analysis and results obtained through the expert interviews. Only one tool (DIAlux) used for lighting simulations is BIM compatible. Moreover, none of the acoustical simulation tool are BIM compatible although they require same geometrical and materials characteristics data as input requirement. In principle, BIM has the potential to deliver information of room geometry and material characteristics for lighting simulations. The same applies to the acoustical simulations. Both of these simulations are performed by specialized engineers with the help of specific tools. Question remains, how to ascertain that all of these building performance criteria's are met without having to deal with hackles of interoperability.

## 5.2 Interoperability and information processes

The literature enlightens many technical perspectives of BIM-based analyses, but interviews reveal more problems that are practical. Some of the current BIM guidance documents provided by large construction clients pay attention to building performance analysis tools in the context of BIM execution plans. In those cases, the considered aspect is typically energy performance (Sacks et al. 2016). A BIM execution plan (The Computer Integrated Construction Research Group, 2010) is a document that should specify the required information and the process to deliver it in a project. To ensure that the models are suitable for use in different simulations, the BIM execution plan must address that (Sacks *et al.*, 2016). Model Level of Development (LOD) has been proposed as a method of specifying the model content and their level of detail in different milestones of the project (Messner *et al.*, 2013). Based on our interviews, application of LOD in practice does not seem to be very clear. 'Level of Detail' is essentially how much detail is included in the model element (Reinhardt and Bedrick, 2017). 'Level of Development' is the degree to which the element's geometry and attached information have been thought through – the degree to which project team members may rely on the information when using the model. In essence, Level of Detail can be thought of as an input to the element, while Level of Development is reliable output. The Finnish common BIM requirements (COBIM, 2012) does not refer to simulations in the context of LOD, and the focus remains on the completeness of the BIM model. There is still debate about the ability of LOD to specify BIM requirements (Bolpagni, 2016; Treldal *et al.*, 2016). The further development of processes and requirements for the LOD of the model in different design phases is needed to satisfy both needs. The better the quality of the input data, the more useful BIM-based model is for performance analyses. A good BIM execution plan should specify the level of development that is to be achieved for each building system and its elements at each milestone of the project (Sacks et al. 2016). With this, much attention should be paid to simulation tools and the quality of the needed input data. The idea of LOD should be further developed and defined corresponding to the stages of design to support iterative design process and the use of simulation tools throughout.

Although the BIM model defines structures and material content of structures and additional information can be included or linked, the nature of data is often text, which cannot be utilized – as not being decipherable – in design, procurement or during operation and maintenance. Classification and structuring of data might improve the possibilities to search and reuse this data. The need for data transfer from the simulation software back to the BIM-based model was addressed by many, which indicates the importance of this problem. Bi-directional approaches do solve this problem, but they are not generic and are user dependent. According to our literature review, there are no tools specifically certified for MVDs performance assessment. Even if in theory a mechanism exists, there is a gap between theory and practice.

The requirements for BIM have increased, especially in public building projects. In model authoring software, more possibilities exist for the presentation or capturing parameters of performance. Very detailed and accurate modelling required by sophisticated simulation software is time-consuming and may not serve for the best efficiency of the overall process. Many tools can retrieve IFC-based BIM data, but still many tools are used separately and often also independently from BIM data. The literature (Oh *et al.*, 2015) also points out that data losses may occur because the IFC format based information exchange is unable to provide complete interoperability due to structural differences of data conversion mechanisms. The lack of semantic information in the model extended by use of ifcPropertySets can be compensated by an already enriched model to supplement data extension (Asmi *et al.*, 2015).

Aspects that are relatively often assessed with the help of BIM data include costs (based on the bill of quantity); energy performance; some parameters of indoor environment (temperatures, air flows); accessibility (visual assessment, not on the basis of calculations); and embodied carbon (based on the bill of quantity). Based on the interviews, energy and thermal comfort are typically assessed separately from the architect's model. A separate model may be created for example to ensure that all needed information is correctly modelled to form an adequate basis for simulations. However, the implementation agreements (such as IDM/MVDs) for IFC do not necessarily allow exchanging all that information. At present, assessment and simulation tools are typically being integrated into the model authoring software either one by one or used separately. Energy performance (and thermal comfort) have gained most of the attention in the tools evaluating the quality of the building design. It remains curious if the implementation of MVDs will become common and solve the data exchange challenges.

Construction Operations Building Information Exchange (COBie) is applied to support the use and maintenance of the building using the MVD approach to represent the mapping between the required information from various domains (buildingSMART International, 2009, 2011). The interviewed design and simulation experts do not seem to be aware or enabled to use the MVDs in practice. Application of COBie as assessed by NBS National report in the UK is only 23% and based on Finnish BIM survey it is only 8% (Finne *et al.*, 2013; National Building Specification, 2014). The interviewees addressed an urgent need of a systematic way to use pre-existing BIM models during the building operation phase. It remains yet to be seen if the application of COBie can support multi-renovation cycles, which will require as-built information to be rather accurate for facility management processes.

## 6. CONCLUSION

The main objectives of the study were to study the capability of BIM compatible simulation tools to support performance-based design, explain stakeholders' current ability and barriers in using BIM for performance-based design, and to identify needs of development. The results of the literature review and expert interviews reinforce that BIM is very successful in managing the performance of the project. Concurrently, this also reflects that the current practice of BIM utilization is more focused on 'performance of a project' than the 'performance of the building', and these two facets should be considered simultaneously.

New research needs and knowledge gaps were identified for integrating BIM-based models to performance-based design for Indoor Air Quality, Acoustics and Lighting to provide all key stakeholders ways to assess a building holistically with BIM across all design stages. Based on our study, the current potential of BIM for energy performance assessment was rated as high, for environmental performance assessment it was rated high from the technical point of view, but rated moderately low regarding practical application; for lighting moderately low, for acoustics low, and for IAQ very low. The most important development needs addressed by the interviewees focused on iterative design processes and rational design flow, multi-criteria performance analyses, service life design and usability of BIM in use and maintenance stages, fewer incompatibility issues among different software and better linkage with external data.

Regarding development towards performance-based design, the main challenge remains in the data exchange between BIM authoring tools and performance assessment tools. To improve data exchange - or more specifically the data set needed for different use cases of BIM-based models- more Model View Definitions should be defined and implemented to provide end users with the tools and processes they need. Observations during the study highlight the need for not only technical standardisation but also process standardisation to better understand who should provide each piece of information. To better support performance-based design along the design process and in early phases, further specifications for 'Level of Detail' and 'Level of Development' should be developed. The specifications should consider the viewpoints of performance simulations. Correspondingly, this aspect should also be taken into account in BIM execution plans. Using BIM-based models for performance-based simulations will allow us to achieve high-performance buildings together with comfortable indoor spaces for all stakeholders.

## ACKNOWLEDGEMENT

This research was performed in the HOLISTEEC project (Holistic and Optimized Life-cycle Integrated Support for Energy-Efficient building design and Construction) (609138) funded under FP7-NMP - Specific Programme "Cooperation": Nanosciences, Nanotechnologies, Materials and new Production Technologies. We would like to thank all our expert interviewees, who provided us with valuable insights through their industry experience.

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## APPENDIX 1

## INTERVIEW QUESTIONS

1. Interviewee's name and contact information
2. Short explanation of the role of the company in projects. What is your relation to design or design management?
3. For what purpose do you need BIM in different phases of design?

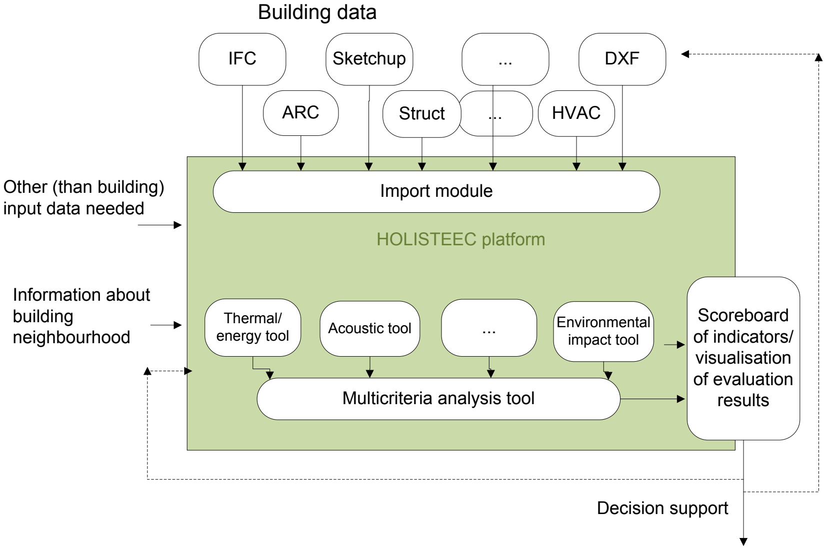
   The phases are predefined as follows.

   - Preparation and brief
   - Concept design
   - Developed design
   - Technical design
   - Construction
   - Handover
   - In-use
4. What is your main motivation and driver for exploiting BIM?
5. What are the most important specific benefits of BIM?
   - ++ very important
   - \+ important
   - \- not important
     - setting quantitative targets
     - monitoring of targets
     - more efficient communication between different actors of the project
     - avoiding design errors and conflicts between design disciplines
     - management of initial data, correctness of initial data
     - comprehensiveness (simultaneous management of infra + building data)
     - predictability of the process
     - avoiding delays
     - improving energy efficiency
     - keeping time tables of design
     - being able to keep original targets
     - avoiding loss of materials
     - other (define)
6. Which are the most important performance aspects the evaluation of which need BIM compatible tools
   - ++ very important
   - \+ important
   - \- not important
     - indoor air quality
     - thermal comfort
     - acoustics
     - lighting
     - fire safety
     - structural safety
     - operational safety
     - security
     - accessibility
     - flexibility
     - service life
     - investment cost
     - life cycle cost
     - energy performance
     - carbon footprint
7. What aspects should be quantitatively monitored (by setting a quantitative target which can be compared to calculated/assessed result)?
   - indoor air quality
   - thermal comfort
   - acoustics
   - lighting
   - fire safety
   - structural safety
   - operational safety
   - security

    - accessibility
    - flexibility
    - service life
    - investment cost
    - life cycle cost
    - energy performance
    - carbon footprint
8. How are these aspects assessed? Are there proper methods and tools to deal with those aspects in different phases of design, construction and operation to ensure the targeted performance? If not, what kind of tools would be needed?
    - indoor air quality
    - thermal comfort
    - acoustics
    - lighting
    - fire safety
    - structural safety
    - operational safety
    - security
    - accessibility
    - flexibility
    - service life
    - investment cost
    - life cycle cost
    - energy performance
    - carbon footprint
9. What are the differences between new building and renovation projects in

    a) using BIM?
    b) performance assessment and assessed aspects?

10. Is there a need for simultaneous and common consideration of different aspects at the same time? Are there tools for that?
11. We are currently developing a holistic platform to support performance based design by providing a "dashboard" for the management, a requirement setting tool, simulation tools that retrieve data from the model, and a "scoreboard" to enable the comparison of results (Figure 1). How a platform like this should support performance based design? Should the platform support multi-criteria optimization?



Planned structure of the HOLISTEEC platform

12. What other features/qualities the platform should have in order to help in the current BIM process (design, modelling, communication, simulation, design management, project management)?

# Appendix B: Publication II

Tarja Häkkinen, Matti Kuittinen, Antti Ruuska, Nusrat Jung*. Reducing Embodied Carbon during the Design Process of Buildings. *Journal of Building Engineering*. Elsevier B.V., Volume 4, Pages 1-13, 2015.

Journal of Building Engineering 4 (2015) 1–13

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

# Reducing embodied carbon during the design process of buildings

Tarja Häkkinen [a], Matti Kuittinen [b], Antti Ruuska [a], Nusrat Jung [a,c,*]

[a] VTT Technical Research Centre of Finland,Espoo, Finland
[b] Aalto University, School of Arts, Design and Architecture, Espoo,Finland
[c] Aalto University, School of Engineering, Department of Energy Technology, Espoo, Finland

ARTICLE INFO

*Article history:*
Received 1 December 2014
Received in revised form
29 May 2015
Accepted 28 June 2015
Available online 21 July 2015

*Keywords:*
Design process
Low-carbon design
Embodied GHGs
Carbon footprint
Life cycle assessment

ABSTRACT

To achieve low-carbon buildings, or buildings with low greenhouse (GHG) emissions, planning must begin during the design phase of a building project. This paper evaluates the current methods as support for the design of low-carbon buildings and the significance of different design phases from the perspective of embodied carbon. Through evaluation of relevant literature, interviews with practicing architects, and a building case study, we recommend to proceed gradually across all design phases for achieving low-carbon building design. This should take place in a systematic way that describes the status, coverage, and accuracy of GHG assessments in each design stage. Furthermore, we outline the framework with the use of the Royal Institute of British Architects (RIBA) stages of design, and for each stage, we identified the objectives, typical deliverables, and milestones necessary for ensuring carbon efficiency. This will require integration of the roles and responsibilities of the relevant stakeholders, including the client, project manager, architect, structural engineer, and Heating Ventilation and Air Conditioning (HVAC) engineer.

## 1. Introduction

The building sector is the largest single contributor to global greenhouse gas (GHG) emissions. The Intergovernmental Panel on Climate Change (IPCC) synthesis report [1] also lists buildings as having the greatest estimated economic mitigation potential of all the sector-linked solutions that were investigated. The IPCC suggests that measures to reduce GHG emissions from buildings include: reducing embodied energy in buildings, reducing energy consumption of buildings, and switching to low-carbon fuels [2].

Sustainable development of buildings brings about the required performance and function with the minimum adverse environmental impact [3]. Sustainable building processes can be defined as those in which the overall quality of the process enables the delivery of sustainable buildings in a way that meets the needs of all people involved [4].

Current building processes need to be changed to become sustainable; this will require significant improvements in the current plan of work and in the use of assessment tools. Sustainability assessment is no longer used only for marketing purposes, but the definition of project objectives is increasingly guided by the sustainability content, especially in public building processes [5–7]. This may require changing the way in which sustainability assessments are performed. The examination of sustainability at the end of the planning phase does not support design for sustainable buildings, therefore the “optimization” of sustainability must take place during the design phase.

This paper considers low-carbon design as one of the most important aspects of sustainable building design and focuses on the design process to reduce embodied carbon. The extraction, processing, manufacture, transportation, assembly and use of a product utilizes energy and induces harmful emissions, including $CO_2$ and other GHGs. With the exception of the generally more evident energy in-use, these impacts are regarded as the hidden or embodied burdens [8]. While there are several methods and tools for the assessment of energy consumption during the operational phase (as summarized by Schlueter and Thesseling [9]) embodied energy and carbon are not, in general practice, a consideration when a building is designed and constructed [8].

While the importance of decision making at an early stage of design has been widely studied and acknowledged, there is limited research on how to account for embodied carbon as a building is designed. This paper seeks to fill knowledge gaps in the literature and aims to support building designers and relevant decision makers on how to account for embodied carbon during the design stage in a step-by-step process.

The hypotheses of the paper are that: (1) important design decisions are done in the early stages of design and design alternatives need to be compared, even though complete building data

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[*] Corresponding author at: VTT Technical Research Centre of Finland, Tekniikantie 4A Espoo, P.O. Box 1000, FI-02044 VTT, Finland.
*E-mail addresses:* Nusrat.Jung@aalto.fi, Nusrat.Jung@vtt.fi (N. Jung).

http://dx.doi.org/10.1016/j.jobe.2015.06.005

is not yet available. (2) Design for low-carbon buildings requires the calculation of embodied GHGs gradually over the course of the building design. By a gradual approach, we mean a step-by-step process which should take place systematically describing the status, coverage and accuracy of GHG assessment in each design stage. (3) In each design stage the designer should be able to understand the significance of the preliminary calculations.

## 2. Objectives

The objective of this paper is to provide key guidance with the help of a systematic procedure required for designing low-carbon buildings, with a focus on embodied GHG emissions. These GHG emissions are induced because of the production processes of construction products (product stage emissions) and in further life cycle stages of construction products (installation into the building, use and maintenance, replacements, demolition, waste processing for re-use, recovery, recycling and disposal) [10,11]. The motivation for this paper is to address the need to apply sustainability related decision making as early as during the preliminary feasibility and preparation work and continuing throughout the initial design phases.

The objectives are as follows:

1. To assess the potentials and drawbacks of the current methods, standards and tools provided as aids for the design for low-carbon buildings.
2. To assess the significance of different design phases from the perspective of embodied carbon.
3. To describe a framework for a gradual low-carbon design approach to consider embodied carbon of buildings throughout the design process phases, mapped with the use of the RIBA Plan of Work [12] and ARK12 Finnish Plan of Work [13].
4. To draw conclusions and recommendations on the information, methods and standards needed.

## 3. Methodology

The study consists of: a review of relevant literature, interviews of principal designers in Finnish architectural offices, and a case study of a building. In the study of literature, we used qualitative research by comparing the findings in the literature in contrast to our hypotheses. The purpose of the semi-structured interviews was to understand at which phase of a building project are selections made for main building components and by whom. The purpose of the case study was to evaluate the relative importance of different building parts to the total embodied carbon of a building.

Environmental or sustainability rating systems such as LEED [18] and BREEAM [19] help designers in sustainable building design by providing indicators and benchmarks. Their main function is to enable the benchmarking of buildings. As a limitation of this article, rating systems are not the focus of this paper, but rather the focus is on the methods that can help the designer to attain the benchmarks – especially low-carbon design. Another limitation of this study is that the interviews are primarily conducted in Finland and the case study building is also constructed and designed based on Finnish regulations. However, it will benefit a larger audience as the architectural practices around the world have overlapping processes.

### 3.1. Study of literature

Through our literature review, we aimed at finding information for the following issues: (a) importance of embodied GHGs compared to total GHGs induced by buildings; (b) importance of the early stages of design with regard to embodied GHGs; (c) potential and drawbacks of current approaches, methods, standards and tools to aid the design low-carbon buildings; and (d) availability of data, process descriptions and frameworks for sustainable building design.

### 3.2. Interviews

The architectural offices were selected randomly with no prior preference or bias of the authors; but they were required to be a member of Association of Finnish Architects offices [Arkkitehtitoimistojen Liitto (ATL)]. ATL comprises more than 240 registered architectural companies across Finland. To be a member of the association, the architectural company must demonstrate the highest professional training and solid experience of working in the industry [www.atl.fi]. Twelve architectural companies were contacted to carry out a semi-structured interview, out of which seven responded positively (58.5% response rate). Being a member of ATL, these seven offices are representative of quality architecture being practiced in Finland; they have a minimum of two to a maximum of forty five full-time architects working on a variety of projects. The seven architectural companies have a collective total of over 200 reference projects that were listed as their best designs on their websites. The design projects included in the interviews conducted for this study were mostly won through national design competitions.

Interviews were conducted between August and October 2013; six were face to face and one was via teleconference. The interview durations varied from 40 to 90 min. All the interviewees are the principal architects in their respective companies and have more than ten years of experience in industry. The architects chose to share information of the projects, where they had the right or the permission of the client to share the details discussed in this article. Table 1 lists twelve buildings with type, location, floor area and the name of respective offices interviewed. The seven principal designers were asked to select a recently designed and commissioned project that is representative of different architectural form and function of the building. This was done to capture the variation in the roles of key decision makers in different types of projects. They were asked to give their responses with help of an Excel spreadsheet to quantitatively assess the role of each actor in each phase of their selected project. This process was repeated individually for each building project evaluated as presented in Table 1. To gauge the general perception of the interviewee on the decision making process, we then asked the participants to elaborate more upon their responses and give reasoning based on the already collected quantitative data about the issues that generally affect the decision making of materials selection. This semi-structured interview approach was found necessary to increase the depth and interpretation of the results especially when such research may involve personal opinions and project specific experiences in construction industry [14]. Desktop analysis was employed to analyze the data collected by the semi-structured interviews. Furthermore, Section 5 presents the results of the interviews.

### 3.3. Building case study

Based on insight gathered from the interviews, we identified the key decision makers at each design stage according to the RIBA plan of work and ARK12 (Finnish plan of work) (Table 2). Each design stage typically corresponds to a building part, where decisions are made for that part or for many parts in parallel. For example, decisions about the building frame are made during the

**Table 1**
List of buildings used for the interviews.

| *Building* | *Building type and use* | *Location* | *Project type* | *Floor area ($m^2$)* | *Designer* |
|---|---|---|---|---|---|
| Entteri School | School | Sipoo, Finland | New building | 4150 | K2S Architects |
| Kindergarten Kalkunvuori | Daycare center | Tampere, Finland | New building | 2400 | Gylling-Vikström Architects |
| YTHS Hospital | Hospital | Helsinki, Finland | New building | 1500 | Sanaksenaho Architects |
| Toukoniitty | Residential building, block of flats | Helsinki, Finland | New building | 11500 | ARK-House |
| Kuilden | Concert hall | Kuilden, Norway | New building | 16000 | ALA Architects |
| Otaniemi Metro | Subway station | Espoo, Finland | New building | 15000 | ALA Architects |
| Kuopio Theatre | City theater | Kuopio, Finland | Renovation and extension project | 10000 | ALA Architects |
| Lappeenranta Theater | City theater | Lappeenranta, Finland | New building | 7500 | ALA Architects |
| Isokuusi | Residential building, block of flats | Tampere, Finland | New building | 9000 | PuustaInnovations |
| Saarijärvi | Residential building, block of flats | Saarijärvi, Finland | New building | 2200 | PuustaInnovations |
| Tervakukka Passive house | Detached house | Tampere, Finland | New building | 198 | Kombi Architects |
| Syysviiru | Senior home | Lohja, Finland | Renovation project | 1900 | Kombi Architects |

**Table 2**
Stages of design in accordance with RIBA Plan of Work and Finnish Plan of Work (ARK12).

| | RIBA Plan of work | Arkkitehtisuunnittelun tehtäväluettelo (ARK12- The Finnish plan of work for architects) |
|---|---|---|
| 0 | Strategic definition | Tarveselvitys (Briefing) |
| 1 | Preparation | Hankesuunnittelu, suunnittelun valmistelu (Preparation) |
| 2 | Concept design | Ehdotussuunnittelu (Concept design) |
| 3 | Developed design | Yleissuunnittelu (Generic design)<br>Rakennuslupatehtävät (Building permissions tasks) |
| 4 | Technical design | Toteutussuunnittelu (Technical design)<br>Rakentamisen valmistelu (Preparation for construction) |
| 5 | Construction | Rakentaminen (Construction) |
| 6 | Handover and close out | Käyttöönotto (Taking in use) |
| 7 | In use | Takuuaika (Warranty period during in use) |

concept design stage and continue until the developed design stage. Similarly, each building component corresponds to a collection of building materials. Thus, to evaluate the effect of decision making on the total material-related embodied carbon of a building, we have calculated the emissions for a real case building over its 50 year life cycle. In this case study, we have only assessed eight such building parts for their respective GHG emissions, as presented in Table 4. We calculated the relative contribution to the total embodied carbon for each of these eight parts. We used quantitative methods to calculate the significance of the share of materials selected in each phase of the design process in terms of its corresponding CF.

We have recently published results of a case building where the significance of embodied GHGs was investigated [15]. In this article, we utilized the same case building for a different purpose to assess the importance of different design phases in terms of carbon footprint (CF). The case building is located in the city of Tampere, Finland and it was built in year 2011. The building is a block of flats with six stories and a basement. It has a total of twenty eight flats with total floor area of 2455 $m^2$, net floor area of 2082 $m^2$ and gross floor area of 3056 $m^2$. The building is constructed mainly of concrete-element structures: the floor slabs, roof structures, lift shafts, and internal and external walls are all made of concrete elements. The foundations and the base-floor slab are cast-in-situ concrete, along with some of the civil-defense shelter structures. The structure represents a typical residential building in Finland constructed by using typical technologies that fulfill the requirements of Finnish building regulation, where (embodied) CF is not a priority at present.

A Building Information Model (BIM) created during the actual design process by the designer of the case building has the bill of quantities which contain information about building elements, structures and materials. This was used to calculate the material quantities and the LIPASTO [16] and ILMARI Carbon accounting tools [17] were used to estimate the CF of the case building. The ILMARI tool is developed by VTT Technical Research Centre of Finland in co-operation with Pöyry Finland Oy. This estimation covers ‘cradle to gate’ phases, assessed transportation, installation losses and the renewal period during the defined service life. The environmental impacts of materials are based on the Finnish environmental declaration of building materials from the Finnish Ministry of the Environment. This information is completed by the generic data developed by VTT together with Finnish manufacturers. The choice of tools in this particular case was natural, since the building is built in compliance with Finnish building codes and regulations. The building components included in the CF calculations are presented in Table 4.

## 4. Study of literature

### 4.1. Introduction

This section studies the significance of low-carbon design and current barriers and prerequisites for low-carbon design, especially from the perspective of tools and the availability of data.

The study of literature also summarizes recent research results about calculation tools that support low-carbon design. GHGs or CF, is a sub-set of the data covered by a more complete Life Cycle Assessment [20,21].

### 4.2. Embodied GHGs compared to total GHGs induced by buildings

Low-carbon design can be defined as an approach to achieve a building with low GHG emissions or to have low CF. Recent research emphasizes the meaning of embodied GHGs when compared to operational GHGs [22,23]. The precise magnitude and share of embodied GHGs compared to operational GHGs depends on building type, climate, comfort requirements, and local regulations [24,25]. The assessment results also depend on methodological choices such as system boundaries, sources of data and completeness of data [25]. The significance of the embodied GHG emissions is increasing [26]. Energy-efficient buildings use less energy in their operation phase and have lower GHG emissions over their lifetime. As the operational GHG emissions are reduced, the relative importance of the embodied GHG emissions associated with building materials increases [8,27,28]. Sartori and Hestnes [29] reviewed 60 case studies from past literature. They summarized that for a conventional building the embodied energy could account for 2–38% of the total life cycle energy, whereas, for a low energy building this range could be 9–46%. Thormark [30] concluded that embodied energy of a low energy house could be

**Table 3**
Who makes the decisions? Professionals who typically participate in the design process are listed in the first column. The numbers in other columns are sums of the points given by the interviewees (0 = no role, 1 = minimal role, 2 = moderate role, 3 = leading role) for each actor in each phase. The last column presents the total sum for each phase.

| | **Location** | **Shape and orientation** | **Maintenance strategy and service life** | **Foundations** | **Piling** | **Excavations** | **Bottom floor slab** | **Building frame** | **Supplementing structures** | **Building services** | **Yard** | **Total sum** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Building owners** | 13 | 11 | 24 | 3 | 6 | 7 | 4 | 11 | 5 | 12 | 3 | ***99*** |
| **Land-owners** | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | *7* |
| **End-users** | 0 | 0 | 4 | 1 | 0 | 0 | 0 | 0 | 3 | 4 | 1 | *13* |
| **Construction company** | 1 | 3 | 3 | 3 | 2 | 3 | 5 | 5 | 2 | 4 | 0 | *31* |
| **Architect** | 0 | 26 | 6 | 8 | 0 | 0 | 19 | 14 | 29 | 3 | 29 | ***134*** |
| **Structural engineer** | 0 | 0 | 1 | 28 | 12 | 23 | 17 | 17 | 15 | 0 | 2 | ***115*** |
| **HVAC engineer** | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 0 | *27* |
| **Interiordesigner** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | *0* |
| **Element planner** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | *0* |
| **Production manager** | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 6 | 0 | 0 | 0 | *12* |
| **City planner** | 17 | 6 | 0 | 3 | 4 | 4 | 0 | 0 | 0 | 0 | 1 | *35* |
| **Building permission authorities** | 0 | 0 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | *8* |
| **Building inspectors** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | *0* |
| **Others** | 5 | 3 | 2 | 4 | 7 | 7 | 2 | 1 | 0 | 5 | 12 | *48* |

equal to 40–60% of total life cycle energy. The GHG emissions from materials' production may increase in absolute terms if some materials are used in larger quantities or others have higher CFs [31]. In addition, the use of renewable energy is expected to lower GHG emissions from energy generation for heat and power. This may also increase the relative importance of GHG emissions linked to materials [15]. The importance of the construction-phase-related GHG emissions may be emphasized because of timing and the significant carbon spike during this phase of construction [32,33]. These findings support the need for considering embodied carbon during the design process. Environmental product declarations (EPDs) [10] have a potential to become essential in low-carbon design. However, when this data is used after the design is commissioned for subsequent assessment, it cannot support decreasing the effect of embodied carbon. Therefore this article provides guidance for to apply the existing knowledge through a step-by-step procedure in order to obtain low-carbon design.

### *4.3. The importance of early design stages with regard to embodied GHGs*

Important decisions regarding sustainable buildings are done in project preparation and in early phases of design. Recent research addresses the significance of the preparation phase [[29,7]] and early design phases [9,34–36] in sustainable building design. The problem of building sustainability in the construction industry can be solved if the concept and principle of sustainable development were taken into consideration at an early stage of building design [37–39]. "Embodied energy, however, can only be reduced if low energy intensive materials and products are selected at the initial stages of building design," as stated by Dixit et al. [40]. In the preparation phase, environmental targets should be set with the help of core indicators. Clear targets for building performance and environmental impacts form the initial step for designing for sustainable buildings [41]. Shi and Yang claim that it is widely agreed that design decisions made in the conceptual stage have the largest impact on the final overall performance of the building [42].

Guillemin and Morel conducted a survey on 67 buildings and found that 57% of technological decisions were made in the conceptual design stage, compared with only 13% in the detailed design stage [43]. According to Schlueter and Thesseling [9] the sustainability assessment should be predominantly applied as early as during the project preparation and early design phases to avoid extensive modifications being required at later stages to meet the performance criteria. According to Kolltveit and Grønhaug [44] key personnel from the construction and building industry believe that a more effective execution of the early phase has a positive influence on the potential for increased project value generation. However, decisions taken at each stage will depend on more accurate knowledge of the impacts of different life cycle stages and of their potential for reduction [23].

### *4.4. Alternative approaches and related barriers for designing low-carbon buildings*

The following sections introduce different approaches for low-carbon design by outlining options to five parts: practical guidelines, rating systems, LCA tools, BIM compatible tools, and simplified tools. The following sections also assess their potential to support early design phases.

#### *4.4.1. Practical guidelines for the support of low-carbon design*

Practical guidelines provide one approach for low-carbon design. Dakwale et al. [45] suggest giving preference to recycled materials, low energy materials or renewable materials. Sev [46] outlines general methods for resource efficiency, such as

**Table 4**
Building components included in the GHG-calculations.

| Analyzed items | Description of items |
|---|---|
| Yard structures | Soil stabilization under yard areas, structural layers, pavements, etc. |
| Excavations and backfills | Excavations and backfills below and around the building's footprint |
| Piling | Piling under the foundations |
| Foundations | Foundations under the external walls and load-bearing internal walls |
| Bottom floor slab | The floor slab of the basement floor |
| Building frame | External walls, load-bearing internal walls, floor slabs and roof. Structures of elevator shaft and civil shelter spaces. |
| Supplementing structures | Balconies, ductwork elements, stairs, partition walls, windows, doors, glazing, equipment and furnishing, materials not attached to any other structures. |
| Building systems | Heating, ventilation, air-conditioning, sanitary, sprinkler, electric and telecom systems, elevator |

incorporating recycled or reclaimed materials, reducing material use by properly sizing the building, selecting durable materials, selecting materials that are recyclable and reducing waste material. In a similar way, environmental rating systems support low-carbon design by providing indirect indicators (such as "content of recycled materials"), on both a building and urban level [47]. However, recently, life cycle assessment (LCA) approaches have been incorporated to many systems (as described by Roh et al. [48]) because of their improved accuracy.

### 4.4.2. Sustainable building rating systems

There are growing interests in the development of building performance assessment methods all across the world. This led to the development of High Environmental Quality (HQE) in 1996; Leadership in Energy and Environmental design (LEED) in 2000; CASBEE (Japan) in 2001; Green Globe (Canada) and Green Star (Australia) in 2002, LEED (India) 2005; GBC (Poland) and LEED (Emirates) in 2006; Green Star (South Africa) in 2007; BREEAM (Netherlands) and LEED (Brazil) in 2008 [49].

Environmental or sustainability rating systems such as LEED [18] and BREEAM [19] help designers in sustainable building design by providing indicators and benchmarks. Voluntary rating systems assist decision makers in setting goals, benchmarking and comparison of alternatives [50,51], but those may also support target setting. However, existing environmental methods require specialist knowledge and are seldom incorporated at the early stages of the design development [52]. Berardi [51] also concludes that the importance of simple systems is in making them useful as design tools; to introduce sustainability rating systems early in the construction process they must be structured not to need detailed information before they are generated.

### 4.4.3. Life cycle analysis (LCA) tools

Research results address that the building design process lacks adequate tools for the consideration of sustainability aspects is early phases of design; the effective use of methods and tools would require the integration of tools for design and building tasks [53–55]. In the early design phase, there is often not enough information

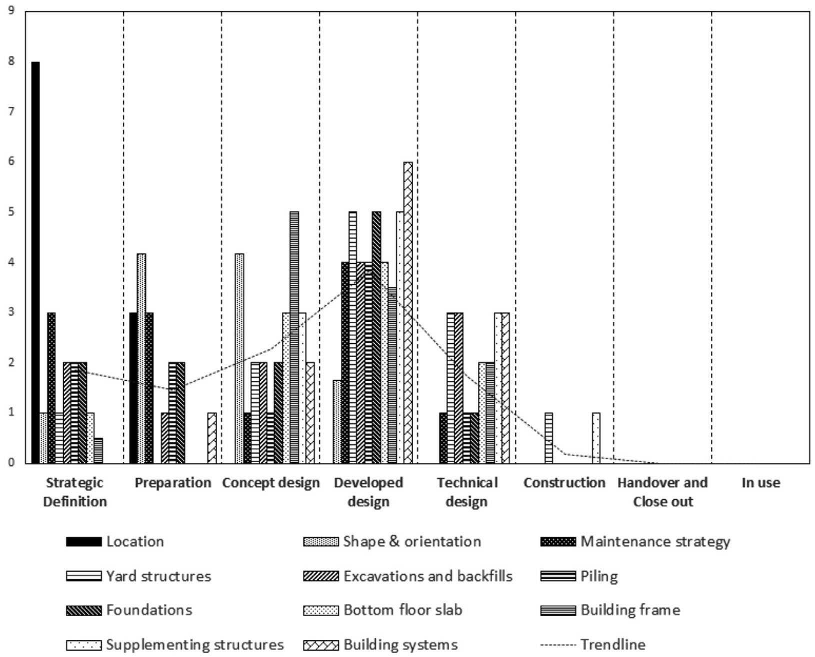

**Fig. 1.** Importance of each design phase with respect to each design consideration. The scale on *Y* axis presents the weighting (out of 1.0) given for different design considerations (such as location and foundations) in different project phases (such as preparation and concept design). The value 1.0 could also be divided among different phases if those were equally important (for example by giving value 0.5 for building frame in concept design and value 0.5 in developed design). Columns show the decisions that are made in each design phase for each design consideration.

**Table 5**
Building components and their share of total building-level GHG emissions and timing of decisions relative to design phases impacting GHG emissions.

| **The source of GHG emission: Building component or energy consumption in different phases** | **Relative share of GHG emissions of the case-building**[a] (Building component specific material-related GHG emissions of the case-building in total are 1670 t of $CO_2$-equ.) (%) | **Design phase based on RIBA and ARK12**[b] |
|---|---|---|
| Yard structures, foundations, piling, excavations and backfills, bottom floor slab | 16 | Strategic definition and preparation |
| Building Frame | 35 | Concept and developed design |
| Supplementing structures | 16 | Concept and developed design |
| Construction, renovation and demolition work | 14 | Concept and developed design |
| Building systems | 2 | Technical design |
| Renovation and refurbishment | 17 | Technical design |

The third column also repeats the main design phase affecting the selection, as presented in Section 5.

[a] Based on results obtained through case building.

[b] Based on interviews conducted as presented in Fig. 1.

available that is required for making a life cycle assessment [56]. The problem is about how to access thedata and manage the knowledge [57]. According to Ding [58], the assessment tools should be reconfigured so that they do not rely on detailed design information before it has been generated by the designer.

On the other hand, there are several assessment tools available (as explained by Poveda and Lipsett [59]). A variety of LCA tools in the form of software exist, along with datasets of environmental impacts of building materials. These tools, such as ATHENA, BEES 4.0, Ecoinvent, Eco-Quantum, Envest 2, OPTIMIZE, LICHEE, SimaPro, etc. provide a user-friendly approach to determine life cycle impacts of a building [40] and many easy-to-use Excel-based tools. Most of these are not intended for use during the design phase by the designers, although the Synergy tool [60] is a typical excel-based calculation tool for the CF of buildings. This tool is available on-line and the excel-based sheets can be downloaded with instructions. The main barrier to the use of LCA in practical building design included the perception that LCA is highly data-demanding and work-intensive, and LCA tools that are well integrated with standardised software applications used by architects are also still rare [61]. Other problems addressed are that none of the existing tools and datasets have the capability to perform a full Life Cycle Assessment of a building [32], environmental and financial issues need concurrent consideration as parts of assessment [62], and an integrated building–urban evaluation model would also be needed [63].

In big projects, collaborative design often involves multiple architects during the conceptual design phase [64]. However, in many cases, building designs are individual design outcomes and the architectural design takes place mainly in small enterprises [65]. The small design offices have no resources to collect needed basic data to make embodied carbon assessments, although the CF data is available as Environmental Product Declarations (EPDs) [10] for individual components and products. The research has shown that the role of the main designer is significant in a sustainable building process [66]. Zaid [22] has indicated that by being aware of the embodied energy of different building parts and materials, the designers are able to radically alter the design; in their research, the total embodied carbon because of a redesign was reduced over 30%.

#### 4.4.4. *Simplified tools*

To solve issues related to data management, Malmqvist et al. [61] proposed to start with a simplified LCA tool by focusing on larger building elements, limited life cycle, and few impact categories. Moncaster and Symons [23] introduce an approach where the tool generates an assumed list of building components with quantities from limited feasibility stage (corresponding to preparation phase in terms of RIBA [13]) information. To support decision making, the highest level of precision is not necessary. Performance assessment for the early design stages has to show the tendencies in making decisions and, most importantly, dependencies of those decisions [9].

#### 4.4.5. *BIM compatible tools*

The benefits of BIM in such design tasks as energy analyses and cost estimation have been shown [67]. Basbagill et al. [35] suggest that environmental information of products can be part of an integrated, BIM-enabled environmental impact feedback process. The suggested process support designers to focus on decisions with large impact during the early design phases by helping designers to understand which decisions have the biggest effect on a building's embodied GHG impact. The framework utilizes a computational method that integrates BIM software with LCA and energy analysis software, in order to quickly evaluate the embodied impacts of building designs. Sensitivity analysis is then performed on these results in order for designers to understand which building components' embodied impacts consistently contribute the largest to a building's environmental impact across the designs. Mora et al. [68] introduce an integrated life-cycle approach for design to consider both service life and environmental aspects.

Fies [69] has studied the possibilities of integrating sustainable building assessment methods with BIMs. Interoperability and openness of different design tools were assessed in terms of data import and data export. Currently, most of the tools are able to retrieve technical information to perform some calculation and edit a report. In it's recent update [(Industry Foundation Classes 4 (IFC)], the IFC has made a significant step forward in the integration of sustainable indicators into BIM. The property set mechanism demonstrates its ability to provide a semantic layer above the IFC elements. Most of BIM/CAD tools propose an export function to

**Table 6**
Results based on the case study calculations and interviews showing the effect of the selection of different building parts on carbon footprint.

| Project phase | Assessed results |
|---|---|
| **Preparation** | The GHG emissions from these items are approximately 15% of the building's total material-related emissions (Table 5).<br>Some specific considerations of the site may include sites with exceptionally poor quality. For cases where soil stabilization is needed, the stabilization materials may add about 60% to the total GHG emissions of materials see [22]. |
| **Concept design and developed design** | Especially the large builders select the construction concepts and structural systems during concept design phase. After this, it is very difficult to make major adjustments to these decisions. The selected construction concept of, for example, pre-cast concrete elements, or massive wood elements, will form the basis for more detailed design (result of interviews).<br>Decisions on such items as structural systems, e.g. frame and supplementing structures, are set. These items account for some 50% of the total GHG emissions of the case-building, when the use phase and operative energy use is excluded (Table 5).<br>The selection of structural system largely sets the level of GHG emissions from site activities, lifetime renovations and the demolition work at the end of the life-cycle. These account for about 15% of the total material-related emissions (Table 5).<br>On the other hand, alternative structural systems can be chosen at this phase. If the case-building was built with a functionally equivalent wood-framed building, the emissions for the frame and supplementing structures would be 45% less than for the case-building with concrete structures [22].<br>For the case-building, it is estimated that the selections of this phase could increase the GHG emissions by approximately 10%, if more massive structures were used [22]. |
| **Technical design** | The lifetime renovations and refurbishment of the case-building account for about 15% of total life-cycle material-related emissions, underlining the importance of maintenance plan (Table 5).<br>The role of building services systems is very low from the viewpoint of material-related emissions (less than 2% of totals) (Table 5).<br>Some exceptions exist, as solar panels may add 15% to the life-cycle total GHG emissions from materials [22]. Such items should be assessed with more detail. |

IFC. The resulting IFC exported files then contain IFC objects with their properties that can be used for Sustainable building assessment [69]. There are also environmental calculation tools that utilize this mechanism. The ELODIE [70] tool developed in France uses EPDs provided by manufacturers that are stored in an external online database, and uses IFC-based data of building components. Similarly, the ILMARI tool [17] developed in Finland, also uses IFC-based data on building components, and calculates the carbon footprint with the help of a CF database that is embedded in the tool.

### 4.5. Availability of data for low-carbon design

The most important prerequisite for the assessment of the GHGs of a building design is the availability of information on the GHG emissions of building materials. This is the data that is required to calculate the embodied carbon emissions of the design. EPDs worked out according to standardized process [10,71] present information on GHGs and other environmental aspects based on a life-cycle approach. To provide comparable information, EPDs must have the same product category rules. EN 15942 tries to support the usability of information in different use situations by defining a structure for the information and requiring data transparency. Examples of comprehensive collections of EPDs include the German IBU [72] and French INIES [73]. Although there are several databases which include embodied energy and carbon of standard building materials and components [74], many countries still lack adequate information on the CF of building materials [75]. Thus generic, commercial databases such as GaBi [76] and EcoInvent [77] are often used. There may be big differences in CF of products produced in different countries because of different manufacturing processes and energy carriers (for example Vares et al. [78]).

### 4.6. Availability of process descriptions and "plans of work" for low-carbon design

Plan of Work 2013 organizes the process of design (such as briefing, designing, constructing, maintaining, operating and using the building projects) into a number of key stages. The content of stages may vary or overlap to suit specific project requirements [13]. Design can be defined as a process of composing ideas and requirements into an understandable scheme or plan for a product [79]. Design tasks for low-carbon buildings could be integrated into existing design procedures by addressing the subtasks to be implemented in each phase and by addressing the use of tools in different phases. However, for example, the current Finnish process description for architectural design [12] does not describe any sub tasks for sustainability assessment. However, it mentions one single task of the assessment of life cycle and environmental impacts to be done within Generic design (see Table 2) and provide no further details (refer Section E 4.9 in ARK12). The British RIBA plan of work [13] includes steps for formulating sustainability aspirations, sustainability strategies and for sustainability checkpoints. The European SuPerBuildings project made a process description for sustainable building process [80] but it does not give detailed guidelines for low-carbon design.

## 5. Interviews

### 5.1. Description of the interviews questions

A questionnaire as an Excel sheet was prepared and the designers were interviewed in mutual sessions. They were asked to identify

1. at which design phases (see Table 2) the decisions about various design considerations of the building, such as location, shape and orientation maintenance strategy, yard structures, excavation and backfills, piling, foundation, bottom floor slab, building frame, supplementing structures, building systems are made in a particular project.
2. which actors (owner, landowner, end user, construction company, architect, structural engineer, HVAC engineer, interior architect, element planner, production manager, city planner, building permission authority, building inspector, other) are the most important decision makers with regard to location, shape and orientation, maintenance strategy and service life, foundation, piling, excavations, bottom floor slab, building frame,

**Table 7**
Influencing low-carbon design in different stages of design.

| |
|---|
| **Stage 0: Strategic Definition** |
| The potential of carbon efficiency should be evaluated and the target should be set. |
| **Stage 1: Preparation** |
| To enable low-carbon design, the initial design brief should clearly define the requirements both for building performance and CF. In addition, the project brief should address methods for assessing and monitoring them along the design and construction project. To enable the compatibility of all calculations during the process, basic rules for the assessment and data bases should be defined. |
| **Stage 2: Concept design** |
| During the lay-out design, the embodied carbon consequences can only be considered with the help of existing expertize and reference knowledge. Working with the help of reference data at this stage means that, also without doing numeral estimation and iteration, the designer works with the help of general understanding and expertize about the effect of such principal choices. |
| This stage should prepare alternative preliminary solutions and assess those in terms of CF. This stage should assess preliminary CF information with the help of existing references considering main building materials, shape and orientation on site, space efficiency, building services concept. The functional requirements can be achieved with the help of shape, lay-out, and type and quality of building envelope, partitions, surfaces, and building services. All these have an effect on the use of materials – and thus on embodied carbon – which have to be taken into account in the next steps. |
| **Stage 3: Developed design** |
| CF estimations may be based on general database values, as product specific environmental information cannot yet be identified. Results from the initial CF assessments should be taken along as one of the variables in a multi-parameter decision making process that leads into the selection of the most feasible design alternative for next project stage. The developed design should assess and iterate (architectural) design alternatives and use generic data for estimation and iteration. |
| Generic data should be relevant for the case representing for typical data. However, currently the possibilities depend much on the availability of databases. At this stage it is possible to consider the following building parts: Base-floor, floor, roof structure, All walls, windows and doors, piles, beams, columns. When looking at only embodied carbon, these building parts typically represent roughly 50-60% of the whole building. The quantitative assessment results are compared to the quantitative goal considering the significance of the choices or to the qualitative goal considering references. |
| **Stage 4: Technical design** |
| After technical documentation is available, an estimation of "CF as designed" can be calculated. Technical design stage should make final calculations for the design and consider the effect of changes compared to the ideas of earlier design, consider the results of maintenance planning and take into account the improved information of periods of renewals, and save the information to be used as reference information in construction stage. |
| The HVAC design brings totally new information for the design. The significance is typically less than 5% in terms of embodied carbon of all building materials. However, in the worst cases technical solutions of air-conditioning and the use of solar energy may have an important effect on the CF on the building-level. Here the optimization between the minimization of embodied carbon and minimization of operational carbon emissions is important. |
| With regard to structural design, the technical design should not bring too much new information, but should improve the accuracy of the estimation. This is especially important with regard to such building parts, the shape of which is complicated and which are not modeled in architectural design in detail. |
| **Stage 5: Construction** |
| Building sites often cause unexpected changes or needs for redesigning small details. For the case of larger reconsiderations, the CF of the proposed change should be examined. At the construction stage of residential buildings, the apartments are sold at this stage. In the marketing process, the residents are often given freedom for selecting the final surface materials in their apartment. The effect of the changes is typically quite small and the selection is often concerned with colors, etc., rather than material choices. |
| The as-built result is calculated on the basis of product specific information. During the procurement process, product specific information is required in accordance with the format agreed during the process. |
| The procurement process can still have an influence on the building's CF. Suppliers may be able to supply products with clearly less (or higher) CF compared to the generic value used in the calculation. With regard to such products as concrete, the manufacturer has several possibilities to affect the properties. |
| **Stage 6: Handover and Close out** |
| Inspecting the finished building should include a review of its carbon footprint "as built". By comparing this value to carbon footprint "as required" and "as designed" the project team can identify where possible gaps occurred and learn for next project. |
| **Stage 7: In use** |
| Operative energy use has a dominant role in the carbon footprint of the use stage. When renovations or refurbishments are carried out, their environmental impact assessment should follow the steps of an individual project and start over from phase 0. |

supplementing structures, building services, yard landscape. The roles of actors were rated from scale 0–3 as having no role, minimal role, moderate role or significant leading role.

We also asked the participants to elaborate more upon their responses and give reasoning based on the already collected quantitative data about the issues that generally affect the decision making of materials selection.

Design stages were described according to RIBA plan of work [13] and ARK12 [12] (Table 2). ARK 12 is a Finnish plan of work which gives guidelines for design tasks in different design phases (as listed in Table 2). Table 2 lists the stages of design in accordance of RIBA and ARK12. The right column gives the Finnish terms and their closest translation in English. The stages 0, 1, 2, 3, and 4 are almost likewise characterized in RIBA and in ARK12. We chose to use the RIBA terms, since those are more generally known and understandable for larger research and design audience also including Finland.

### 5.2. Results of the interviews

A variety of design considerations and different project phases were considered (Fig. 1). A second set of questions focused on investigating the influence of stakeholders (listed in Table 3) in the decision making process.

The results of the interview (Fig. 1) reveal that most of the decisions that affect the selection of building materials and parts are carried out in the developed design phase, however, certain important decisions, e.g. location, shape and orientation were decided earlier. Preparation and concept design phases are also very important, especially when projects are commissioned by large construction companies in design-build projects or public actors who have pre-defined structure types and construction concepts. Such definitions were reported to be difficult to alter later on. Phases after the construction work have started were not reported to have an impact on the decision making.

Our results also show that architects, structural engineers and representatives of the owners of the building seem to have the main role in the decision making process when it comes to defining building parts. Architects and structural engineers are seen as being most influential in the decision making process on average (as indicated in Table 3 by total sums of 134 for architects and 115 for structural engineers). However, depending on the case, owners of the building may make most of the decisions (as indicated in Table 3 by total sum of 99). The role of city planners was important as well, as their decisions affect the need for excavations, piling and even façade materials in some countries.

Decisions will also be made by a variety of stakeholders who hold responsibility for different activities, including clients, designers, contractors and facility managers [23]. Two additional findings emerged in the oral interviews. First, there seems to be high project-type specific variation in the decision making process. Large constructors were reported to have developed standardised construction processes and fixed material definitions, considered "non-negotiable." On the other hand, less frequent constructors

**Table 8**
Proposal for including gradual implementation of carbon footprint assessment during the design phases.

| Design phase | CF value for the design | |
|---|---|---|
| Preparation | Target value | Target set for the building with reference to the reference value or benchmark [a].<br>Assessment of the effect of excavations, foundations and yard structures. |
| Conceptual design, developed design | Standard value | Calculated with the help of standard structures and generic material data[b]. Consideration of base-floor, floors, roof structure, all walls, windows and doors, piles, beams, columns |
| Technical design | Quantified value | Calculated with the help of designed structures and generic material data[b]. Consideration of HVAC additionally. |
| Construction | Specified value | Calculated for the whole building with the help of designed structures and product specific values[c]. Consideration of surface materials and fixed furniture additionally. |

[a] Comprehensive sources for benchmarks are missing but the need is identified; for example proposals for new work items are being made within ISO process.
[b] Generic material data is available in different LCI data bases such as for example GaBi [51]
[c] Product specific data or values are available as EPDs.

could propose significant changes in later design phases. Secondly, the preparation and concept design phases were seen as crucial in public building projects. The project models of municipal constructors include definitions about the location, orientation, building services, energy efficiency, and service life & maintenance strategy. The goal-setting in these matters would be of high importance if the goal was to optimize the CF of the building.

## 6. Results of the case study

The case-building had total embodied material-related emissions of 546 kg/m$^2$ (gross area) (total 1670 t of embodied emissions) for the 50-year life-cycle. Table 4 shows the building components included in GHG-calculations. Table 5 shows how the total embodied GHG emissions are divided between different building components in the case building.

By combining the results presented in Fig. 1 with the results of the case-building we receive the following outcomes for the significance of different design phases (Tables 5 and 6).

## 7. Discussion and recommendations

On the basis of the study of literature, recent research shows that embodied GHGs are important compared to the overall GHGs induced by buildings, and addresses the significance of the preparation phase and early design phases in design for environmentally benign buildings. In the beginning of a design process, the opportunities for affecting the impacts of the building – be they economic, social or environmental – lay open. As the design process continues, choices will have to be made that limit these options. It has been pointed out in previous studies [81], that in the beginning of the process the impacts cannot be fully recognized and utilized. The importance of early phases of building projects was also confirmed by interviews which revealed that most of the decisions that affect the selection of building materials and parts are done in the preparation, concept design phase and developed design phase. The first phases are especially important if projects are commissioned by large construction companies or public actors and later alterations are difficult. The importance of the first phases was also validated with the help of the case study. Our results also show that architects and engineers have an important role in the decision making process when it comes to defining building parts. These findings emphasize the need of design tools that support design for low-carbon buildings within concept and developed design phases. On the basis of the study of literature, recent research introduces alternative approaches for low-carbon design and addresses problems for these. The main problems of alternative approaches are as follows:

- working with practical guidelines may not give holistic results;
- sustainable rating systems support target setting rather than design parameters;
- the main barrier to the use of LCA in practical building design includes the perception that LCA is highly data-demanding and work-intensive, and LCA tools that are well integrated with standardised software applications used by, e.g. architects, are also still rare [61];
- simplified tools may be useful but also inaccurate – however, performance assessment for the early design stages has to show the tendencies and dependencies of decisions [9];
- BIM compatible tools provide potential to assess CF in a step-by-step way as integrated tools in design process, but there are still important problems like the availability of carbon information.

On the basis of the study of literature, recent research also points out the different status of generic data and product specific data. Results indicate that by being aware of the embodied energy of different building parts and materials the designers are able to radically alter the design. Zaid [22] showed that the total embodied carbon was reduced over 30% by redesign. This emphasizes the need of alternative designs in sustainable building design. However, from the designer point of view there are three concerns: (1) the calculation is time-consuming because these kinds of tools work independently and the data input has to be done manually, (2) comparison of alternatives in not easy and the designer has to repeat the process for different design options, (3) these kinds of tools do not support the comparison in early phases of design because the designer lacks a complete list of building materials.

The following Table 7 describes each stage in accordance with RIBA [13] and proposes preliminary recommendations for influencing low-carbon design on the basis of the results.

On the basis of the case study, the CF value calculated in different stages of design has a different meaning because (1) the coverage of the value is different, and (2) it can be based either general (average or typical) CF values of different building products or specific CF values of selected products (produced in specific manufacturing plants). After a thorough literature study as presented in this article, we found that there is a need for specific terms that describe the nature of data required to do CF assessment. Here, we propose the following terms to help to capture the meaning of assessed CF data:

- Reference data (calculated for structures and buildings with the help of generic data) and benchmarking data (calculated for different types of buildings )
- Generic data (average, typical)
- Product specific data.

The availability of data, exhaustive requirements in standards and missing reference data can cause significant challenges for a

**Table 9**
Objectives, deliverables, milestones and roles in low-carbon design process.

| | | **Design stages according to RIBA Plan of Work 2013**<br>**0 Strategic definition** | **1 Preparation** | **2 Concept design** | **3 Developed design** | **4 Technical design** | **5 Construction** | **6 Handover** | **7 Use** |
|---|---|---|---|---|---|---|---|---|---|
| | **Objectives** | • Identify client's needs | Develop project objectives: Outcome, quality, sustainability, feasibility etc. | • Prepare concept design<br>• Develop project strategies<br>• Issue final brief | • Prepare developed design<br>• Outline building services and structural design | • Prepare technical design | • Construct the building as planned | • Handover and inspect the finished building<br>• Begin maintenance | |
| | **Typical deliverables** | • Strategic Brief | • Initial Project Brief | • Concept Design<br>• Project Strategies: Sustainability, Cost, Maintenance etc.<br>• Final project brief | • Developed design<br>• Preliminary cost information | • Completed technical design<br>• Bills of quantities<br>• Tendering documents | • Revise documents to ”as built” status | • Maintenance documentation | |
| **ENSURING CARBON EFFICIENCY** | **Milestones** | Identify the potential of carbon efficiency in the project | • Include CF target in sustainability strategy<br>• Set assessment and monitoring methods for design phase<br>• **Set CF ”as required”** (Target value) | • Estimate CF of alternative designs<br>• Data: Generic<br>• Calculate values for CF (Standard value) and compare to Target value | • Estimate CF of alternative designs<br>• Data: Generic<br>• Calculate values for CF (Standard value) and compare to Target value | • **Estimate CF ”as designed”**<br>• Data: EPD´s + general<br>• Calculate values for CF (Quantified value) | • Calculate the CF value (Specified value) and compare to Target value<br>• Give feedback about how proposed changes would affect to CF | • **Calculate CF ”as built”** according to EN 15978<br>• Data: EPD´s + possible site documentation of construction work | |
| **Roles and responsibilities for ensuring carbon efficiency** | **Client Project manager** | • Consider if low CF can result in taxing, funding, marketing or bring other benefits<br>• Set criteria for green public procurement of design (if applicable) | • Approve CF goals<br>• Define preliminary quantitative CF goals<br>• Define assessed indicators<br>• Select system boundaries and databases | • Supporting role | • Supporting role | • Approve CF as designed<br>• Compare outcome to original goals<br>• Set criteria for green public procurement of construction work and products | • Supporting role<br>• Approve changes to CF caused by changes in materials | Approve final CF calculationsCompare to goalsDocument ”lessons learned” | |
| | **Architect** | | | • Assess preliminary CF with help of main building materials, floor area and nr. of occupants<br>• Study the CF-efficiency of alternatives for reaching the functional requirements | • Iterate preliminary CF for base floor, floors, roof, walls, windows and doors, frame | • Ensure the consistency of calculations<br>• Make final CF calculations<br>• Consider the results of maintenance planning<br>• Save information for reference for construction phase | • Supporting role | • Calculate CF as built (Specified value) | |
| | **Structural engineer** | | • Supporting role | • Supporting role | | | • Supporting role | • Supporting role | |
| | **HVAC engineer** | | • Develop alternative energy concepts | • Develop chosen energy concept | • Make final energy calculations | | • Supporting role | • Update energy certificate ”as built” | |

low-carbon design process. The existing technical standards for the sustainability assessment of a building do not seem to fit for iterative assessment during a design process. Setting the extensive system boundary for the assessment seems to bring challenges if it is an integral part of decision making during the design process.

### 7.1. Proposal for a gradual assessment process

On the basis of the results presented in Sections 5 and 6, we present that it is possible and necessary to proceed gradually in the design process for low-carbon building. As an alternative for labor-consuming LCA tools, simplified tools or baseline practical guidelines to consider non-polluting materials and techniques [82], a clear structure for low-carbon design is needed. This should take place in a systematic way , as proposed in Table 8 to describe the status, coverage and accuracy of GHG assessments in different stages of design. Tools that work which provide approximate values and can be used in feasibility design phase offer one option [23]. However, the development of these kind of tools and needed assumptions requires a lot of information to ensure that the assumptions are realistic.

On the basis of the results we also conclude that a framework is needed that presents the main objectives for eachstage of the design process, characterizes the main deliverables, describes the milestones for low-carbon design and describes the roles and responsibilities for ensuring carbon efficiency as proposed in Table 9. We outlined the framework with the use of RIBA stages of design and for each stage we identified the objectives, typical deliverables, and milestones for ensuring carbon efficiency, as the responsibility of the client, project manager, architect, structural engineer and HVAC engineer. These are the important decision makers for design considerations affecting the low-carbon design as also shown in Table 3 as the result of interviews. The milestones presented in the Table 9 include the use of EPDs and EN 15978 standard to estimate the CF “as built”.

## 8. Conclusions

This research investigates the design process from the perspective of reducing GHG emissions during the design stages of a building and studies the effect of decision making during the different phases of the design on the embodied carbon of buildings. This research appraises the current design process (with reference to RIBA Plan of Work [13]), by adding new information required for assessment of GHGs in order to design and build low-carbon buildings. This research also discusses various opportunities to improve GHG assessment in different design phases based on a literature analysis, results from a case study and the results of interviews conducted by the authors.

The study of literature indicates that there is lack of both design-integrated tools and process descriptions for low-carbon design of buildings. The results of interviews and our case study present that the significant design decisions affecting GHG emissions are made in the early phases of a design process of a building. However, the current standards and tools serve mainly for subsequent assessment of the design. This research indicates the need to proceed with the help of a gradual approach where conscience design decisions can be made to reduce the emissions. Tables 8 and 9 describe a preliminary framework to designate the status, coverage and accuracy of GHG assessments in different phases of design. If the designer has a good understanding about the significance of different phases (as described in Tables 5 and 6) and product selections in terms of embodied carbon, the designer can make gradual conscience decisions which can lead to overall reduction of the embodied GHGs.

The results of the case study and interviews reveal that most of the decisions that affect the selection of building parameters and components are carried out in a developed design phase. The preparation and concept design phases were seen as crucial stages of decision making, especially for public building projects and in large building projects.

Current technical standards for the sustainability assessment of a building do not fit for iterative assessment during a design process. On the basis of the study, we conclude that new standardised process descriptions are needed to support the design for low-carbon building. Standardised definitions (as suggested in Table 8) are also needed to support the stakeholders' understanding about the meaning of terms and tasks. Also, there is a need to define such terms as target value, standard value, quantified value, and specified value, in order to support the process with common language and understanding about the meaning of different values for the assessed embodied carbon.

On the basis of the study we also conclude that BIM-based solutions and tools are already available for gradual carbon design though not yet generally accessible (as described in the literature study). Essential drawbacks include the lack of data availability for calculation purposes (which should cover both typical and product specific values relevant in different regions/countries) and lack of knowledge about reference and benchmark values.

To conclude, this research provides a systematic procedure as presented in Table 9 presenting the guidelines required for gradual assessment of reduced GHG to obtain a design for low-carbon building. The recommendation builds upon the structure of RIBA plan of work, completes the stages to follow gradual carbon design (as defined in Table 8) and describes the (importance of) roles of different stakeholders based on the results of the interviews. Table 9 presents the main objectives for each stage of the design process, characterizes the main deliverables, describes the milestones for low-carbon design and describes the roles and responsibilities for ensuring carbon efficiency. We hope that this table can be used by the buildings designers and relevant stakeholders to calculate and assess, step-by-step, the embodied carbon of a building during the design process.

## Acknowledgments

This work was supported by the project *Ownership in sustainable building (OKRA)* funded by Tekes, Finnish Funding Agency and project *Building information model (BIM) based product data management in industrialized construction supply chain (BIMCON)* under Built Environment Process Re-engineering Research Program (PRE). N. Jung was also funded through the Academy of Finland Energy Efficiency and Systems (EES) doctoral program at Aalto University. We would also like to thank the Finnish architectural companies; ALA Architects Oy, K2S Architects, Gylling-Vikstöm Architects, Sanaksenaho Architects, ARK-House, Puustalnnovations and Kombi Architects, for sharing their knowledge and expertize in the conducted interviews.

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# Appendix C: Publication III (with supporting information)

Nusrat Jung*, Satu Paiho, Jari Shemeikka, Risto Lahdelma, Miimu Airaksinen. Energy Performance Analysis of an Office Building in Three Climate Zones. *Energy and Buildings*. Elsevier B.V., Volume 158, Pages 1023-1035, 2018a.

Energy and Buildings 158 (2018) 1023–1035

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

# Energy performance analysis of an office building in three climate zones

Nusrat Jung[a,b,*], Satu Paiho[b], Jari Shemeikka[b], Risto Lahdelma[a,c], Miimu Airaksinen[b]

[a] *Department of Mechanical Engineering, School of Engineering, Aalto University, Espoo, Finland*
[b] *VTT Technical Research Centre of Finland, Espoo, Finland*
[c] *Department of Mathematics and Systems Analysis, School of Science, Aalto University, Espoo, Finland*

ARTICLE INFO

*Article history:*
Received 9 May 2017
Received in revised form 3 September 2017
Accepted 5 October 2017
Available online 6 October 2017

*Keywords:*
Energy performance
Energy efficiency
nZEB
Multi zone
Office buildings
Dynamic simulations
Helsinki
London
Bucharest
Radiant ceiling panels
Radiant floor panels
IDA ICE

ABSTRACT

Most of the studies encompassing dynamic simulations of multi-storey buildings account only for a few selected zones, to simplify, decrease simulation run-time and to reduce the complexity of the 'to be simulated' model. This conventional method neglects the opportunity to see the interaction between different zones as it relates to whole building performance. This paper presents fifteen individual cases of dynamic simulations of a six-storey office building with 160 zones. The energy performance analysis was conducted for three climate zones including Helsinki in Finland, London in the United Kingdom and Bucharest in Romania. For each location, the following three cases were simulated: (i) building as usual simulated according to valid national building codes; (ii) Energy-efficient (EE) case with selected necessary parameters enhanced to reduce total delivered energy demand; and (iii) nZEB case representing partial enhancement of the EE case based on the parametric analysis. The results of nZEB indicate that for Helsinki, it is possible to reduce the space-heating load by 86%, electricity consumed by lighting, appliance, and HVAC by 32%. For London, the heating load is reduced by 95%, cooling load is slightly increased, and electricity demand is decreased by 33%. For Bucharest, 92% of energy in heating can be saved, cooling energy demand was reduced by 60% and electricity consumption by 34%. Based on the nZEB cases for each location, alternative heating and cooling choices of a radiant floor panel system and radiant ceiling panel system were explored. There are small differences in absolute consumption demand for heating, cooling, and electricity for three cases in each location. The specific energy/m$^2$ for heating remained nearly the same in all systems for all three cases in each location. Alternative choices for heating and cooling by using Radiant Ceiling Panel (RCP) and Radiant Floor Panel (RFP) were investigated for all final nZEB cases. Marginal difference in heating energy required for space heating can be seen for London nZEB IHC and London nZEB RCP of 0.8 kWh/m$^2$/year and for Bucharest nZEB IHC and Bucharest nZEB RCP case of 1.3 kWh/m$^2$/year. RFP has the availability of large surface area for heat exchange and can provide heating at a low temperature and cooling at high temperature, but requires supporting air based cooling during the humid season. For RCP, the limited temperature exchange surface may increase the airflow rate, but supplies it at a lower temperature for the same load.

## 1. Introduction

As we proceed towards 2020, the EU directives [1] and country specific guidelines (e.g., [2–4]) are becoming more stringent to reduce energy consumed by buildings. European building policies such as that of Energy Performance of Building Directive (EPBD, Directive 2002/91/EC) and EPBD recast stated the implementation of nearly zero energy from 2018 onwards [5,6]. An nearly zero energy building (nZEB) can be described as a high-performance building [7] that may use the on-site produced renewable energy, or supply energy to energy grids, but zero balance is not required. In the same frame of reference lies the net zero energy building (NZEB), which is defined as a building that produces as much energy as it consumes and has zero kWh/m$^2$ annual balance of net delivered energy. However, there is no established definition of a zero energy building such as described in [8–12], nor the terms used, such as nZEB and NZEBs [13,14]. In addition to the terminology used, the energy balance and calculation methods also differ for NZEBs [15]. The Federation of European Heating, Ventilation, and Air-Conditioning Associations has suggested an approach for nZEB [16]. Both definitions require very high energy-efficiency, although nZEB approach allows for more flexibility in design and solutions

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* Corresponding author at: Department of Mechanical Engineering, School of Engineering, Aalto University, Espoo, Finland.
*E-mail addresses:* Nusrat.jung@aalto.fi, nusrat.jung@vtt.fi (N. Jung).

https://doi.org/10.1016/j.enbuild.2017.10.030
0378-7788/

**Nomenclature**

| | |
|---|---|
| nZEB | Nearly zero energy building |
| NZEB | Net zero energy building |
| BAU | Building as usual |
| EE | Energy efficient |
| DHW | Domestic hot water |
| VAV | Variable air volume |
| CAV | Constant air volume |
| SFP | Specific fan power |
| AHU | Air handling unit |
| $CO_2$ | Carbon dioxide |
| $\Delta T$ | Temperature difference |
| RFP | Radiant floor panel |
| SE | Specific energy |
| ASHRAE | American society for heating, refrigerating and air-Conditioning engineers |
| FMI | Finnish metrological institute |
| IDA ICE | IDA indoor climate and energy |
| HVAC | Heating ventilation and air conditioning |
| U-value | Heat transfer coefficient ($W/m^2$ K) |
| g value | Solar energy transmittance of the glass |
| n50 $1/h^1$ | Air changes at a differential pressure of 50 Pa |
| ppm | Part per million |
| COP | Coefficient of performance |
| $Q_{solar}$ | Transmitted direct and diffused solar radiation |
| DH | District heating |
| RCP | Radiant ceiling panel |
| DCV | Demand controlled ventilation |

based on economic optimization. Even though much research has been conducted in past years on nZEBs and NZEBs, only a few have been built, [10,13,17] indicating that major barriers to realization still exist. Besides, many of the studies suggested system solutions that are complicated requiring different kinds of skills in implementation and building operation phases [18].

In Europe, office buildings are the second largest category of the non-residential building stock with a floor space corresponding to one-quarter of the total non-residential area. During the last 20 years, the electricity consumed by the non-residential buildings has increased by 74% [19]. The annual energy consumption in the non-residential sector in the EU is 280 $kWh/m^2$ covering all end-uses, which is at least 40% greater than the equivalent value for the residential sector. In Finland, there were approximately 10,900 office buildings with the total gross floor area of 19.3 million $m^2$ at the end of 2013. About 43% of the Finnish office buildings are connected to district heating (DH), 24% are heated with oil, and 25% by electrical heating [20]. In the UK, there are 350,000 offices [21–23]. According to Enerdata's data, the total floor area of office spaces in the UK was approximately 135.7 million $m^2$ in 2008, representing 18% of the total non-residential building stock [24]. Gas provides the majority of space heating and hot water [25]. In Romania, 19,100 office buildings form 13% of the non-residential building stock with total floor area of 7.8 million $m^2$. A large number of Romanian buildings are connected to the DH network that is in need of major repairs [2]. Large scale commercial buildings such as offices, have greater fluctuations in internal gains due to multiple spaces requiring heating and cooling [26]. This study follows the hierarchical approach proposed by EPBD [1] which priorities the energy efficiency measures first to ensure the use of efficient techniques to reduce the total delivered energy demand in three climate zones.

The dataset on typical energy consumption of office building stock is far less covered as compared to residential buildings [19]. Main reason being that the office buildings are often categorized as a subset of non-residential building stock, commercial building stock, service sector or tertiary sector making it difficult to track [27]. nZEB energy requirements as defined by the EU Member States for non-residential buildings for Finland and UK are under development for new or existing buildings [4]. For Romania, it is set as maximum primary energy of 50–192 $kWh/m^2/y$ for new non-residential buildings and is not yet defined for the existing non-residential buildings [28]. Based on the data provided by Building Performance Institute Europe, the specific energy use in Finnish offices is approximately 260 $kWh/m^2$ and in the UK offices it is about 320 $kWh/m^2$ [19]. In the UK, the mean electrical energy use is 115 $kWh/m^2$, and the mean fossil-thermal energy consumption is 137 $kWh/m^2$ in general for office buildings [23]. The average energy use of all Romanian buildings is 275 $kWh/m^2$ [29], which is quite high when compared to all Finnish buildings with average energy consumption of 125 $kWh/m^2$. Based on the reference cases of simulation studies by Ahmed et al. and Mohamed et al. [30,31], for the year 2012, the specific heating energy required by Finnish offices is $\sim$22–60 $kWh/m^2$/year, and cooling energy is $\sim$8–17 $kWh/m^2$/year. For London, specific heating energy is $\sim$15–17 $kWh/m^2$/year, and cooling energy is $\sim$9–10 $kWh/m^2$/year with weather data for year 2010 based on Boyano et al. [32]. For Bucharest, specific heating energy is between $\sim$56–117 $kWh/m^2$/year, and cooling energy is $\sim$22–37 $kWh/m^2$/year based on [2,33]. The extrapolated data from the mentioned studies is available in Table S1. However, the specific heating and cooling energy demand are only examples, and may vary greatly among themselves due to differences in calculation methodologies, accounted energy flows, variation in case building properties, country legislation, building code, primary energy factor, construction year, indoor thermal condition, etc. Within the same country these values may vary depending on the year of construction, applied weather data, building type, occupancy level, installed heating and cooling systems, etc.

Another persistent discussion is the accuracy of the simulation studies based on the number of zones simulated. Most of the conventional simulation based studies encompassing energy performance analysis of multi-storey buildings account for few selected zones. This approach is often adopted to simplify, decrease simulation run-time and to reduce the complexity of the 'to be simulated' model. Studying a few selected zones of a building has its limitations, especially in the Nordic climate zone because of uneven temperature distribution related to air heating in residential buildings with an uneven usage of space [34]. This conventional method neglects the opportunity to see the interaction between different zones to the whole building performance. As demonstrated by Simson et al. [35] average error increases with the decrease in modeling detail. Besides, the simplified methods are not able to distinguish the differences in power needs accurately. This is an apparent gap since progressively more and more intermittent renewable energies are being supplied to the energy networks, requiring quick and more accurate response from the demand side. Therefore, creating the need for more accurate simulations on the demand side.

Despite the complications of dealing with larger data sets and arduous processes, a full scale building simulation model with 160 zones was created to more accurately assess multiple performance level parameters of a real building in three different climate zones. This study aims to obtain robust and diversified solutions for large office buildings that can be: (a) applied to reduce the amount of delivered energy or net energy supplied to the office building (b) that can be conveniently set and perform in three different climate zones. In addition to that, it will provide new data on energy demand profile of office building in three climate zones making it comparable to each other. The climate zones studied in this study include Helsinki, representing northern Europe as heating dominated climate; London, representing moderate climate; and Bucharest, representing southeastern Europe with a balanced demand for heating and cooling annually. This will aid extrapolation of variables (to some extent) and suitability of certain techniques to demonstrate how a building performed in one climate zone in comparison with other climate zone [36].

## 2. Methodology

### 2.1. Organisation of this study

This study is organized in sections, where Section 2.2 presents a step-wise methodology that was followed to conduct the dynamic simulations. Section 3 describes the building model, building envelope properties and operational parameters applied to all three climate zones. Section 4 presents the results and further discusses the parameters on the reduction of delivered energy demand by application of the selected cumulative strategies. Section 4.2 presents the comparison between two alternative heating and cooling systems of radiant floor panel system (RFP) and radiant ceiling panel (RCP) system. Section 4.3 presents the optimum building parameters to consider to achieve nZEB office buildings based on the results of this study. Section 4.4 describes the limitations of this study followed by conclusions presented in Section 5.

### 2.2. Simulation cases

Annual dynamic simulations (8760 h) were conducted in three different energy performance cases to determine the near optimal solution for each climate zone. The near optimal solutions are implemented by changing the value of one parameter at a time until sufficient reduction in delivered energy is achieved, or the effect of parameter change becomes insignificant. Table 1 describes the simulation plan carried out to assess the energy performance analysis of an office building in three climate zones. For, each location, three cases of (i) building as usual simulated according to valid national building codes; (ii) Energy-efficient (EE) case with selected necessary parameters enhanced to reduce total delivered energy demand; and (iii) nZEB case representing partial enhancement of the EE case based on the parametric analysis were simulated. In the nZEB case, the input variables were optimized and guided by expert knowledge and experience. The variables presented in the study were tested by conducting several rounds of simulations to obtain an optimum building envelope with improved system properties that are viable in practice. The execution of the simulation plan was carried out in the following two phases as presented in Fig. 1

Phase *I* – The simulation model was created using the industry foundation classes file format from an architect's building information model. It is based on the realistic measurements of the building, system types, and its various components. The properties of the architects model were mapped to IDA ICE software for conducting dynamic simulations in three climate zones. The heating dominated climate zone of Northern Europe is represented by Helsinki-Finland, London-United Kingdom represents the moderate climate, and southeastern Europe is represented by Bucharest-Romania. Associated building envelope and ventilation properties were determined based on the climate zone and its corresponding building code regulations. Section 3.1 comprehensively describes the used input variables for the simulations. Parametric analysis was conducted only for the northern climate zone. A different set of input variables for the set of combination parameters was carried out specifically for the type of solar shading, type of window glazing, the thermal mass of building slabs (thickness), temperature set point during night-time was varied, and ventilation system and control type (variable air volume sizing for each of 160 zones). The most efficient design parameters obtained from the parametric analysis were applied in EE and nZEB cases to achieve the maximum benefits in reducing delivered energy demand. The results of parametric study were presented in [38] and are not discussed in this study (Table 2–6).

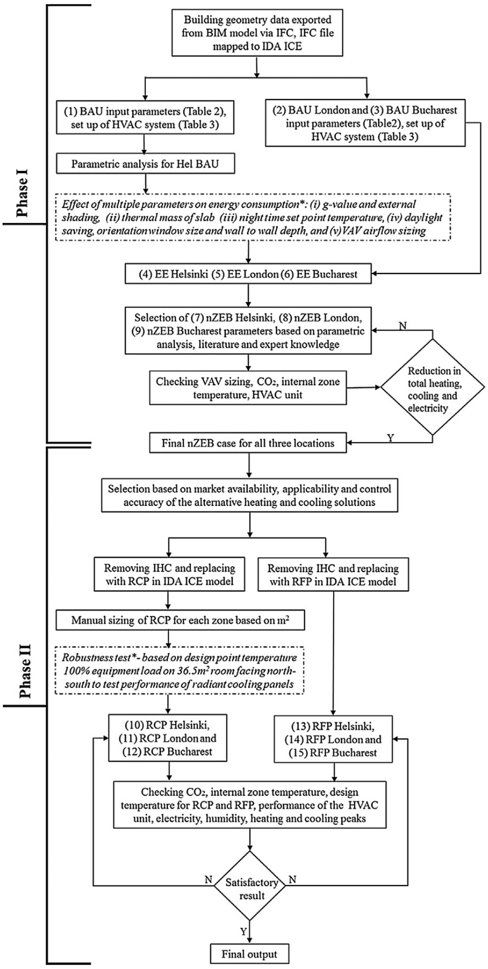

**Fig. 1.** Flowchart describing the simulation plan (**data not presented in this study*).

*Phase II* – For the nZEB cases simulated in phase I, the heating was achieved with the radiator, which is categorized as ideal heaters in IDA ICE, and cooling was achieved by using room-conditioning units. These units were removed and replaced with (i) a radiant floor panel (RFP) system and (ii) a radiant ceiling panel (RCP) system for all three climate zones. RCP had to be sized manually based on the availability of the ceiling area due to the beam structure depicted in the graphical abstract. Selection of heating and cooling alternatives was based on the market availability, applicability and control accuracy; more details are presented in Section 3.1. Benefits and challenges of both systems were studied and are presented in Section 4.2. As the final step, Table 7 presents the cumulative results of the simulations as a set of near optimal solutions for heating and cooling systems suggesting the specific system level parameters, definitions, and considerations required or needed to achieve an nZEB office building.

**Table 1**
Organization of the simulation plan.

| Climate data files | Helsinki, Finland, | London, United Kingdom, | Romania, Bucharest |
|---|---|---|---|
| | FMI 2012 | ASHRAE 2013 | ASHRAE 2013 |
| Phase I | (1) Helsinki BAU<br>(4) Helsinki EE<br>(7) Helsinki nZEB | (2) London BAU<br>(5) London EE<br>(8) London nZEB | (3) Bucharest BAU<br>(6) Bucharest EE<br>(9) Bucharest nZEB |
| Phase II | (10) Helsinki nZEB radiant floor panel (RFP) system<br>(13) Helsinki nZEB radiant ceiling panel (RCP) system | (11) London nZEB radiant floor panel (RFP) system<br>(14) London nZEB radiant ceiling panel (RCP) system | (12) Bucharest nZEB radiant floor panel (RFP) system<br>(15) Bucharest nZEB radiant ceiling panel (RCP) system |

**Table 2**
Building envelope properties and building operational parameters used as input values for simulations.

| Parameter/Units | Northern Europe, Helsinki, Finland | | | Central Europe, London, United Kingdom | | | South-Eastern Europe, Bucharest, Romania | | |
|---|---|---|---|---|---|---|---|---|---|
| | BAU | EE | nZEB | BAU | EE | nZEB | BAU | EE | nZEB |
| External wall U-value, W/m$^2$K | 0.17 | 0.16 | 0.12 | 0.26 | 0.25 | 0.1 | 0.80 | 0.45 | 0.15 |
| Roof U-value, W/m$^2$K | 0.09 | 0.09 | 0.09 | 0.18 | 0.18 | 0.1 | 0.40 | 0.30 | 0.1 |
| External floor U-value, W/m$^2$K | 0.16 | 0.14 | 0.1 | 0.22 | 0.22 | 0.15 | 1.50 | 1 | 0.25 |
| Internal floor U-value, W/m$^2$K | 2.3 | 2 | 1. 7 | 1 | 1 | 0.15 | 1.50 | 1 | 0.80 |
| Air tightness, n50 1/h[a] | 2 | 2 | 0.5 | 10 m$^3$/(hm$^2$) | 3 m$^3$/(hm$^2$) | 2 m$^3$/(hm$^2$) | 5 | 3 | 0.6 |
| Window glazing U-value, W/m$^2$K | 1 | 0.9 | 0.45 | 1.80 | 1.60 | 0.5 | 3 | 2 | 0.45 |
| Window g value | 0.35 | 0.35 | 0.24 | 0.40 | 0.40 | 0.2 | 0.85 | 0.65 | 0.24 |
| Window shading | Blinds between window panes | | | Blinds between window panes | | | Blinds between window panes | | |
| Shading strategy | Blinds on, if Q-sol > 150W/m$^2$ | | | Blinds on, if Q-sol > 150W/m$^2$ | | | Blinds on, if Q-sol > 150W/m$^2$ | | |
| Ext. Door U-value, W/m$^2$K | 1 | 1 | 0.7 | 2.20 | 2.20 | 0.7 | 4 | 2.50 | 1 |
| Approx. Lighting control | No lighting control | | Presence & daylight control | No lighting control | | Presence & daylight control | No lighting control | | Presence & daylight control |
| Lighting power | 9 W/m$^2$ | | | 7.5W/m$^2$ | | | 9 W/m$^2$ | | |
| Equipment load | 100%<br>12W/m$^2$ | | 30% reduced 8.4 W/m$^2$ | 100%<br>12W/m$^2$ | | 30% reduced 8.4 W/m$^2$ | 100%<br>12W/m$^2$ | | 30% reduced 8.4 W/m$^2$ |

[a] Virtual pressure test.

**Table 3**
HVAC system parameters.

| Location | Case | Unit | Type | Pressure head supply/exhaust [Pa/Pa] | Fan efficiency Supply/Exhaust | System SFP [kW/(m$^3$/s)] | Heat exchanger temp. Ratio/min exhaust temp. |
|---|---|---|---|---|---|---|---|
| Helsinki | BAU | AHU 1 | CAV | 780/770 | 0.78/0.77 | 1/1 | 0.5/0 |
| | | AHU2 | CAV | 780/770 | 0.78/0.77 | 1/1 | 0.5/5 |
| | EE | AHU 1 | CAV | 780/770 | 0.78/0.77 | 1/1 | 0.79/−5 |
| | | AHU2 | CAV | 780/770 | 0.78/0.77 | 1/1 | 0.59/0 |
| | nZEB | AHU 1 | VAV + CO$_2$+ temp | 1200/1200 | 0.6/0.6 | 2/2 | 0.85/−10 |
| | | AHU2 | CAV | 450/450 | 0.6/0.6 | 0.75/0.75 | 0.75/0 |
| London | BAU | AHU 1 | CAV | 780/770 | 0.78/0.77 | 1/1 | None |
| | | AHU2 | CAV | 780/770 | 0.78/0.77 | 1/1 | 0/5 |
| | EE | AHU 1 | CAV | 780/770 | 0.78/0.77 | 1/1 | 0.79/−5 |
| | | AHU2 | CAV | 780/770 | 0.78/0.77 | 1/1 | 0.59/0 |
| | nZEB | AHU 1 | VAV + CO$_2$+ temp | 1200/1200 | 0.6/0.6 | 2/2 | 0.85/−10 |
| | | AHU2 | CAV | 450/450 | 0.6/0.6 | 0.75/0.75 | 0.75/0 |
| Bucharest | BAU | AHU 1 | CAV | 780/770 | 0.78/0.77 | 1/1 | None |
| | | AHU2 | CAV | 780/770 | 0.78/0.77 | 1/1 | 0/5 |
| | EE | AHU 1 | CAV | 780/770 | 0.78/0.77 | 1/1 | 0.73/5 |
| | | AHU2 | CAV | 780/770 | 0.78/0.77 | 1/1 | 0.59/0 |
| | nZEB | AHU 1 | VAV + CO$_2$+ temp | 1200/1200 | 0.6/0.6 | 2/2 | 0.80/−10 |
| | | AHU2 | CAV | 450/450 | 0.6/0.6 | 0.75/0.75 | 0.75/0 |

## 3. Building model description

The multi-storey office-building model used for the dynamic simulation is located near Helsinki, Finland, and it is newly built. The office building consists of six floors with a ground floor area of 1600 m$^2$, a net floor area of 9400 m$^2$, a total floor area of 9775 m$^2$, and flat rooftop area of 1400 m$^2$. The total external wall area is 3400 m$^2$ with doors covering a total of 42 m$^2$ and windows covering 22.2% of the vertical walls. The building has the main entrance in the central C-shape area as shown in Fig. 2. It has a typical cell office layout where the C shape of the building enables windows on both the inside and external walls, the office cells are running separated by a shape corridor and a central foyer with lift access on each floor. The office building has elevators, individual office rooms, multipurpose rooms, storage rooms, mechanical room, multiple lobbys, technical spaces and other facilities (see Table S2 in supporting information).

**Table 4**
Delivered energy (kWh/m$^2$/year) comparisons for BAU, EE case and nZEB case of all three climate zones.

| | Hel BAU | HelEE | Hel nZEB | Lon BAU | Lon EE | Lon nZEB | Buc BAU | BucEE | Buc nZEB |
|---|---|---|---|---|---|---|---|---|---|
| Lighting electricity | 22.7 | 16.6 | 8.9 | 20.5 | 20.5 | 8.3 | 22.7 | 22.7 | 9.8 |
| Appliances electricity | 25.7 | 25.7 | 18 | 25.7 | 25.7 | 18 | 25.7 | 25.7 | 18 |
| HVAC electricity | 15.8 | 15.6 | 16.8 | 16.3 | 16.2 | 15.5 | 16.4 | 16.2 | 14.7 |
| Total electricity | 64.2 | 57.9 | 43.7 | 62.5 | 62.4 | 41.8 | 64.8 | 64.6 | 42.5 |
| Space heating (DH) | 73.2 | 50.1 | 10.2 | 88.7 | 34.4 | 4.1 | 153 | 70.7 | 12.5 |
| Hot water (DH) | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 |
| Total heating | 81.5 | 58.4 | 18.5 | 97 | 42.7 | 12.4 | 161.3 | 79 | 20.8 |
| Total Cooling | 3.9 | 3.6 | 1.1 | 4.4 | 5 | 4.8 | 18.2 | 16 | 11 |
| Total | 149.6 | 119.9 | 63.3 | 163.9 | 110.1 | 59 | 244.3 | 159.6 | 74.3 |

**Table 5**
Load distribution between zone heating/cooling and AHU heating/cooling in kWh/m$^2$/year.

| Case | Zone Heating | AHU Heating | Zone Cooling | AHU Cooling | Domestic Hot Water |
|---|---|---|---|---|---|
| Helsinki BAU | 33.09 | 37.96 | 5.63 | 4.21 | 7.76 |
| Helsinki EE | 32.94 | 15.10 | 4.96 | 4.10 | 7.76 |
| Helsinki nZEB | 6.26 | 3.57 | 2.50 | 0.30 | 7.76 |
| London BAU | 31.69 | 55.00 | 3.40 | 7.61 | 7.76 |
| London EE | 18.37 | 14.86 | 5.30 | 7.31 | 7.76 |
| London nZEB | 3.16 | 0.75 | 0.29 | 11.62 | 7.76 |
| Bucharest BAU | 82.57 | 65.18 | 18.57 | 27.00 | 7.76 |
| Bucharest EE | 46.80 | 20.90 | 16.26 | 23.74 | 7.76 |
| Bucharest nZEB | 9.93 | 1.95 | 0.64 | 26.93 | 7.76 |

**Table 6**
Delivered energy (kWh/m$^2$/year) comparisons for nZEB case with ideal heater and coolers (IHC), radiant floor panels (RFP) and radiant ceiling panels (RCP) of all three climate zones.

| | Hel nZEB (kWh/m$^2$/year) | | | Lon nZEB (kWh/m$^2$/year) | | | Buc nZEB (kWh/m$^2$/year) | | |
|---|---|---|---|---|---|---|---|---|---|
| | IHC | RFP | RCP | IHC | RFP | RCP | IHC | RFP | RCP |
| Lighting electricity | 8.9 | 8.9 | 8.9 | 8.3 | 8.3 | 8.3 | 9.8 | 9.8 | 9.8 |
| Appliances electricity | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| HVAC electricity | 14.3 | 14.4 | 10.9 | 15.4 | 9.4 | 10.7 | 14.7 | 10.4 | 12.3 |
| Total electricity | 41.2 | 41.3 | 37.8 | 41.7 | 35.7 | 37 | 42.5 | 38.2 | 40.1 |
| Space heating (DH) | 9.4 | 9.7 | 9.7 | 4.0 | 3.1 | 3.2 | 12.8 | 11.8 | 11.5 |
| Hot water (DH) | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 |
| Total heating | 17.6 | 18 | 18 | 12.3 | 11.3 | 11.5 | 21.1 | 20.1 | 19.7 |
| Total Cooling | 0.4 | 0.6 | 2.5 | 3.9 | 3.7 | 7.3 | 11.2 | 8.8 | 8.9 |
| Total | 59.2 | 59.9 | 58.3 | 57.9 | 50.7 | 55.8 | 74.8 | 67.1 | 68.7 |

**Table 7**
Typical parameters to achieve an nZEB office building in three types of climate zones.

| Parameter or measures required to achieve nZEB | Discussion for heating-dominated, moderate and cooling dominated climate zones |
|---|---|
| Building envelope U value, W/(m$^2$K) | Average U value for Helsinki is 0.1931 W/(m$^2$K); for London is 0.1998 W/(m$^2$K) and for Bucharest is 0.3411 W/(m$^2$K) |
| Window glazing U-value and g value<br>Lighting control and power | Please refer to Table 2 Building envelope properties and building operational parameters used as input values for simulations |
| Ventilation min. air flow | Based on national regulations, for example, 0.15 l/s,m$^2$ during office hours |
| Ventilation max. air flow (l/s,m$^2$) | Typical average value during occupancy was 1 l/s,m$^2$, about 3 l/s,m$^2$ extra should be reserved in case of cooling peaks |
| Ventilation heat recovery (%) | For heating dominated and moderate climate zones >80% is recommended, for cooling dominated zones >75% was found to be sufficient |
| Demand controlled ventilation or Variable Air Volume with CO$_2$ control and temperature control | It is recommended for all nZEB buildings as it minimizes the unnecessary ventilation based on occupancy while maintaining thermal comfort of the occupants |
| Low-temperature heating | Recommended for all climate zones, as it was found to enable higher efficiency in the heat pump |
| High-temperature cooling | Having high-temperature cooling allows a substantial share of cooling which can be harvested from the geothermal energy piles if they are used for energy generation |
| Heating emission in space | Radiant heating panel with supply temperature 35–40 °C in the design point is recommended. Based on this study, RFP for heating are not recommend, as it results in control challenges due to intermitted operation of heating and long-time constants of a zero energy building |
| Cooling emission in space | Radiant cooling panels together with CAV can be used. Supply temperature should be at least min 17 °C in the design point. Cooling peaks should be supported by the ventilation. Based on this study, RFP for cooling is not suggested, as it presents some control challenges due to intermitted operation of heating and long-time constants of a zero energy building |
| Cooling in the ventilation unit | Supports the space cooling during cooling demand peaks. Sizing between 7/12 °C is recommended to enable the dehumidification during hot and humid seasons. |
| Night cooling | Natural ventilation approach resulted as the best outcome among others. It needs a vast amount of air change rates. If it is arranged with mechanical fans, the energy efficiency benefit might be lost |
| Heating set point set-back during unoccupied hours<br>Cooling set point set-up during unoccupied hours | The possibility of high morning peaks for both heating and cooling set points. The intelligent control can avoid the use of chiller for cooling and heating in the first hours of the occupancy. If renewable energy systems such as geothermal energy piles coupled with heat pump are available, the intelligent control can use the pile-cooling and heating energy first to avoid morning peaks |
| Room level local indoor environment control | For heating, cooling, lighting and CO$_2$ |
| Humidity control in the ventilation unit | According to the local climate, it is usually not needed in the heating dominated climates |

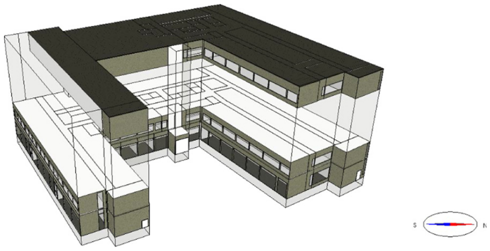

**Fig. 2.** Three dimensions' representation of ground floor, first floor and sixth floor as modeled in IDA-ICE simulation tool.

The ground floor mainly consists of meeting and has of 4.2 m floor-to-floor height. The floor-to-floor height of the second floor, third floor, fourth floor and the fifth floor are 3.6 m each, and the sixth floor is 3.9 m high.

The building performance simulation program IDA ICE version 4.2 is dynamic multi-zone simulation software used to conduct the energy simulations for this study. The simulation tool is widely used and has been validated by ASHRAE 140–2004 CEN 13791, CEN 15255, CEN 15256 (2007), Technical Memorandum 33 (TM33), and International Energy Agency SHC Task 34 [39]. The model used in this study for energy performance analysis is based on realistic measurements, components, and system types of the building. Fig. 3 presents the zones in the simulation model showing the typical ground floor plan, first-floor plan at level 4.2 m and sixth-floor plan at level 18.6 m with thermal zones . The floor plan of the second, third, fourth and fifth-floor area are duplicates, thus to simplify the model, the IDA ICE zone multiplier function was used. The simulation model has 160 zones as presented in and the model floor area is 9365.1 $m^2$.

Table S2 (in supplementary information) provides more details on zone-specific floor area, external window area, and wetted external wall area.

For the nZEB case, approximately 217 optimized rounds of dynamic simulations were carried out for all climate zones. Twelve days of dynamic start-up were used, which means twelve days were simulated before the proper simulation at the beginning of the year based on the corresponding weather file. A dynamic time step of 1.5 h with the tolerance of 0.02 was used; tolerance defines the degree of accuracy to be reached in the calculated variables. Typically, a simulation run for one location and one case lasted 1–2 h (housing an Intel® Xeon ® CPU E5-2650v2 with 32 logical processors). For the radiant heating and cooling systems, simulations lasted from 2.5–6 h. During the parametric analysis, the time was extended to 3–15 h at each attempt due to the increased number of cases.

### *3.1. Building envelope properties and operational parameters for helsinki, London, and bucharest*

Reference weather data files available from the Finnish Metrological Institute (FMI) for Helsinki 2012 were used for the simulation model. Bucharest and London weather data files were used in IDA ICE based on data from ASHRAE Fundamentals as available in the simulation program. The following describes the parameters that were changed during the simulations:

#### *3.1.1. Helsinki parameters*

originate from the Finnish Building Code D2-Indoor Climate and Ventilation of Buildings [40]; Building Code D3 – Energy Management in Buildings [41]. Some values for the EE case were used from Building Code D5 – Calculation of Power and Energy Needs for Heating of Buildings [42]. nZEB case values are based on expert knowledge and experiences. For heating demand, DH was used, and 0.94 efficiency ratio was assumed for DH supply system. Domestic hot water consumption was at 103 l/($m^2$, year) for all cases. For cooling, chillers were used with 2.5 COP (metered energy to water). The zone supply temperature setpoint was 20 °C and AHU supply temperature setpoint was 9 °C.

#### *3.1.2. London parameters*

were used as given in the National Calculation Methodology modeling guide for buildings other than dwellings in England and Wales [43]. EE case values were formulated upon the Target Zero 70% improvement in Part L emissions for an office building [44]. Commercial development of large-scale decentralized district heating plants is underway in London, [45] considering that, DH was used at an efficiency ratio of 0.94. Electric chillers for cooling energy production were similar to that of the Helsinki case.

#### *3.1.3. Bucharest parameters*

values are based on the Romanian norm C107-2005 modified in the year 2010 [46]. In Romania, minimum requirements for office U-values do not exist, but typical values for new construction are 0.60 W/$m^2$K for walls, 0.25 W/$m^2$K for roofs, 0.35 W/$m^2$K for floors and 1.30 W/$m^2$K for windows [2]. The EE and nZEB case values are based on expert knowledge and practical experiences. Bucharest has some examples of successful DH supply systems; thus, DH was used in the simulation model with 0.94 efficiency ratio, although the typical efficiency is much lower.

#### *3.1.4. Set point for temperatures for standard air handling units*

during winter the set point was 21 °C, and during summer it was less than 25 °C based on prEN15251:2015; these set points define the lower and upper limit for all office indoor environments. In this study class II, categorized as the reasonable level of expectation was used where the temperature range for heating during winter should be between 20 and 24 °C and the temperature range for cooling during summer should be between 23 and 26 °C [47]. The heating was simulated with the radiators (categorized as ideal heaters in IDA ICE), and cooling was achieved by using room conditioning units (categorized as ideal coolers in IDA ICE) with the mechanical supply of air with heat recovery [48]. For the HVAC system, Variable Air Volume (VAV), $CO_2$ and temperature control was used in the nZEB cases, the indoor temperature was reduced to 24 °C due to intermittent control and, 1 °C was gained by heating caused by the operation of the fan in HVAC unit.

#### *3.1.5. Ventilation strategies*

the $CO_2$ concentration in a zone is frequently used as a measure of the ventilation rate per occupant [49,50], being an indicator for the emission of human bio-effluents [51]. The $CO_2$ concentrations were kept at all times below 900 ppm to meet the criteria for classification level II of 800 ppm and III of 1350 ppm respectively [52]. The mechanical airflow with constant air volume (CAV) and VAV rate were between 1.5–5 $dm^3/(s\ m^2)$, i.e., depending on the size of the room. Two standard air handling units (AHUs) were modeled. The first AHU was applied to cater individual office rooms, conference and meeting rooms etc. with running times from 7:00-17:00. For all the nZEB cases, the first AHU was modeled to take advantage of VAV, $CO_2$ control and temperature control; it was kept off at occasions when the rooms are not occupied. The second AHU serviced the common areas such as storage rooms, corridors, staircases, water closets, etc. with running times from 7:00-18:00 and was operating at 25% at other times. The second air AHU was modeled with CAV for all cases (BAU, EE and nZEB).

The operational time for the fans in the first AHU were based on the presence of occupants as defined by the sched-

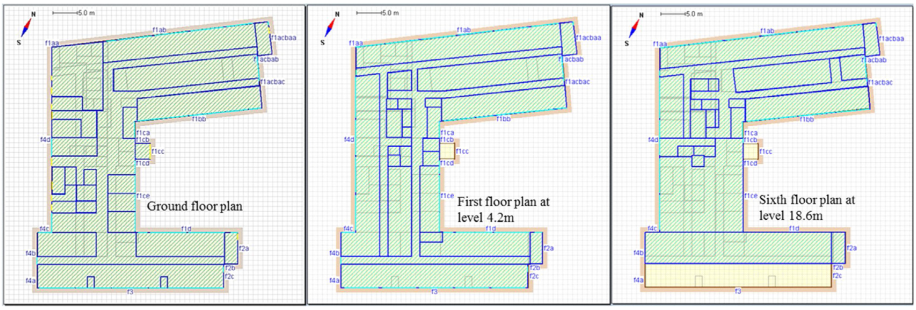

**Fig. 3.** Typical ground floor plan, first-floor plan at level 4.2m, and sixth-floor plan at level 18.6 m with thermal zones as described in Table S2, modeled in IDA ICE.

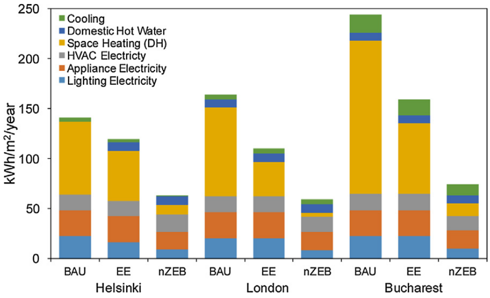

**Fig. 4.** Specific energy demand for BAU, EE, and nZEB in three climate zones.

ule. The schedule in BAU case was based on Finnish building code D3; for the EE case, the schedule was set at 25% during [7:00-8:00;17:00-18:00], 75% during [8:00-9:00; 16:00-17:00], 100% during [9:00-16:00] througout the week except Saturday's and Sunday's. For the nZEB case, the scedule was set at 25% during [7:00-8:00;17:00-18:00], 75% during [8:00-9:00;11:00-13:00; 15:00-16:00], at 100% during [9:00-11:00; 13:00-15:00] and 50% during [16:00-17:00]. The schedule was selected considering [7:00-8:00; 17:00-18:00] 25% during [7:00-8:00;17:00-18:00], 75% during [8:00-9:00; 16:00-17:00], 100% during [9:00-16:00] througout the week except Saturday's and Sunday's. For the nZEB case, the scedule was set at 25% during [7:00-8:00;17:00-18:00], 75% during [8:00-9:00;11:00-13:00; 15:00-16:00], at 100% during [9:00-11:00; 13:00-15:00] and 50% during [16:00-17:00]. The schedule was selected considering, that office workers arrive and leave the work place gradually during morning hours and evening hours. A similar approach was taken by varying the schedule during lunchtime. The HVAC system parameters are presented in Table 3.

### 3.1.6. Lighting and appliances

lighting levels at work desks were considered 500 lux 9 W/m$^2$ in office rooms based on EN1246-1:2011 and ISO 8995-1, and vary between 0- 15 W/m$^2$ based on the size and usage of the room [53,54]. The appliances for nZEB simulation cases in all three climate zones were 30% more efficient as compared to cases BAU and EE. For lighting, three parameters were varied, including rated input per unit, luminous efficacy, and the convective fraction. The T-5 regular fluorescent tube was used, which has a higher luminous efficacy than T8 or T12 lamps, which are commonly used in office buildings. In this study, 50 lm/W was used as the input value for luminous efficacy, which is the value at the desk, due to typical optical properties of luminaires. Corridor lighting was modified which was kept at 100% during office hours and 50% during non-office hours: 100% [7:30–18:00], 20% otherwise. Occupancy was set at 15 m$^2$/occupant. The lights for storage rooms and technical rooms were always kept off on the schedule. For the zero energy cases, intelligent lighting with presence and daylight controls was considered 95% during office hours to 5% during non-office hours. The equipment load was reduced to 70% for all nZEB cases; this load reduction can be realistically achieved by using power management system.

### 3.1.7. Alternative heating, cooling and ventilation concepts for nZEBs

The nZEB cases of all three locations were used as a base to apply alternative heating and cooling solutions. From heating and cooling emission point of view, radiant floor panel (RFP) and radiant ceiling panel (RFP) were also shown as variant systems by [36]. The choice of alternative heating and cooling system were made based on the market availability, applicability and control accuracy. The cost-efficiency, while not evaluated in this study, was considered indirectly by restricting the choice of parameters to available solutions on the market. Other than that, hypothetical scenarios to enable future coupling of diverse renewable energy technologies with the building for it to become nZEB were considered.

For the nZEB case, the heating was simulated with the radiator, which is categorized as ideal heaters in IDA ICE, and cooling was achieved by using room conditioning units. These units were removed and replaced with RFP and RCP systems. The design power for RFP was 40 W/m$^2$ with $\Delta$T (water) at design power of 5 °C with a sensor based on air temperature. In IDA ICE, the temperature differences and the design power is used to calculate supply mass flow. Additionally, when VAV is used together with alternative cooling systems in IDA ICE, the control algorithm uses VAV first, and set points of other room units are automatically offset by 2 °C. The design power for RCP was sized manually for each and every 160 zones depending on the availability of ceiling area of the case building (see beam structure in graphical abstract) . The sizing was done to operate the RCP system effectively as presented in Section 4.2. The design conditions $\Delta$T (water-zone air) at design power were between 6.5-16.5 °C, and $\Delta$T (water) at design power were set at 3–5 °C. The modelling approach in the steady state applied in IDA ICE is based upon the resistance method described in the standard EN 15377-1 [48].

## 4. Results and discussion

### 4.1. BAU, EE, and nZEB

The overall results demonstrate a significant improvement in building energy performance and reduction in total energy supplied to the building for both EE and nZEB cases as compared to BAU. The delivered energy demand in kWh/m$^2$/year for heating, cool-

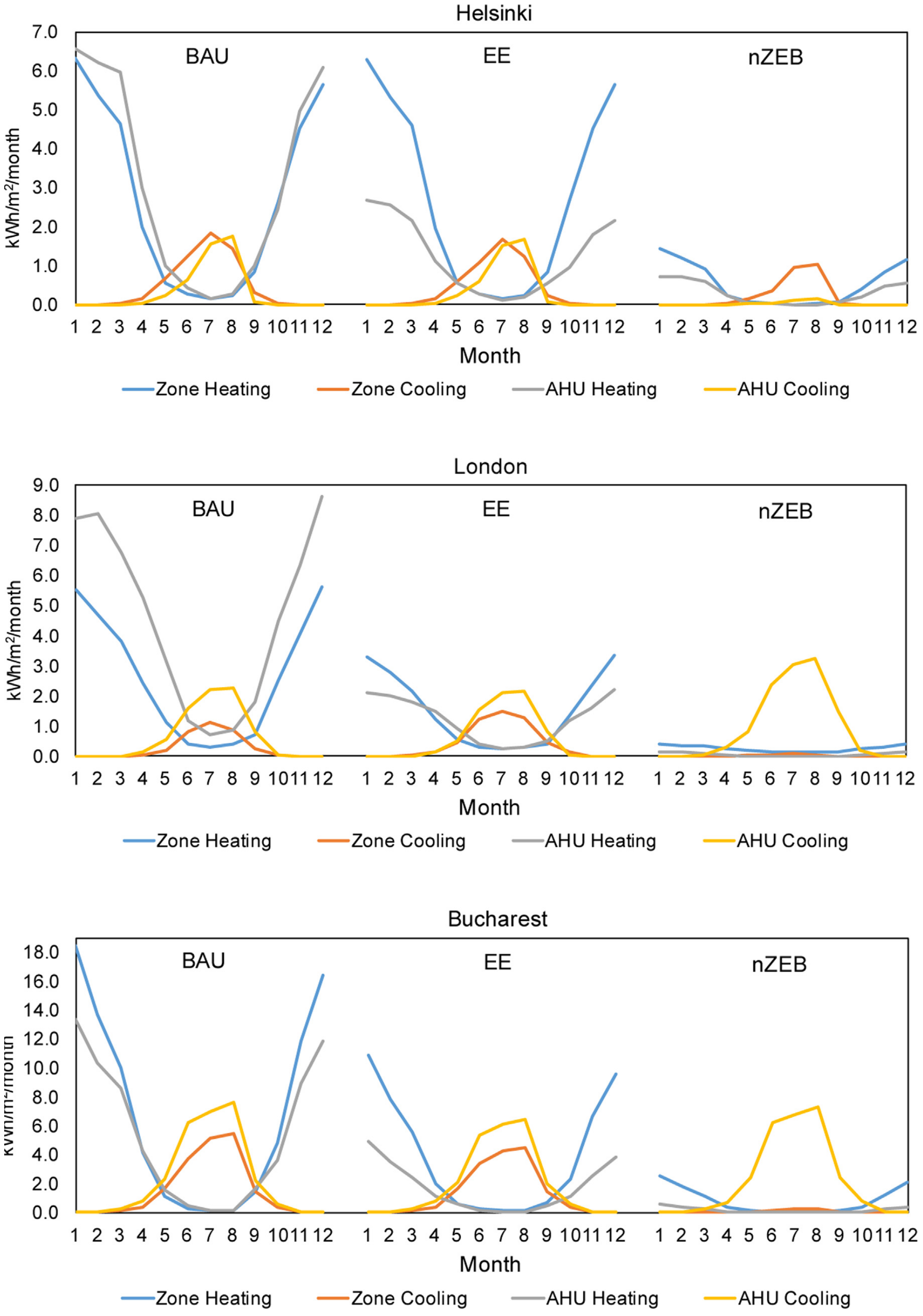

Fig. 5. Monthly zone and AHU heating and cooling demand for BAU, EE, and nZEB in three climate zones. Note: the y-axis upper-limit is different for each location.

ing and electricity usage for three performance levels in Helsinki, London, and Bucharest climate zones is presented in Fig. 4 and Table 4. These results account for the combination of the parameters, which were improved incrementally through the BAU, EE case and nZEB case, as evident through chooseninput variables in Table 2 and Table 3.

For Helsinki, it is possible to reduce the space heating load by 86% and electricity consumed by lighting, appliance, and HVAC by 32% when compared to the BAU case. There was not much reduction in the cooling load since the demand for seasonal cooling is rather small. Similarly, for London, the heating load is reduced by 95%, cooling load is slightly increased, and electricity demand is decreased by 33% in the nZEB case. For Bucharest, most energy savings can be seen in heating by 92%, cooling energy demand reduced by 60% and electricity consumption by 34% as compared to the BAU. The BAU input values for Bucharest were rather poor and were chosen based on existing office buildings. They may not represent the new construction scenario. Section Section 4.1.1 further elaborates on the effect of changing building envelope, windows and lighting strategies on the energy consumption, and Section Section 4.1.2 describes the effects of parameters chosen on reducing the delivered energy demand for HVAC control strategies in the building.

Month-by-month variations in heating and cooling demand for BAU, EE, and nZEB cases for all three climate zones are presented in Fig. 5. The y-axis is scaled differently for each climate zone to improve visualization of the results. The annual pattern in heating and cooling demand remains similar across all three cases for each city, however, the magnitude is systematically reduced between BAU and nZEB cases due to energy performance improvements in HVAC and building envelope parameters. For all climate zones, monthly zone heating and cooling and AHU heating energy demand are reduced between BAU and nZEB. However, the reduction in AHU cooling between BAU and nZEB is less noticeable, and for London, actually increases from 7.61 to 11.62 kWh/m$^2$/year. This is because the temperature setpoint for the nZEB VAV, $CO_2$ and temperature control is reduced from 25 to 24 °C. Thus, additional energy input into the cooling coils of the AHU is required to maintain the lower temperature.

### 4.1.1. *Building envelope and lighting*

The building envelope and its structural properties have a significant role in building energy performance. The properties of the external and internal walls, roof, intermediate floors, outside windows, and doors and their frames were enhanced for all three climate zones across all cases. The volume of the model was 34801.4 m$^3$. Average U-value for the model varied for all cases. For example, for Helsinki BAU to Helsinki nZEB, the average U-value varied from 0.3523 W/(m$^2$K) to 0.1931 W/(m$^2$K). Fig. 6 shows the amount of total (net) thermal energy supply and losses during the year. Evidently, the building insulation properties of Helsinki (Table 2) are relatively better in comparison to those of London and Bucharest. This is mainly due to the colder climate requiring better building envelope properties to reduce heat losses. During the parametric analysis, it was found that for a typical commercial multi-storey building, the lower roof and floor U-value (W/m$^2$K) is less important. For example, the roof U-value for the nZEB Helsinki case was preferred to be 0.9 W/m$^2$K instead of 0.5 W/m$^2$K because the influence on heating energy was marginal as compared to the investment cost.

Among other parameters, reducing window U-values from 1 W/m$^2$K from the BAU to 0.45 W/m$^2$K and g-value from 0.35 to 0.24 for the Helsinki nZEB case reduced the solar losses by 96% yearly. For London, the average U-value for BAU case was 0.5722 W/(m$^2$K) and the nZEB case was 0.1998 W/(m$^2$K). The window and solar losses for London were reduced by 100% from BAU to the nZEB case. Solar gains of 3.71 kWh/m$^2$/year were observed in London nZEB. As can be seen from Fig. 6, mechanical supply air forms a large need for thermal energy losses in all cases in all locations, but in comparison to BAU cases it was reduced by 35% in Helsinki nZEB case, 15% in London nZEB and 24% in Bucharest nZEB. For Bucharest, the average U-value for BAU was 1.085 W/(m$^2$K), and for nZEB, the average U-value was 0.3411 W/(m$^2$K). The Bucharest BAU insulations were comparatively weaker than those of Helsinki and London, leading to greater reduction in thermal losses of 17 kWh/m$^2$ by varying the wall U-value from 0.80 W/m$^2$K to 0.30 W/m$^2$K. Solar gains of 4.13 kWh/m$^2$/year were observed in Bucharest EE case and & 6.25 kWh/m$^2$/year were observed in Bucharest nZEB case.

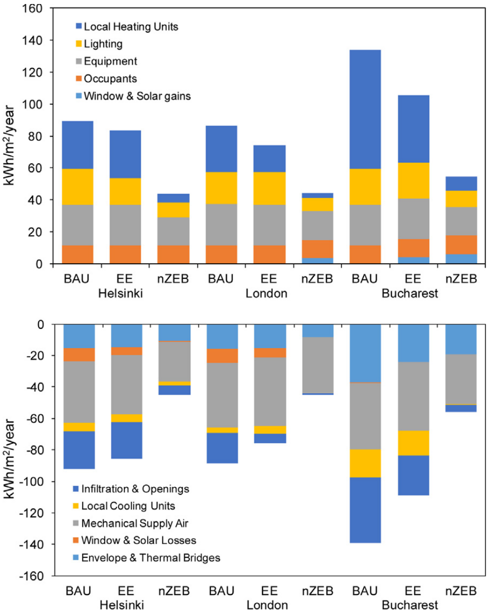

**Fig. 6.** Total thermal energy supply and losses for each case.

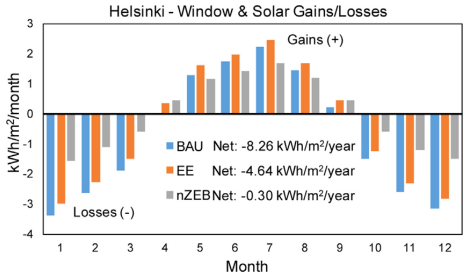

**Fig. 7.** Monthly variation in window and solar energy gains and losses for Helsinki BAU, EE, and nZEB cases.

Minimizing solar gain is vital and can be better controlled by influencing the g value depending on the energy demand. As an example, the window and solar gains and losses are shown for each month of the year in Fig. 7 for Helsinki BAU, EE, and nZEB cases, along with the corresponding annual net gain or loss. The net effect over the period of twelve months for Helsinki resulted in a loss and thus doesn't show a window and solar gain in Figure 6. Also, window daylight transparency for nZEB cases was adjusted to be less than 0.45 to enable daylight savings working in tandem with the electrical lighting systems. This lighting control strategy reduced electricity use by using artificial light and provided indirect benefit by reducing internal heat gains by 30% in nZEB cases and the respective cooling load. Presence lighting control was also applied by altering the use of artificial light in various spaces depending on the presence of occupants in the areas in all nZEB cases. This parameter reduced the heating gains as a result of lighting by 60% from

BAU to nZEB cases for Helsinki and London; for Bucharest nZEB case, these gains were reduced by 57%.

#### 4.1.2. HVAC and infiltration

Mechanical ventilation and infiltration of the outdoor air have significant impacts on the annual energy demand of a building. Along with the tightened building envelope, heat recovery methods along with VAV, $CO_2$ and temperature control in the spaces were incorporated in all nZEB cases. For all three climate zones, BAU and EE case included a CAV ventilation system with heat recovery. Across all climate zones, improved heat recovery was applied to support the transfer of heat from the effluent airstream to the influent air stream, therefore, retaining part of the thermal energy. The effectiveness of the heat exchanger in the heat recovery system for Helsinki increased from 0.5 to 0.79 for AHU 1 between BAU and EE cases, resulting in increased heat recovery from 49.41 to 70.56 kWh/m$^2$/year. Due to the enhanced heat recovery, the amount of energy needed to heat the supply air (AHU heating) decreased from 27.05 to 5.81 kWh/m$^2$/year in AHU 1. A similar trend was observed in the London and Bucharest cases. The VAV, $CO_2$ and temperature control in IDA ICE can both heat and cool with the supply air and can force air depending upon the maximum limit set. Therefore, the airflow rate varied based on occupancy aiding in minimizing the additional ventilation at the same time while maintaining the zone temperature. Table 5 presents the load distribution with zone heating/cooling, which is delivered from the ideal heaters and coolers (IHC), AHU heating is the heat supplied to all heating coils of the AHU, and AHU cooling is the energy removed by all cooling coils of the AHU. DHW remained constant and represented the energy delivered to the hot water circuit. The cumulative results in Table 5 demonstrate that by using the combination strategies, it is possible to reduce the AHU heating and zone heating demand significantly.

As shown in Table 3, the input variables for demonstrating lower supply and exhaust fan efficiency (0.6) in all nZEB cases is due to the VAV which is increasing or decreasing the pressure drop in the air according to the requirement in the zones, resulting in lower operating efficiency value for the fan. For example, in each city, the supply/exhaust pressure head increased from 780/770 Pa for BAU and EE to 1200/1200 Pa for nZEB as CAV was replaced by VAV. However, the power loss of mechanical supply air additionally is dependent on the reduced airflow due to the adjustment of the operation of the fan for the VAV system.

### 4.2. Radiant floor panel and radiant ceiling panel systems

The nZEB cases of all three locations were used as a base to apply alternative heating and cooling solutions. For the nZEB case, the heating was simulated with the radiator, which is categorized as ideal heaters in IDA ICE, and cooling was achieved by using room-conditioning units. These units were removed and replaced with radiant floor panel (RFP) and radiant ceiling panel (RCP) systems. Fig. 8 presents the results of the comparative analysis as delivered energy (kWh/m$^2$/year) of the radiant floor panel (RFP) and radiant ceiling panel (RCP) systems for Helsinki, London, and Bucharest. As evident from the results, there are small differences in absolute consumption demand for heating, cooling, and electricity for three cases in each location. The specific energy/m$^2$ for heating remained nearly the same in all systems for all three cases in each location. Marginal difference in heating energy required for space heating can be seen for London nZEB IHC and London nZEB RCP of 0.8 kWh/m$^2$/year and for Bucharest nZEB IHC and Bucharest nZEB RCP case of 1.3 kWh/m$^2$/year. Figure 8 shows the annual distribution of zone heating, zone cooling, AHU heating and AHU cooling. The heating and cooling in building zones was supplied via IHC, RCP and RFP. For the IHC, the cooling energy is limited to the air flow rate supplied by the duct. For radiant floor panel systems, the design points for heating at 35/30 °C and cooling at 17/20 °C were found to be favorable; additionally, the air system requires 3l/sqm$^2$ for dehumidification and control accuracy. RFP has the availability of large surface area for heat exchange offering greater flexibility to varying design load. It can handle heating at a low temperature and cooling at high temperature, but requires supporting air based cooling during the humid season. Whenever the cooling load is large due to internal gains, the VAV-ventilation with cooled air will handle the extra cooling demand. However, the challenge in the case building remains that extra 100 mm thick concrete slab is required and should be part of the building structure if RCP system was to be implemented.

For radiant ceiling panel, the design points for heating at 40/35 °C and cooling at 17/20 °C were found to be optimum. The benefit was mainly seen because it can be effortlessly controlled. However, it had limited capacity and was found to be sensitive to the high internal load levels because of restricted heat exchange space which was approx. 50% due to the beam structure in the case building. During the robustness test (not presented in this paper), it was noted that the increases in equipment load elevate the heat dissipation from the equipment, thereby necessitating greater cooling through the ceiling panel cooling system. As shown in Fig. 8, limited temperature exchange surface may increase the air flow rate but supplies it at lower temperature for the same load. However, radiant ceiling panel seems to accommodate different internal loads reasonably. It also requires higher temperature level for heating and supporting VAV based cooling during peaks when compared to the radiant floor panel system.

### 4.3. Near optimal solutions for nZEB

The energy savings for space heating can be achieved by reducing envelope transmission and infiltration losses, using high-efficiency heat recovery system, utilizing solar gains and by choosing a heating system which can distribute heat efficiently in spaces. To avoid a high cooling load, the solar gains during summer can be reduced by integrating blind within windows, using ventilation cooling during night time. Delivered electricity can be reduced by using high-efficiency electric appliances, intelligent lighting with presence and daylight controls, reducing fan and pump energy in HVAC unit. Table 7 presents the typical parameters, which can be deduced from this study. These parameters (i) can be applied to reduce the amount of delivered energy or net energy supplied the office building and (ii) can be conveniently set and perform in three different climate zones, which are heating dominated (similar to Helsinki), moderate climate zones (similar to that of London), and climate zones, which have balanced demand of heating and cooling annually (similar to that of Bucharest).

### 4.4. Limitations

Many European countries calculate and compare primary energy instead of end-use energy [55]. Primary energy is defined as the total amount of a natural resource needed to produce a certain amount of end-use energy, including extraction, processing, transportation, transformation and distribution losses down the stream [56,57]. End-use energy is the final delivered energy to the building, required for space heating, hot water, cooling, and electricity, often also referred to as final energy. BPIE argues that “that the current approach using the Primary Energy Factors (PEFs) is detrimental to understanding the real energy performance of a building”[58]. The primary energy factors are often based on politics after strong lobbying by different stakeholders including energy carriers and do not as such reflect the actual physics of the real energy chains. Drawing energy balance boundaries around a single service or goods, as in the case of ZEBs, may lead to shortfalls in energy and emis-

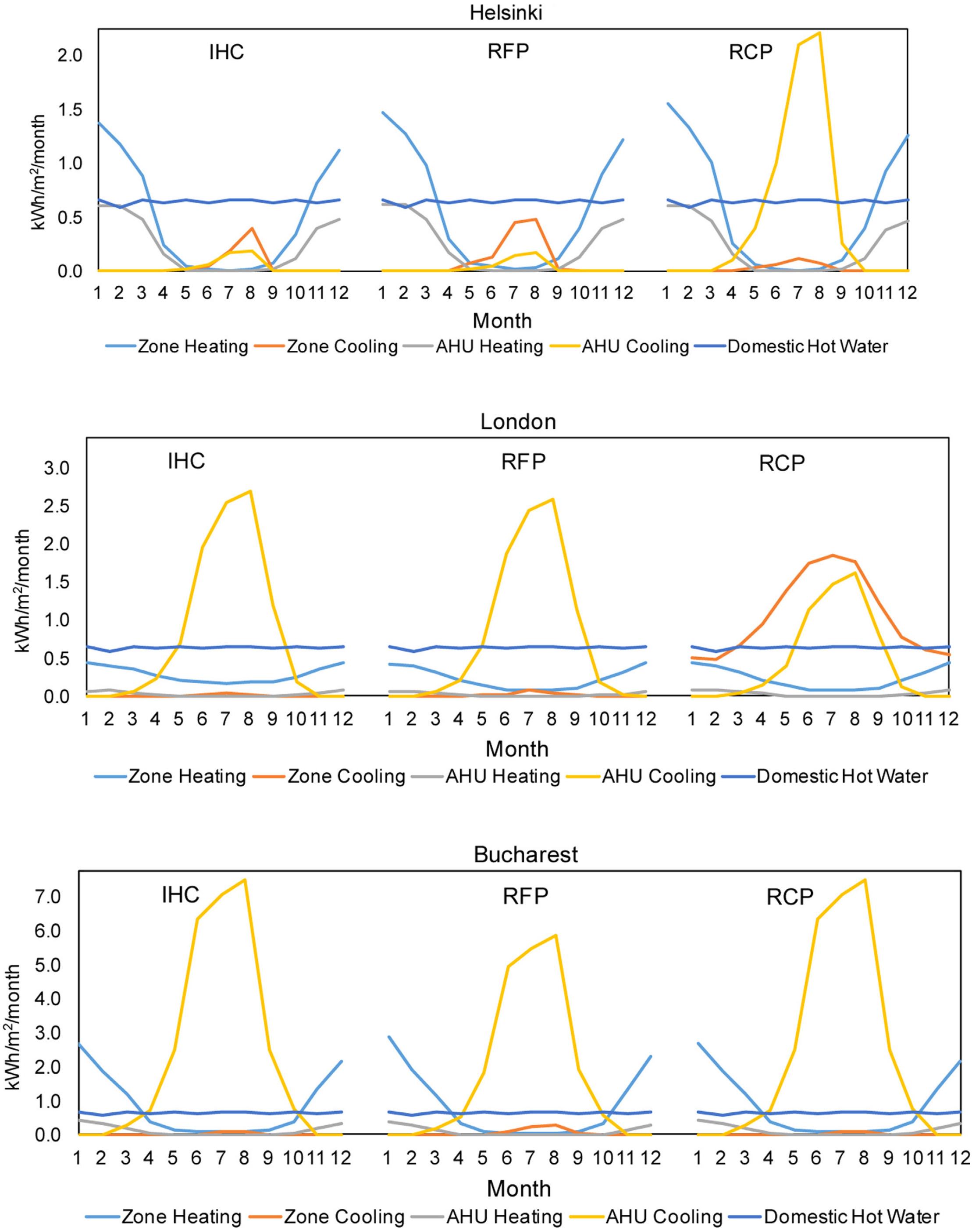

**Fig. 8.** Annual distributions between zone heating/cooling versus AHU heating and cooling for ideal heaters and coolers (IHC), Radiant floor panel (RFP) and Radiant ceiling panel (RCP). Note: the y-axis upper-limit is different for each location.

sion accounting [59]. So, it was selected to consider annual end-use energy demands on a building level rather than primary energy.The comparative analysis of heating and cooling demand is not affected by country or region specific primary energy factors. However, the approach selected enables to continue the analyses on a macro-level, e.g. country-level, by also using the primary energy approach.

At times, the simulation model was too complicated because of intermittent HVAC controls during radiant heating and cooling systems simulation, which had VAV, $CO_2$ and temperature control. The solver attempted to run the single case of radiant ceiling panels over 17 h to 5 days. This issue was resolved by editing minimum supply air temperature set point by 1 °C and gaining it by heating caused by the operation of the fan in HVAC unit. On the contrary, the control system could have been modeled better by the authors to avoid this problem.

DH was found to be prevalent in Romania, and thus typical DH losses of 6% were applied to the EE and nZEB cases in the model. However, based on [60] the system-wide energy losses in DH are rather high ranging from 35%-75% including generation, transport, distribution and final consumption. This may mean that the heating demand in Romania can be further decreased than as presented in Fig. 4 if the efficiency rate was chosen to be 0.65 in the simulations.

## 5. Conclusion

This study presented full-scale energy performance simulations of an office building with 160 zones. Three cases of building as usual based on country specific regulation, energy efficient case and nearly zero energy case were simulated for three climate zones of Helsinki, London and Bucharest. The objective was fulfilled by reducing the amount of delivered energy or net energy supplied to the office building and the results demonstrated that the chosen parameters can be conveniently set and perform in three different climate zones. Typical parameters to achieve a nearly zero energy building were recommended in Table 7 based on the finding of this study. For Helsinki, it is possible to reduce the space heating load by 86% and electricity consumed by lighting, appliance, and HVAC by 32%. For London, the heating load is reduced by 95%, cooling load is slightly increased, and electricity demand can be decreased by 33%. For Bucharest, 92% of energy in heating can be saved, and cooling energy demand was reduced by 60% and electricity consumption by 34%. The overall conclusion suggests that it is easier to minimize the heating and cooling demand by using energy efficient measures than having to reduce the electricity consumption in office buildings. On the other hand, if the energy generated by renewables is coupled with the building, the production can straightforwardly support the required delivered energy for the electricity.

The nearly zero energy cases were further studied in all climate zones with two alternative heating and cooling solutions using radiant floor panels (RFP) and radiant ceiling panels (RCP). Both radiant heating and cooling systems are feasible solutions that can be readily implemented into a building design. There are small differences in absolute consumption demand for heating, cooling, and electricity for three cases in each location. The specific energy/$m^2$ for heating remained nearly the same in all systems for all three cases in each location. Marginal difference in heating energy required for space heating can be seen for London nZEB IHC and London nZEB RCP of 0.8 kWh/$m^2$/year and for Bucharest nZEB IHC and Bucharest nZEB RCP case of 1.3 kWh/$m^2$/year. RFP has the availability of large surface area for heat exchange and can provide heating at a low temperature and cooling at high temperature, but requires supporting air based cooling during humid season. For RCP, limited temperature exchange surface may increase the air flow rate but supplies it at lower temperature for the same load.

To further develop this study for achieving a net zero energy building with annual balance of zerokWh/$m^2$, ground source heat exchangers can be added to support the use of heat pump and chiller. Solar collectors can be installed to supply hot water demand and if required to re-inject heat into the ground source heat exchanger. Also, a heat pump can support the AHU and hot water needed for radiant panel heating, whereas, an AHU based chiller can be used for radiant panel cooling. In addition to that, an auxiliary electric heater can be added if the solar collectors and heat pump are unable to fulfill the demand. It would become essential to consider thermal storages for heating, hot water, and cooling.

## Acknowledgements

This work was supported by project ZEMUSIC (*Zero energy solutions for multifunctional steel intensive commercial buildings*), grant number RFSR-CT-2011-00032 by the European Union's Research Fund for Coal and Steel (RFCS) research programme. The authors would like to thank Jyrki Kesti from Ruukki Construction for leading the coordination of ZEMUSIC project. Nusrat Jung was also funded by energy efficiency in systems (EES) grant from the Academy of Finland. The authors would like to thank Teemu Vesanen from VTT Technical research Centre of Finland for helping with the simulation model. We would also like to thank Ala Hasan from VTT for insightful discussions. We owe gratitude to Mika Vuolle and Erkki Karjalainen from EQUA Finland for being prompt in answering our queries regarding our simulation model.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.enbuild.2017.10.030.

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**Table S1**. Total Specific Energy in kWh/m$^2$/year of the reference cases used in simulation studies.

| **Reference** | **Helsinki ,Finland** | **Heating** | **DHW** | **Cooling** | **Lighting** | **Auxiliary** | **Total specific energy** |
|---|---|---|---|---|---|---|---|
| Ahmed, K. et al. (2015) (Ahmed *et al.*, 2015) | Simulation tool+ measured data: IDA ICE<br>Year: 2012 (calibrated reference cáse with CAV)<br>No. of floors: 8 story + 3 basement, measured and simulated zone: & 6th floor, 382.6 m$^2$<br>Gross floor area: 9100 m$^2$, Orientation: North-south | 21.3 | 7.7 | 16.6 | 21.6 | 27.3 | 86.8 |
| Ahmed, K. et al. (2015) (Ahmed *et al.*, 2015) | Simulation tool + measured data: IDA ICE<br>Year: 2012 (calibrated reference cáse with DCV)<br>No. of floors: 8 story + 3 basement, measured and simulated zone: & 6th floor, 382.6 m$^2$<br>Gross floor area: 9100 m$^2$, Orientation: North-south | 11.6 | 7.7 | 11.6 | 21.6 | 24.9 | 69.7 |
| ENTRANZE, P. Zangheri et al. (2014)(Zangheri *et al.*, 2014) *the numbers were extrapolated from table 12 on page 69 | Simulation tool: EnergyPlus v7.0-7.2<br>Year: 1960-1970<br>No. of floors: 5 stories<br>Gross floor area: 2400 m$^2$<br>Orientation: South-north | 244.7 | 10.2 | 4.7 | n.a. | n.a. | 259.6 |
| Mohamed, A. et al. (2015) (Mohamed *et al.*, 2015) | Simulation tool: IDA ICE<br>Year: 2012 (reference cáse)<br>No. of floors: 6 story<br>Gross floor area: 5615 m$^2$, Orientation: East-west | 61 | 6.0 | 8.9 | 22.3 | 35.6 | 133.9 |
|  | **London, United Kingdom** | **Heating** | **DHW** | **Cooling** | **Lighting** | **Auxiliary** | **Total specific energy** |
| Boyano, A. et al. (2013) (Boyano *et al.*, 2013) | Simulation tool: EnergyPlus,<br>Year: 2010 (base case)<br>No. of floors: 3 story + 1 basement<br>Gross floor area: 4620 m$^2$,<br>Orientation: East-west | 16.96 | 3.84 | 9.97 | 38.52 | 3.22 | 72.51 |
| Boyano, A. et al. (2013)(Boyano *et al.*, 2013) | Simulation tool: EnergyPlus,<br>Year: 2010 (base case)<br>No. of floors: 3 story+1(basement),<br>Gross floor area: 4620 m$^2$,<br>Orientation: North-south | 15.42 | 3.84 | 9.63 | 38.52 | 3.22 | 70.63 |
|  | **Bucharest, Romania** | **Heating** | **DHW** | **Cooling** | **Lighting** | **Auxiliary** | **Total specific energy** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| BPIE (2012) (Buildings Performance Institue Europe (BPIE), 2012) *the numbers were extrapolated from figure on page 34 | Simulation tool: TRNSYS v.17<br>Year: n.a.<br>No. of floors: 3-5 stories<br>Gross floor area: 2817 m$^2$<br>Orientation: n.a. | 56 | 3.60 | 22 | 20 | 8 | 109.6 |
| ENTRANZE, P. Zangheri et al. (2014)(Zangheri *et al.*, 2014) *the numbers were extrapolated from table 12 on page 69 | Simulation tool: EnergyPlus v7.0-7.2<br>Year: 1960-1970<br>No. of floors: 5 stories<br>Gross floor area: 2400 m$^2$<br>Orientation: South-north | 118.6 | 9.3 | 37.4 | n.a. | n.a. | 165.3 |

Ahmed, K., Kurnitski, J. and Sormunen, P. (2015). Demand controlled ventilation indoor climate and energy performance in a high performance building with air flow rate controlled chilled beams, *Energy & Buildings* 109: 115–126. Retrieved from http://dx.doi.org/10.1016/j.enbuild.2015.09.052

Boyano, A., Hernandez, P. and Wolf, O. (2013). Energy demands and potential savings in European office buildings: Case studies based on EnergyPlus simulations, *Energy and Buildings* 65: 19–28. Retrieved from http://dx.doi.org/10.1016/j.enbuild.2013.05.039

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**Table S2.** Description of the office zones and their respective parameters in IDA ICE model

| | **Zone Floor** | **Zone Name/Function** | **Zone Multiplier** | **Floor area, m$^2$** | **Ext win. area, m$^2$** | **Wetted external wall area, m$^2$** |
|---|---|---|---|---|---|---|
| 1 | Ground Floor | Conference room 1 | 1 | 20.72 | 11.886 | 3.822 |
| 2 | Ground Floor | Conference room 2 | 1 | 20.75 | 11.707 | 4.027 |
| 3 | Ground Floor | Conference room 3 | 1 | 23.87 | 12.508 | 5.594 |
| 4 | Ground Floor | Technical space | 1 | 12.05 | 0 | 7.44 |
| 5 | Ground Floor | Transformer substation | 1 | 14.43 | 0 | 19.47 |
| 6 | Ground Floor | Storage and toilet for physically challenged | 1 | 8.742 | 0 | 0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 7 | Ground Floor | District heating and water metering | 1 | 11.46 | 0 | 3.366 |
| 8 | Ground Floor | Technical space | 1 | 9.751 | 0 | 0 |
| 9 | Ground Floor | Toilet 1 | 1 | 12.96 | 0 | 0 |
| 10 | Ground Floor | Toilet 2 | 1 | 8.156 | 0 | 0 |
| 11 | Ground Floor | Lobby 1 | 1 | 3.274 | 26.407 | 1.937 |
| 12 | Ground Floor | Lobby 2 | 1 | 3.246 | 22.375 | 2.269 |
| 13 | Ground Floor | Office and mail | 1 | 34.94 | 9.1 | 6.763 |
| 14 | Ground Floor | Cleaning and storage | 1 | 22.75 | 0 | 15.85 |
| 15 | Ground Floor | Staircase B | 1 | 28.02 | 0 | 3.485 |
| 16 | Ground Floor | Staircase D | 1 | 17.88 | 0 | 9.221 |
| 17 | Ground Floor | Workspace and storages | 1 | 123 | 0 | 81.84 |
| 88 | Ground Floor | Work space1 | 1 | 142.8 | 67.82 | 63.56 |
| 18 | Ground Floor | Work space2 | 1 | 147.1 | 11 | 9.703 |
| 19 | Ground Floor | Lifts | 1 | 16.7 | 11.118 | 3.632 |
| 20 | Ground Floor | Work space3 | 1 | 117 | 78.137 | 48.94 |
| 21 | Ground Floor | Staircase A | 1 | 17.25 | 3.855 | 43.759 |
| 22 | Ground Floor | Staircase C | 1 | 18.83 | 2.275 | 46.84 |
| 23 | Ground Floor | Office space4 | 1 | 59.02 | 6.864 | 20.58 |
| 24 | Ground Floor | Office space5 | 1 | 88.54 | 42.469 | 33.42 |
| 25 | Ground Floor | Office space6 | 1 | 176.4 | 115.46 | 72.85 |
| 26 | Ground Floor | Corridors | 1 | 403.1 | 26.31 | 40.563 |
| 27 | Ground Floor | Lobby | 1 | 9.912 | 0 | 29.09 |
| 28 | Ground Floor | Office space | 4 | 181.7 | 61.95 | 109.64 |
| 29 | First Floor | Multi-purpose room | 4 | 9.648 | 0 | 2.246 |
| 30 | First Floor | Office space2 | 4 | 101.6 | 28.093 | 36.4 |
| 31 | First Floor | Office space3 | 4 | 54.39 | 21.19 | 27.45 |
| 32 | First Floor | Office space4 | 4 | 89.31 | 0 | 0 |
| 33 | First Floor | Office space5 | 4 | 194.9 | 57.184 | 86.04 |
| 34 | First Floor | Office space6 | 4 | 19.32 | 0 | 0 |
| 35 | First Floor | Office space7 | 4 | 190 | 65.96 | 100.09 |
| 36 | First Floor | Office space8 | 4 | 147.3 | 7.48 | 10.26 |
| 37 | First Floor | Office space 9 | 4 | 117.5 | 40.622 | 68.36 |
| 40 | First Floor | Multi-purpose room | 4 | 5.648 | 0 | 0 |
| 41 | First Floor | Storage room | 4 | 4.404 | 0 | 0 |
| 42 | First Floor | Electric meter room | 4 | 9.415 | 0 | 0 |
| 43 | First Floor | Staircase B | 4 | 18.24 | 0 | 0 |
| 44 | First Floor | Toilet for physically challenged | 4 | 4.043 | 0 | 0 |
| 45 | First Floor | Multi-purpose room | 4 | 7.03 | 0 | 0 |
| 46 | First Floor | Multi-purpose room | 4 | 5.009 | 0 | 0 |
| 47 | First Floor | Toilet 1 | 4 | 6.033 | 0 | 0 |
| 48 | First Floor | Toilet 2 | 4 | 5.799 | 0 | 0 |
| 49 | First Floor | Lift | 4 | 16.75 | 5.78 | 8.39 |
| 50 | First Floor | Toilet 3 | 4 | 9.285 | 0 | 0 |
| 51 | First Floor | Toilet 4 | 4 | 10.13 | 1.955 | 0 |
| 52 | First Floor | Corridor | 4 | 321.3 | 7.76 | 11.28 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 53 | First Floor | Staircase C | 4 | 18.91 | 2.275 | 42.27 |
| 54 | First Floor | Staircase A | 4 | 15.72 | 3.855 | 36.93 |
| 56 | Sixth Floor | Staircase B4 | 1 | 18.58 | 0 | 0 |
| 57 | Sixth Floor | Multi-purpose room | 1 | 5.009 | 0 | 0 |
| 58 | Sixth Floor | Toilet 4 | 1 | 7.494 | 0 | 0 |
| 59 | Sixth Floor | Multi-purpose room | 1 | 7.03 | 0 | 0 |
| 60 | Sixth Floor | Toilet 2 | 1 | 9 | 0 | 0 |
| 61 | Sixth Floor | Toilet for disabled | 1 | 5.25 | 0 | 0 |
| 62 | Sixth Floor | Electricity space | 1 | 2.436 | 0 | 0 |
| 63 | Sixth Floor | Mechanical room for air conditioning2 | 1 | 245.1 | 0 | 25.07 |
| 64 | Sixth Floor | Staircase A | 1 | 18.56 | 0 | 47.59 |
| 65 | Sixth Floor | Office space 14 | 1 | 190 | 65.96 | 113.92 |
| 66 | Sixth Floor | Staircase C4 | 1 | 18.91 | 2.275 | 46 |
| 67 | Sixth Floor | Office space | 1 | 25.07 | 7.48 | 11.54 |
| 68 | Sixth Floor | Office space 2 | 1 | 97.02 | 0 | 0 |
| 69 | Sixth Floor | Toilet 14 | 1 | 5.799 | 0 | 0 |
| 70 | Sixth Floor | Lifts4 | 1 | 16.75 | 5.78 | 9.57 |
| 71 | Sixth Floor | Office space 3 | 1 | 117.5 | 40.622 | 106.67 |
| 72 | Sixth Floor | Office space 3 | 1 | 62.7 | 19.958 | 0 |
| 73 | Sixth Floor | Building ICT | 1 | 26.25 | 5.695 | 9.04 |
| 74 | Sixth Floor | Multi-purpose room | 1 | 5.648 | 0 | 0 |
| 75 | Sixth Floor | Telephone cross-connection site | 1 | 6.906 | 0 | 0 |
| 76 | Sixth Floor | Technical space | 1 | 9.056 | 0 | 0 |
| 77 | Sixth Floor | Mechanical room for air conditioning 1 | 1 | 280.3 | 25.568 | 36.22 |
| 78 | Sixth Floor | Corridors | 1 | 199 | 2.72 | 10.3 |
| 79 | Semi Basement | Air handling units for air-raid shelter | 1 | 7.609 | 0 | 11.94 |
| 80 | Semi Basement | Protective shelter room 1 | 1 | 48.34 | 0 | 10.8 |
| 81 | Semi Basement | Staircase D | 1 | 17.88 | 0 | 5.36 |
| 82 | Semi Basement | Multi-purpose room | 1 | 2.258 | 0 | 0 |
| 83 | Semi Basement | Protective shelter room 2 | 1 | 37.4 | 0 | 0 |
| 84 | Semi Basement | Shower and changing room 1 | 1 | 12.7 | 0 | 6.69 |
| 85 | Semi Basement | Shower and changing room 2 | 1 | 15.17 | 0 | 0 |
| 86 | Semi Basement | Water tanks | 1 | 7.878 | 0 | 5.73 |
| 87 | Semi Basement | Trash cans | 1 | 10.28 | 0 | 3.822 |

## Appendix D: Publication IV (with supporting information)

Nusrat Jung*, Munjur E. Moula, Tingting Fang, Mohamed Hamdy, Risto Lahdelma. Social Acceptance of Renewable Energy Technologies for Buildings in the Helsinki Metropolitan Area of Finland. *Renewable Energy*. Elsevier B.V., Volume 99, Pages 813-824, 2016.

Renewable Energy 99 (2016) 813–824

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

# Social acceptance of renewable energy technologies for buildings in the Helsinki Metropolitan Area of Finland

Nusrat Jung [a, b, *], Munjur E. Moula [a, c], Tingting Fang [a], Mohamed Hamdy [d, e], Risto Lahdelma [a]

[a] Department of Mechanical Engineering, School of Engineering, Aalto University, Espoo, Finland
[b] VTT Technical Research Centre of Finland, Espoo, Finland
[c] Department of Social Research, Faculty of Social Sciences, Helsinki University, Finland
[d] Department of Built Environment, Eindhoven University of Technology, Eindhoven, The Netherlands
[e] Department of Mechanical Power Engineering, Helwan University, Cairo, Egypt

ARTICLE INFO

*Article history:*
Received 2 January 2016
Received in revised form
13 May 2016
Accepted 4 July 2016
Available online 1 August 2016

*Keywords:*
SMAA
Finland
Renewable energy
Public perceptions
nZEBs

ABSTRACT

The application of renewable energy technologies (RETs) in the residential building sector requires acceptance of technical solutions by key stakeholders, such as building owners, real-estate developers, and energy providers. The objective of this study is to identify the current status of public perceptions of RETs that are available in the Finnish market and associated influencing factors, such as perceived reliability, investment cost, payback time, and national incentives. A web-based questionnaire was disseminated to the general public in the Helsinki Metropolitan Area ($n = 246$). Social perceptions of building-integrated RETs were evaluated through integration of survey data and Stochastic Multicriteria Acceptability Analysis (SMAA), which was applied to analyse the robustness of the survey results. The SMAA demonstrated that Finnish residents exhibit broad acceptance of multiple options, rather than preference for a single RET. Solar technologies and ground source heat pumps were the most preferred options and evaluated as very reliable, whereas wind-based technologies and combined heat and power were ranked as the least popular. In general, respondents indicated a strong willingness to financially invest in RETs as a means to reduce their carbon footprint and preferred tax deductions as an incentive to invest in RETs.

## 1. Introduction

Finland provides 36.8% of total energy demand through renewable energy sources (Fig. 1), ranking near the top among European Union (EU) Member States. In accordance with the EU 2020 target, Finland aims to raise the share of renewable energy to 38% by 2020 [1,2].

Improving the energy performance of both existing and future building stock has become essential to achieve EU climate and energy objectives. These targets are focused on public transport and building sectors, where the potential for energy savings is the greatest [3,4]. The EU has also set an ambitious target to increase the number of 'nearly Zero Energy Buildings' (nZEBs). Acknowledging the variations in building culture and climate throughout Europe, the European Building Legislation (EPBD) does not prescribe a uniform approach to nZEBs [5]. The current 'National Plan of Finland' [6] also intends to increase the number of nZEBs, but does not give detailed specifications. Nonetheless, definitions of nearly zero energy construction and associated specifications are underway.

Since 1983, the Ministry of the Environment in Finland (in Finnish: Ympäristöministeriö) has been responsible for leading national efforts on energy efficiency of buildings [7]. Directive 2002/91/EC of the European Parliament and of the Council on the Energy Performance of Buildings was issued on 16 December 2002, from which amendments were applied to both existing and new buildings [8]. During the past decade, numerous incremental improvements have been made in the National Building Code of Finland to set minimum levels of energy efficiency for new buildings [9].

The Helsinki City Council approved a new energy policy

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[*] Corresponding author. Department of Mechanical Engineering, School of Engineering, Aalto University, Espoo, Finland.
*E-mail address:* nusrat.jung@aalto.fi (N. Jung).

http://dx.doi.org/10.1016/j.renene.2016.07.006

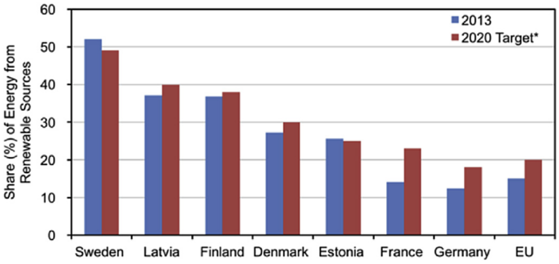

**Fig. 1.** Share of renewable energy in the final consumption of energy in selected EU Member States as a percentage [1].

guideline in 2008 which specifies increasing the share of renewable energy from 4% to 20% by 2020 [10]. This commitment by the City Council is intended to cover all energy use in areas which fall under its jurisdiction (e.g. building sector). An important part of this commitment is to activate citizens to get involved in reducing their GHG emissions and developing measures for reduction [11].

Building owners and users represent the most critical stakeholders in determining the share of energy efficiency and renewable energy technology (RET) potential for buildings as renovations are made at their cost [12]. There are several barriers which may prevent an individual from seeking an environmentally friendly home, including: cost effectiveness of the investment, lack of attractive products and services, limited knowledge, priority for comfort, and other non-energy aspects [13–15]. A study on the acceptability of nZEB renovation strategies in Norway [13] found that social and economic factors, such as initial cost, payback time, and return on investment, could significantly affect the selection of the renovation option by the home owner.

There are only a few scientific studies presenting the key factors which influence societal acceptance of renewable energy-based heating and cooling technologies in the Nordic region. The objective of this study is to identify the current status of public perceptions of RETs currently available in the Finnish market and associated influencing factors, such as perceived reliability of RETs, investment cost, payback time, national incentives, and housing type. The RETs referred to in this study can be defined as a mechanism to generate renewable energy to either support net energy need in a building or to produce surplus energy to be stored or exported to the grid. A web based questionnaire was disseminated and received 248 respondents with a 21% response rate. Selected results of the survey study were analysed with Stochastic Multicriteria Acceptability Analysis (SMAA) to identify preference rankings of different RETs in the Helsinki Metropolitan Area (henceforth referred to as Helsinki) and to identify the associated uncertainty of the rankings. The results will support policy makers, technology providers, stakeholders in the energy and building sector, and building engineers to enable development and adoption of RETs for residential buildings, including nZEBs, in urban centres of Finland.

### 1.1. *Attitudes and perceptions towards renewable energy in Finland*

The attitudes of the Finnish public towards different energy sources were investigated in an EU study (as presented in Fig. 2). In general, the public is in support of renewable energy sources [16]. Additionally, the Finnish Energy Industries have conducted annual surveys on the energy attitudes of the Finnish public since 1983 [17]. In 2006, 86% of the respondents agreed and 4% disagreed with the statement that climate change is a real and extremely serious threat that requires immediate actions. By 2014, only 75% agreed, which could mean that people are becoming immune to hearing about climate change. However, the climate change hypothesis is largely accepted by the residents of Finland.

A recent study found that residents in countries that express more environmental concerns related to energy use (e.g. Denmark, Finland, and Sweden) are also less optimistic about advancements in technology solving environmental problems in the future [12]. Another survey indicated that residents of Finland expect the public sector to be the forerunner for renewable energy production [18]. At the same time, one of the conclusions of a survey study conducted in 2007 was that Finnish residents believe their own individual consumer choices can be extremely significant in making a difference in the energy sector [19]. Our study focuses on specific RETs which have an established market in Finland and can be implemented in a nZEB or an environmentally-friendly home.

### 1.2. *Incentives to promote RETs and energy efficiency in Finland*

Often in environmental law, incentives are divided into tax-based, economic, volunteer-based, or eco-labeling. Finland has primarily used tax incentives to promote wind energy and other renewable electricity until 2010. Finland had no obligations or binding recommendations for power companies to promote energy production from renewable energy sources [20]. Economic incentives were lacking to encourage wood pellet use for thermal energy production. Recently, Finland's energy taxation and subsidies have been developed to promote GHG reduction, energy efficiency, and the use of renewable energy. In order to promote electricity generation based on renewable sources, Finland introduced a feed-in tariff system operating on market terms partially replacing the tax subsidies and some of the investment subsidies for electricity generation. In 2010, the feed-in tariff system entered into force offering electricity users to pay the difference between the market price and the feed-in tariff if the market price is below the agreed feed-in tariff [21]. The feed-in tariff system developed mainly to promote electricity production from wind power and biogas, however, it also involved other renewable sources.

Beside the above incentives, building regulations were developed in 2010, requiring additional energy efficiency measures, such as additional insulation and tighter building envelope, to be applied in new construction. Recently, regulations and guidelines codes for Indoor Climate and Ventilation of Buildings (Building Code D2), Energy Management in Buildings (Building Code D3), and Calculation of Power and Energy Needs for Heating of Buildings (Building Code D5) were revised and reformed and have been under force from July 2012.

For buildings requiring renovation, energy subsidies for the improvement of energy efficiency and changes in heating systems were granted for residential buildings, mainly for apartment blocks and terraced houses. Refurbishments of energy systems in detached houses became eligible for improved domestic help credits. Moreover, grants for energy improvements in detached houses were used as a supplementary aid for low-income households.

In Finland (2006), renovation investment was estimated to be roughly half of the total construction investment. Residential buildings account for half of the renovation activities and their share is expected to increase as the stock built in 1960–1970 will soon come to an age requiring renovation. The renovation investments for 2006–2015 are estimated to be around €1800 million per year. Due to subsidies and ownership structures, renovation activities in the rental sector are likely to be higher than in the owner-occupied sector [22].

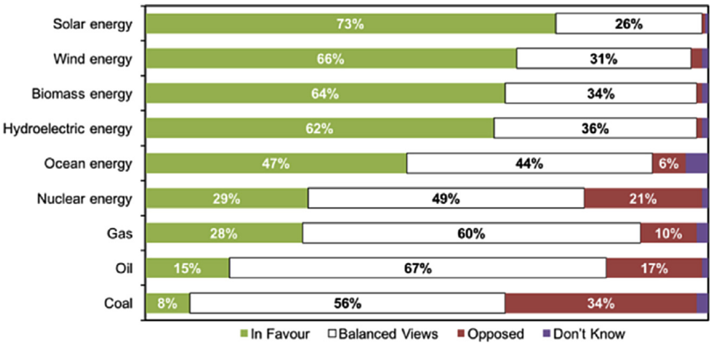

**Fig. 2.** Attitudes and perceptions of residents of Finland (in favour, balanced views, opposed, and don't know) towards different energy sources [16].

### *1.3. Social acceptance*

Societal acceptance is a major concern in energy policy and in the marketing of new innovative solutions. Social acceptance is a dynamic process rather than a static feature of a technology [23]. Societal acceptance is not merely a dichotomy, but can range from active support to active resistance. A study by Devine-Wright [24] argues that there is little clarification in research as whole about what is meant by public acceptance or public resistance and how these relate to the unit of analysis. It is commonly assumed that "public attitudes" need to change to make more radical scenarios about the implementation of RETs feasible. There is hence a need for more systematic research on public acceptance driven by coherent theoretical frameworks drawn from psychology and other social science disciplines, explicit definitions of concepts, the use of innovative methodological tools, and a greater emphasis upon symbolic and affective aspects [25].

Socio-political acceptance, community acceptance, and market acceptance of energy-efficiency and RET solutions have been distinguished in Ref. [26]. Two kinds of market acceptance were identified by Ref. [12] as "acceptance in principal" and "acceptance in actual adoption and use." Based on this classification, acceptance in principle does not necessarily mean that stakeholders are willing to, capable of, or prone to investing in or using a particular solution. The level of public acceptance in terms of actual adoption depends on the social conditions and/or investment behaviour conditions of the decision makers, such as the building owner [27]. For instance, in Refs. [18], it is presented that 53% of Finnish interviewees accept in principle that it's important to develop the RETs at the moment. However, only 43% of the sample expressed their acceptance in 'actual adoption and use' to take practical steps for renewable energy developments, e.g. installing solar panels on their roof.

Most empirical research on the public's acceptance of various RETs uses a quantitative or market research type of methodology and is, hence, not informed about the underlying social or psychological processes [24]. To measure context-based social acceptance, many indicators can be used, such as the socio-economic background, age group, political beliefs, and attitudes of the participants [18,28]. There is a need for an abrupt change in public attitudes with respect to energy use [29]. In our study, we focus on market acceptance of RETs by the general public as the key stakeholder. Such studies are necessary to go beyond case studies or national opinion polls and offer the possibility to assess to what extent differences in governance, demography, and culture are reflected in different public beliefs about energy issues in general [30].

## 2. Methodology

### *2.1. Survey design and questionnaire*

Respondents for this study were residents of Helsinki. In the questionnaire they were classified into stakeholder groups of researchers, energy company employees, industry, real estate developers, and others. During the study phase, teams of researchers were consulted periodically in working group meetings, including experts from field of social sciences and energy technology, to assist in the formulation of a web-based questionnaire survey. The questionnaire survey was prepared in three stages, where the first stage focused on identifying key topics, questions, and multiple choice formulations to achieve the tangible results (in both English and Finnish). The second stage involved a pre-test field survey ($n = 24$) conducted at central locations in Helsinki city centre (Kamppi) in order to understand the common problems in understanding the survey questions and their multiple choices addressed by the respondents. This was done to identify the difficulties that a larger number of audiences might encounter when answering the survey online, resulting in implementation of minor changes, such as using simplified words. The third stage resulted in the development and implementation of an improved web-based questionnaire (Table S1) which was disseminated through social media channels in the Helsinki Metropolitan Area (Fall 2014-Winter 2015, $n = 246$).

#### *2.1.1. Case description*

The Helsinki Metropolitan Area is divided into four sub-regions, including Helsinki, Vantaa, Espoo, and Kauniainen, with a total population of 1.4 million inhabitants and 746,280 household units, of which 31% are rented [31,32]. Types of residential housing include block of flats, detached and semi-detached houses, attached houses, and other buildings and nearly all are supplied with basic amenities [33,34]. Residential housing accounted for approximately 20% of the final energy consumption in 2013. As presented in Table S2, the three largest sources of heating are district heating, wood, and electrical heating [35]. Helsinki is an established global leader in district heating (DH), operating five combined heat and power (CHP) plants, with greater than 90% efficiency, and an advanced large scale heat pump station capable of producing simultaneously district heating and cooling. The DH provider (Helen Oy) serves 400,000 customers and provides 93% of city's heated space. Consequently, Helsinki is equipped with approximately 1200 km of underground DH pipes, making it one of the largest DH networks in the world. The city itself provides an interesting platform to study why the general public would have an interest to invest in RETs for space heating and domestic hot water, which is available for 67 €/MWh in 2015 [36].

### 2.2. Multi criteria decision problem

Stochastic Multicriteria Acceptability Analysis (SMAA) was applied to the results from segment 4 of the survey (see Table S1). A total of 8 alternative RETs that are available in Finland were considered in the survey, as listed in Table 1 with their abbreviations. The respondents were asked to rank their preference from 1 to 8, where the most favourable technology was ranked as 1 and the least favourable as 8 (shown as b1–b8 in Fig. 5). Respondents were organised into respondent groups based on how they choose to categorise their profession. The respondent groups correspond to criteria in multicriteria analysis (G1-G5). This was deliberate to separate the opinion from the 'Others' category, defined as a resident of Finland. Some of the respondents had answered the survey incompletely, and these responses were therefore removed from the analysis, as shown in the 'Removed' column in Table 2.

A typical way to analyse survey results is to use the average of a data set to derive results. Table 3 shows the average of the rankings that different respondent groups have given to the RET alternatives. The standard deviations for the average rankings were in the range 1.2–2.8, which indicates significant uncertainty in the results caused by disagreement between the respondents. Therefore, computing results based only on averages will not indicate the reliability of the overall ranking. Also, using standard deviations to assess the robustness of the results is not sufficient, because standard deviations do not carry information on the dependencies of the uncertainties. For example, respondents who prefer technology A may systematically also prefer technology B and disfavour technology C. In general, such multi-dimensional and potentially non-linear dependencies can be considered in statistical analysis only by using a simulation approach. For this reason, we use the simulation based SMAA method to evaluate the robustness of the ranking. SMAA can be used with arbitrary probability distributions for modelling both independent and dependent uncertainties in criteria measurements, but it is also possible to use sample data directly in the simulation. The article [37] compares using the criteria sample directly with applying a multivariate Gaussian distribution to represent dependent uncertainties in SMAA. In this study, we extended the sample-based approach into a two-phase sampling technique, as described later.

### 2.3. Application of SMAA

SMAA is a multicriteria decision support method for problems that involve significant uncertainty or imprecision in criteria measurements and decision makers' preference assessment [35,36]. SMAA considers simultaneously the uncertainty in all parameters. Therefore, SMAA is particularly useful for robustness analysis of different multicriteria decision models [38,39]. SMAA was initially developed to support various public environmental decision problems, such as relocating the Helsinki cargo harbour [40], developing the Kirkkonummi general plan [41], and siting waste treatment plants [42]. A recent application was the evaluation of sustainable heating choices for a new residential area in Loviisa city, Finland, that provides an overview of the background and application of SMAA [43].

The multicriteria problem is represented as a matrix $\mathbf{x} = [x_{ij}]$ of criteria measurements, where index $i$ refers to alternatives and $j$ refers to criteria. In the current problem, the measurement matrix contains 8 rows for the RET alternatives and 5 columns for the stakeholder groups corresponding to criteria. The criteria are combined together by a utility or value function u ($\mathbf{x}_i$,$\mathbf{w}$), which computes for each alternative an overall utility value $u_i$ based on criteria measurements and subjective weights $w_j$ of the decision maker. The utility function is scaled so that 1 is the best (ideal) value and 0 is the worst value. The most commonly used type for the utility function is the additive form that computes the overall utility as a weighted average of the partial utilities:

$$u_i = u(\mathbf{x}_i,\mathbf{w}) = \textstyle\sum_j w_j\, u_j(x_{ij}). \tag{1}$$

Here $u_j$ ($x_{ij}$) are the *partial utility functions* for criteria, and their purpose is to map the criteria measurements to the interval [0,1], where 1 is the best value. The weights are normalised so that they are non-negative and their sum is 1. This means that the *set of feasible weights* is defined as:

$$\mathbf{W} = \{\mathbf{w} \in \mathrm{R}^n \mid w_j \geq 0 \text{ and } \textstyle\sum_j w_j = 1\}. \tag{2}$$

SMAA is designed to assist in problems where both criteria measurements and weights can be imprecise or uncertain. Any uncertain or imprecise information is represented by stochastic variables with suitable probability distributions: $f_X(\mathbf{x})$ for criteria measurements and $f_W(\mathbf{w})$ for weights. The distributions can be independent or multi-dimensional joint distributions, according to needs. For example, ordinal criteria can be represented by a special kind of joint distribution, as explained later.

The information collected in surveys is uncertain for several reasons. The respondents who chose to answer the survey assumingly had an interest in the topic and therefore may not form an unbiased sample of the general population. Also, any subjective information collected from the general public will be imprecise or uncertain and may change with time. For this reason, we applied SMAA for analysing the robustness of the respondents' preference rankings.

Different kinds of preference information are represented by a suitable joint distribution for the weights. In this study, the analysis was conducted with absent preference information. Absent weight information is represented by a uniform distribution in **W**, which means that any feasible weight vector is considered equally

**Table 1**
RET as choices for ranking the preferred alternative and the abbreviation used.

| | RET alternative provided for ranking | Abbreviation |
|---|---|---|
| 1 | Solar electricity by photovoltaic cells | SOLAR |
| 2 | Ground source heat pump | GSHP |
| 3 | Solar heat for space heating and domestic hot water | SHEAT |
| 4 | Combination of a solar thermal system for space heating, domestic hot water, and electric power | SHEATP |
| 5 | Combined heat and power production based on renewable biomass such as wood chips, etc. | CHPR |
| 6 | Small scale wind turbine | WINDS |
| 7 | Combined heat and power production based on community waste | CHPW |
| 8 | Roof mounted small scale wind turbine | WINDR |

**Table 2**
Categories of respondent groups.

| Criteria as represented in SMAA | Categorisation of respondents based on their profession | Number of respondents in each criteria | Percentage of responses removed | Percentage of responses used in SMAA |
|---|---|---|---|---|
| G1 | Industry employee (any field) | 56 | 12.5% | 87.5% |
| G2 | Energy company employee | 8 | 12.5% | 87.5% |
| G3 | Researcher/Scientist (any field) | 61 | 13.1% | 86.9% |
| G4 | Real estate developer in Finland | 8 | 12.5% | 87.5% |
| G5 | Others | 113 | 15% | 85% |
| Total | | 246 | 13.8% | 86.2% |

**Table 3**
Averages of the rankings given by respondent groups to RET alternatives.

| RET alternative | G1 | G2 | G3 | G4 | G5 |
|---|---|---|---|---|---|
| SOLAR | 3.59 | 3.43 | 3.53 | 3.86 | 3.03 |
| GSHP | 5.31 | 4.71 | 5.21 | 4.43 | 5.02 |
| SHEAT | 5.59 | 5.14 | 5.25 | 5.43 | 5.42 |
| SHEATP | 3.98 | 4.14 | 3.51 | 3.71 | 3.23 |
| CHPR | 4.04 | 4.14 | 3.72 | 4.86 | 3.59 |
| WINDS | 4.86 | 4.86 | 4.21 | 4.43 | 4.93 |
| CHPW | 2.92 | 4.29 | 4.70 | 3.71 | 4.34 |

probable. In the current problem with 5 stakeholder groups representing criteria, this means that there are five non-negative weights, which are constrained only by $w_1+w_2+w_3+w_4+w_5 = 1$. On average, the responses of each stakeholder group will receive equal weight. However, the analysis will consider all possible combinations of weights for different stakeholder groups, both for cases where only the responses of each single group are given all the weight, and everything in between.

Based on the decision model and distributions for criteria and preference information, SMAA computes a number of descriptive measures for the alternatives. The main measures are the following:

- The *acceptability index* $a_i$ is a measure for the variety of different weights that make an alternative most preferred, i.e. how widely acceptable the alternative is. Zero acceptability index means that the alternative is *inefficient*, i.e. no weights make it most preferred. Fig. 3 illustrates the acceptability indices in the case of three alternatives ($\mathbf{x}_1$, $\mathbf{x}_2$, $\mathbf{x}_3$) and two criteria to be maximised. Each of the three alternatives can be considered the best one subject to *favourable weights*, which are plotted as sectors ($\mathbf{W}_1$, $\mathbf{W}_2$, $\mathbf{W}_3$) at each alternative. The acceptability indices ($a_1$, $a_2$, $a_3$) are the relative sizes of these sectors.
- The *rank acceptability* index $b_i^r$ is a measure for the variety of different weights that place an alternative on rank *r*. In other words, the rank acceptability index generalises the acceptability index for ranks other than the first one. The rank acceptability indices give a rough ranking for the alternatives and can be easily visualised by a 3-dimensional column chart.
- The *central weight vector* $\mathbf{w}_i^c$ is the centre of gravity of the weights that are favourable for an alternative, i.e. make it most preferred. The central weight vector describes typical weights that support choosing an alternative and they can be presented to the decision makers in order to help them understand how different weights correspond to different choices. In Fig. 3 the central weight vectors ($\mathbf{w}_1^c$, $\mathbf{w}_2^c$, $\mathbf{w}_3^c$) are illustrated as arrows at the centre of the favourable weight sectors.
- The *confidence factor* $p_i^c$ is the probability for an alternative to obtain the first rank when its central weight vector is chosen. It measures how robust a choice for the first rank an alternative is if the central weight vector is chosen. If the confidence factors for all alternatives are low, it means that the criteria measurements are not accurate enough to discriminate the alternatives robustly. In such a situation, collecting more accurate preference information is not sufficient: instead the criteria should be measured more accurately.

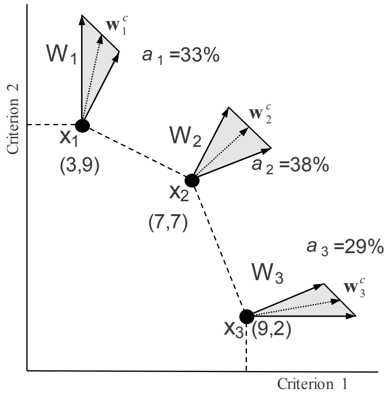

**Fig. 3.** Acceptability indices ($\boldsymbol{a}_i$) in case of two criteria and three alternatives - central weight vectors ($\mathbf{w}_i^c$) for alternatives are drawn as dotted arrows.

SMAA measures can be computed efficiently using numerical Monte Carlo simulation. Therefore, the method does not require any simple function shapes for the decision model or criteria and weight distributions. Instead, any function shapes and also direct sampled data can be used to represent the problem specifically. In each simulation round, criteria measurements and weights are generated randomly from their corresponding distributions and alternatives are ranked based on their utilities. During the simulation, statistics are collected to compute the measures. A sufficient number of simulation rounds is between 10,000 and 100,000 [44].

Criteria measurements can be cardinal or ordinal in SMAA. Ordinal measurement means that there is information only about the preference order of the alternatives with respect to the criterion, but no knowledge as to how much better one alternative is in comparison to the others. In this study, only ordinal criteria were used, because the survey respondents were asked to give a preference order for the alternatives. Asking the large audience to quantify the strength of their preferences numerically was considered too difficult in this survey.

Ordinal criteria measurements are treated during the simulation by mapping the different ranks of the alternatives to random cardinal values in the range [0, 1], so that these values are consistent with the specified ranking. For example, if a respondent has ranked three alternatives on ranks (1, 2, 3), consistent cardinal values for these alternatives would be (1, z, 0), with any random value for z between 0 and 1. For details of this process, see Ref. [45].

Traditionally in SMAA, ordinal criteria have been measured by a team of experts, who agree on a complete or partial ranking for the alternatives. However, in this study a large set of respondents from five different stakeholder groups provided their individual rankings, making it impossible to form a consensus ranking. For this reason, a new way to treat the ranking information was developed:

- The opinions of each respondent group were treated as one ordinal criterion. In this way, the influence of one respondent group does not depend on the number of respondents in that group. This was considered necessary because there was a great variation in group size (7 real estate developers versus 113 others), but we did not want to give more or less weight to any particular group.
- Furthermore, a two-phase sampling technique was developed to treat each ordinal criterion. In the first phase, a random respondent from the group is selected. In the second phase, the traditional SMAA mapping technique is applied to convert the selected respondent's ranking into a cardinal value.

## 3. Results and discussion

The survey was made short (estimated completion time of 15 min) and relatively simple to increase the probability of receiving an increased number of respondents. A total of 246 people responded to the online survey, with a response rate of 21%. The results and discussion of the survey are presented in section 3.1. The results of the SMAA, which are the main outcome of this study, are presented in section 3.2.

### 3.1. Survey results

This section explains the survey results from segment 1, 2 and 3 of the questionnaire (Table S1). Table 4 presents the respondents' background information, indicating that two-thirds of the sample population live in the urban area of Helsinki and 80% have a college or advanced degree.

Decisions on investment cost for RETs are made to reduce the life cycle cost of a building, although higher energy efficiency may not result in increased value of the property [46].

Table 5 illustrates respondents' opinion on climate change and their occupational status in comparison with associated investment amount in RETs for an environmentally friendly home. Willingness to pay for RETs has been discussed by many studies and has been correlated to socioeconomic characteristics, including education, interest in environmental issues, and knowledge of RETs [47–50].

77% of the respondents who selected that they wish to save environmental and energy resources are willing to invest their money (in any monetary amount > 1000€) in RETs, with 43% are willing to invest over 6000€ in RETs. Among those who selected 'they care, but cannot do anything alone' in regard to climate change, 56% are willing to invest (in any monetary amount > 1000€) in RETs and 26% are willing to invest over 6000€ in RETs. This suggests that people are generally open to invest in either case. 21 respondents indicated that they feel climate change does not affect them personally or that they do not care about climate change. Among these respondents, only three intend to invest (in any monetary amount > 1000€) in RETs. 11% of all respondents selected the investment bracket of 11,000 to 21,000€ and twelve respondents listed that they are willing to invest greater than 21,000€. Nearly one third (32%) of all respondents indicated that they would consider investing in RETs. Monetary amounts listed in the 'Other' category typically included investment amounts of several hundred euros. These results suggest that Helsinki residents are generally concerned about climate change and are willing to, or will consider in the future, investing in RETs as a means to reduce their carbon footprint.

Decisions to invest in RETs were also found to be influenced by occupational status. Hast et al. (2015) found that financial affordability has greater influence on consumer choice over environmental reasons [51]. In our study, 68% of respondents reported to be employed, 27% as students, and 9% as unemployed. Among those who are employed, 69% are willing to invest (in any monetary amount > 1000€) in RETs and 37% are willing to invest over 6000€. A significant fraction of students (63%) are willing to invest over 1000€ in RETs. Although unemployed, 45% of these respondents are willing to invest over 1000€ in RETs. Occupational status among Helsinki residents appears to primarily influence investment decisions beyond 6000€, with all respondents, regardless of employment status, indicating a desire to invest.

The respondents represent a diverse collection of housing types, as shown in Fig. 4. The backyard area (Fig. 4a and percentage of the backyard and roof area one would make available to install RETs (Fig. 4b), is largely dependent on housing type. Occupants who rent or own an apartment or live in student housing have limited ownership of exposed backyard space, whereas the majority of respondents who live in single family or semi-detached homes have access to over 10 m$^2$ of space. The latter group of respondents show a much greater interest in utilizing this space to install RETs (over 60% are willing to use over 26% of available space), such as photovoltaic panels, than the former group, who are not able to or are unsure about their ability to install on-site RETs.

Only eight respondents selected that they do not wish to install any RETs on their property (roof or backyard). Thus, it can be concluded that the prevalence of the not in my backyard (NIMBY) mind-set is very small among the surveyed Helsinki residents. The NIMBY hypothesis has been discussed and debated in several studies [52,53] and can be described as a form of local opposition to a facility siting [54]. This has been a prevalent subject to study, especially in the case of on-site and off-site wind farms in a community setting [52,55], suggesting people accept RETs as long as the RETs are not located in their own backyard [26].

As presented in Table 6, in order to reduce the carbon footprint of their homes, 37% of the respondents would prefer to reduce their current heating and electricity consumption by use of automated control devices, whereas 58% of respondents would prefer to produce energy from renewable energy sources. Among those that selected both of these options, 54% of the respondents have opted for energy efficiency renovations, such as overhauling of heating, ventilation, and air conditioning systems and efficient windows to improve the building performance their current home. Operational energy appears to be the most important aspect for the design of buildings that are energy efficient throughout their life cycle [57].

**Table 4**
Background information of the respondents.

| Sort | Response choice | Share of respondents (%) |
|---|---|---|
| Gender | Male | 52.4 |
| | Female | 47.6 |
| Age | <30 years | 34.2 |
| | >30 years | 65.8 |
| Education | High school | 18.3 |
| | Bachelor's Degree | 32.1 |
| | Master's Degree | 39 |
| | Doctoral Degree or Licentiate | 8.9 |
| Occupational Status | Employed | 68.4 |
| | Unemployed | 9 |
| | Student | 27.5 |
| Location | Suburban area | 29.1 |
| | Urban area | 66.4 |
| | Other | 4.5 |

**Table 5**
Opinion on climate change and occupational status vs. willingness to invest in RETs.

| Opinion on climate change | Investment amount | | | | | |
|---|---|---|---|---|---|---|
| | 1000–5000 € | 6000–10,000 € | 11,000–20,000 € | >21,000 € | I will consider it | Other, please specify |
| 1: I want to save environmental and energy resources | 52 | 33 | 22 | 11 | 34 | 2 |
| 2: I care, but I feel I cannot do anything alone | 18 | 12 | 4 | | 24 | 3 |
| 3: It does not affect me personally | 2 | | | | 10 | |
| 4: I do not care | 1 | | | | 6 | 2 |
| 5: Other | 3 | 1 | | 1 | 4 | |
| **Occupational status** | | | | | | |
| Employed | 44 | 39 | 23 | 9 | 48 | 4 |
| Unemployed | 6 | 2 | 1 | 1 | 12 | |
| Student | 29 | 8 | 3 | 2 | 21 | 4 |

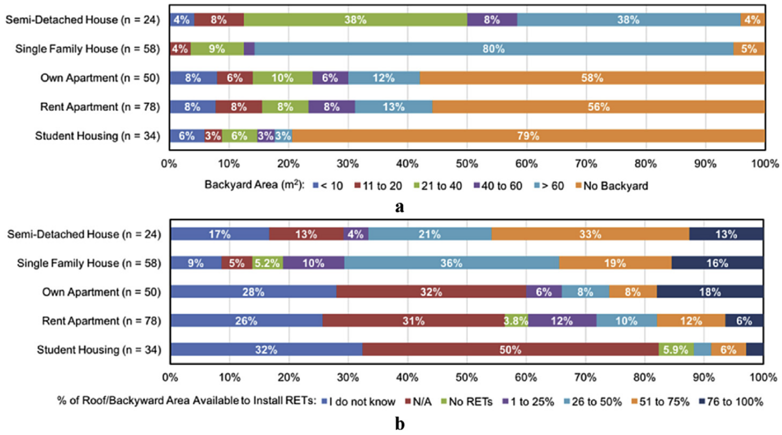

**Fig. 4. a**. Backyard area (in m$^2$) and **4b**. percentage of roof and backyard area one would make available to install RETs, both as categorized by respondent housing type.

**Table 6**
Selected questionnaire responses.

| Question | Options | % Selected |
|---|---|---|
| Payback time for the financial investment in RETs $n = 244$ | 5 years | 36.5% |
| | 10 years | 36% |
| | 15 years | 13.9% |
| | 20 years | 4.9% |
| | 30 years | 1.2% |
| How much extra would you invest for an environmental friendly home $n = 246$ | From 1000 to 5000 Euro | 29.7% |
| | From 6000 to 10,000 Euro | 18.3% |
| | From 11,000 to 20,000 Euro | 10.2% |
| | Above 21,000 Euro or more | 3.3% |
| | I will consider it | 31.3% |
| Preference in order to reduce environmental footprint of your home (multiple selection) | Reducing your heating/electricity consumption (less comfortable conditions) | 37.6% |
| | Producing energy from renewable energy sources (additional investment) | 58.8% |
| | Renovation (HVAC, efficient windows, materials) to improve building performance | 53.9% |
| Preferred incentives by the respondents (multiple selection) | Feed in tariff | 34.4% |
| | Tax deductible | 61.9% |
| | Investment grant | 47.1% |

By extensive refurbishment, it is possible to surpass the performance of new building designs based on perception of building occupants [58]. The renovation of older buildings can result in 30–40% saving in energy consumption [10]. Another example of home owners being proactive in taking steps to implement sustainable home energy technologies is presented by Refs. [56], where the study reported 192 heat pump and wood pellet burning systems inventions by home owners in Finland between 2005 and 2012.

In a consumer stated preference survey study by Menegaki (2011), the absence of subsidies and regulatory requirements are observed in most European countries [59]. Tuominen et al. (2012)

studied the barriers related to regulations and interviewed the stakeholders. For Finland, the lack of subsidies for energy efficiency of residential buildings was reported by the interviewed stakeholders [60]. In this study, one-third (33.6%) of respondents indicated that they were aware of the Finnish government investment grant for RET implementation.

When evaluating the preferred type of incentives, 61% of the respondents would invest in RETs if it would become tax deductible, 47% showed preference for availability of an investment grant, and 34% of the respondents chose feed in tariff (see Table 6). In the Finnish context, the effectiveness of the feed-in-tariff as an incentive towards n/NZEB has been investigated in for a single family house and an office building, respectively [61,62]. The current feed-in tariff scheme for wind power has come to a closure, as it is no longer considered cost-effective and market oriented [63]. This scheme was for rather large scale generation facilities with minimum nominal capacity of 0.5 MVA, making it inaccessible for very small scale production.

Ahvenniemi et al. (2013) reported the trends and influencing factors of the low-energy building market situation involving forty real estate industry experts in eight northern European countries. It was found that an additional investment cost is a large hindrance for low-energy construction businesses. Approximately half of these experts believe that tax deduction could support in covering the additional investment costs. Whereas, tenders or subsidies as a support mechanism was observed only by 10% [64]. Approximately one-third of respondents in our survey were satisfied with a 5-year payback time, another one-third selected 10 years, with the remaining respondents preferring a 20–30-year payback time.

Willingness to pay was observed to be mostly dependent on the cost instead of preference or reliability for a specific RETs, as discussed by Refs. [12,47–51]. It is difficult to explicitly differentiate between the preference and the reliability for a RET. Reliability can include factors such as ease of use and continuous supply of energy requiring no effort from the end-user. Preference (as evaluated with SMAA in the following section) is a matter of choice and can be defined as "*a rank of importance of the dimensions over which the product is defined*" which can be based on popularity, cost, competing energy providers, sizing of the unit, and many other factors [65]. Through our survey, we also evaluated how people perceive the reliability of the eight RETs when compared to preferences. Fig. 5 shows the number of respondents who identified the RET as being reliable and its associated ranking (b1–b8) concurrently. Both SOLAR and GSHP were perceived as the most reliable of the eight RETs. WINDR, WINDS, CHPW, and CHPR were comparatively less reliable as evaluated by the respondents.

### 3.2. SMAA results

SMAA was applied to the results of survey segment 4, as previously discussed. The respondents were asked to choose the stakeholder group they belong to as presented in Table 2. Some of the answers were incomplete, i.e. the respondent had answered only a part of the question. For example, some respondents only ranked one or a few best alternatives in segment 4 of the survey (see Table S1). Such responses were removed from the SMAA analysis, since it was difficult to derive a complete or even partial ranking of RETs from incomplete information. In some cases, the respondent had ranked a few best and a few worst alternatives; in that case we assumed that the non-ranked alternatives were considered intermediate, and were assigned a 'middle rank' of 5 among the 8 alternatives. Table 2 shows each respondent group and the number of removed responses per category.

It can be seen that the number of real estate developers and energy company respondents are relatively low in comparison with other respondent groups; however, in general, they are likely to be more informed of the practical implementation of these technologies in the building sector when compared to other groups. For this reason, the responses of all stakeholder groups have been considered equally important in SMAA, regardless the size of the group.

Fig. 6 is illustrates the rank acceptability indices for different alternatives according to SMAA. They reveal the share of possible weighting among respondent groups that make an alternative most preferred ($b^1$) or place it on any subsequent rank ($b^2 \ldots b^8$). The alternatives in the figure are sorted according to their first rank acceptability index. We can see that SOLAR is the most widely acceptable solution for the first rank, with GSHP second. This is followed by SHEAT, SHEATP, CHPR, WINDS, CHPW, and WINDR as last. The top alternatives also have high acceptability for the second and third ranks ($b^2$, $b^3$), which means they are widely accepted for the best ranks. In contrast, the three last alternatives (WINDR, CHPW, WINDS) have high indices for the lasts rank, which means

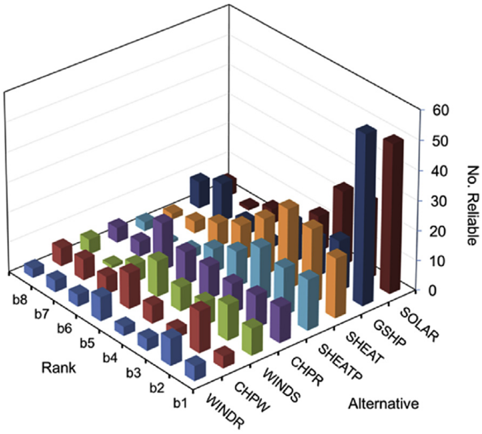

**Fig. 5.** Number of respondents who identified the selected RET as being reliable and its associated ranking by the respondent (b1–b8).

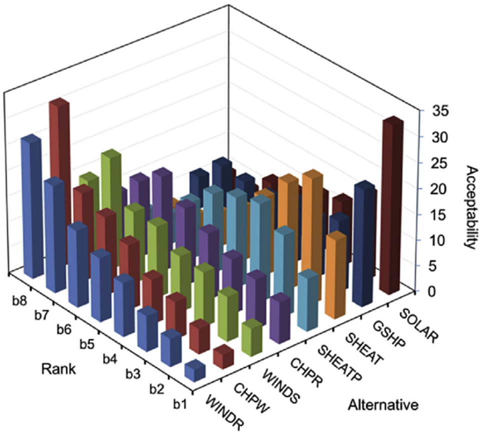

**Fig. 6.** Rank acceptability indices for RET alternatives, showing the variety of possible preferences that place alternatives on different ranks. Alternatives are sorted according to their first rank acceptability index.

that they are inferior choices when subjected to many possible opinions.

The central weight vectors are illustrated in Fig. 7 and are also shown in Table 3 for RET alternatives as selected by the respondent groups. They reveal how the opinions of different respondent groups should be emphasized in order to make the alternative most preferred. The SOLAR, SHEAT and SHEATP alternatives remain the steady choices among all respondent groups. Also, the second most preferred alternative GSHP is supported uniformly. CHPR is supported by emphasizing the opinions of people employed at energy companies (G2) and placing less weight on the others group (G5). The central weights for the last three alternatives, WINDS, CHPW, and WIND show great variation among the respondent groups. This variation may be due to the relatively small number of respondents selecting one of these alternatives as the most preferred one. CHPW is favoured by emphasizing the opinions of real estate developers (G4) very highly, and placing minimal weight for the respondent groups industry (G1) and others (G5). Interestingly, the central weight profiles for WINDS and WINDR are almost opposite (Fig. 7). It is difficult to identify a clear reason for such opinions. It is possible that the differentiation between the WINDS and WINDR alternatives was not clarified well enough in the questionnaire.

Table 7 presents the confidence factors for the alternatives (probability to be most preferred when the central weight vector is chosen). The confidence factors for all alternatives, even for the top alternatives, are quite low. This means that the survey responses are uncertain and it is impossible to determine the best alternative, even if precise weights for the different stakeholder groups were specified. If a single alternative was to be chosen, the confidence factor in statistical/scientific contexts should be about 90–99%, and in a decision making situation with subjective information, it should be more than 50%. In this study, we are not choosing a single best alternative. Instead we have identified a ranking, which reveals multiple best (most preferred) alternatives. For this reason, the precise order of the top alternatives is not critical.

SMAA results clearly indicate that solar energy technologies were the most pronounced choice of the respondents. The top alternatives for solar power, ground source heat pump, solar heat and combined solar heat & power were widely acceptable either for the first rank, or for the top ranks. Ground source heat pumps are energy efficient techniques and common in Finland, which may increase their acceptability. Solar energy, and in particular photovoltaic panels, is a very highly advertised and widely implemented technology in some European countries, such as Germany and Denmark. This, together with recent development of lower prices for photovoltaic panels, has positively influenced the popularity of solar power in Finland. Many studies have indicated that when comparing knowledge levels of RETs, most of the public is aware of solar and wind technologies [66,67]. For Finland, as estimated by Refs. [68], solar thermal and solar photovoltaic can marginally improve the share of renewable energy sources in primary energy consumption by only 0.3% and 1%-point at maximum, respectively. Solar power is not a complete solution at Finnish latitude and climate conditions. At best, it is only a partial solution for nZEBs due to non-coincidence between supply and demand. It needs to be augmented by storage techniques, renewable-based combustion, and power transmission across borders. Yet respondents designated it as both a reliable and preferred RET, as presented in Figs. 5 and 6.

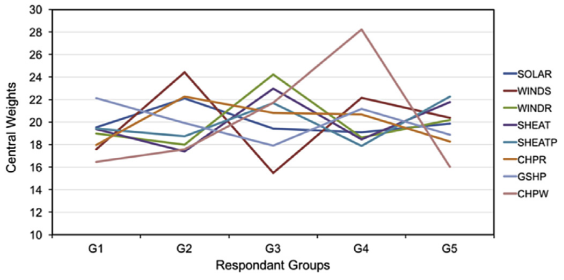

**Fig. 7.** Central weights for alternatives by respondent groups.

**Table 7**
Confidence factors and central weights for alternatives.

| Alternative | Confidence factor | Central weights | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $b^1$ | $b^2$ | $b^3$ | $b^4$ | $b^5$ | $b^6$ | $b^7$ | $b^8$ |
| SOLAR | 39 | 33 | 17 | 13 | 11 | 9 | 8 | 4 | 5 |
| GSHP | 24 | 23 | 14 | 12 | 13 | 10 | 11 | 11 | 6 |
| SHEAT | 20 | 15 | 24 | 21 | 15 | 11 | 7 | 4 | 3 |
| SHEATP | 11 | 10 | 16 | 19 | 18 | 16 | 11 | 6 | 4 |
| CHPR | 7 | 8 | 10 | 11 | 13 | 15 | 19 | 15 | 10 |
| WINDS | 4 | 5 | 9 | 11 | 11 | 14 | 14 | 22 | 15 |
| CHPW | 3 | 3 | 5 | 7 | 9 | 13 | 15 | 17 | 31 |
| WINDR | 1 | 2 | 5 | 7 | 10 | 12 | 15 | 21 | 26 |

Renewable-based combined heat and power (CHPR) is a very efficient technique to simultaneously produce heat, power, and cooling from scarce resources. CHPR and CHPW remained the least opted for among the respondents. The reasoning behind this result could be based on the fact that end users, in general, are not very involved in Finland; these alternatives are large scale plants owned by big companies. Micro-scale CHPR and CHPW production units are not common in Finland because the investments are relatively high and the return is low [69,70]. Another reason for low acceptance of CHPW could be due to an infamous waste incineration plant near the city centre which polluted its surroundings [71]. This plant was shut down in 1983 due to citizen movement. Current waste incineration technology does not cause similar emissions. As an example, a new solid waste CHP plant in the neighbouring city Vantaa opened in 2014 by Vantaan Energia. The plant is able to produce 920 GWh of district heat per year, which is 30% of the heating needed for the city of Vantaa. This plant operates with 20% reduction in $CO_2$ emissions and 30% less fossil fuels [72]. In Finland, the majority of the fuel mix used in CHP plants is based on fossil fuels, including coal and natural gas [73], nevertheless, there is potential to switch the fuel type towards renewables.

### 3.3. Study limitations

The questionnaire excluded advanced heat pump solutions for combined district heating and cooling systems, options of investment potential in community-based RETs, and other off-site energy generation approaches (e.g. hydroelectric, nuclear). It was also noted from the feedback of respondent groups that our questionnaire did not ask about the monetary value of previously made investment by the respondent in RETs. However, this information was captured in segment 2 of questionnaire as presented in Table S1, where the respondents were asked to choose the installed heating system in their home.

When assessing the survey critically, it should have provided better numerical assessment of the alternatives based on price per capacity or equipment instead of a lump sum amount of RETs. This is recommended for the future studies when assessing the willingness to invest, however, the pricing is complicated to estimate because of numerous types of technologies and technology providers. The survey data and SMAA only reflect preferences for the eight RETs listed, and thus, social perceptions of renewable energy sources not explicitly mentioned in the survey could not be evaluated. Lastly, the study did not consider perceptions of energy performance certificates for buildings in Finland. The certificates selectively target certain renewable energy production methods at the building- and community-level, and thus, may influence one's preferences for a RET [74].

## 4. Conclusions

This study presents the public perceptions of RETs in the capital region of Finland and uses SMAA for analysing the robustness of the respondents' ranking of preferred RETs. In this study, a large set of respondents from different stakeholder groups (e.g. industry, energy, general public) provided their individual rankings. Because forming a consensus ranking was impossible, we developed a novel way to treat the ranking information. The opinions of each respondent group were treated as a criterion. Then a two-phase sampling technique was applied to convert the respondent's survey answers into ordinal criteria measurements. This approach was successful by giving balanced weight to each respondent group regardless the number of respondents in each group.

The results show wide array of variance between the preferred choices by the respondents. The key finding of this study is that multiple different RETs are preferred, implying that we are not limited to the preference of only one or two RETs (e.g. photovoltaic panels), and rather have a spectrum of options that are acceptable as a top choice to consumers. The diversity of Finland's energy production has always been a strength, however, small-scale energy production can have a significant impact on overall energy production [29].

Because the public has dissimilar opinions on the preference ranking of RETs, choosing only one or two RETs to promote energy efficiency will not necessarily yield wide implementation. The political implication of this study is that the government should subsidise implementation of different RETs in a balanced manner, allowing people to choose, based on their preferences, perceptions of reliability, and local conditions, the most suitable technologies for their home.

Respondents indicated a strong willingness to invest in RETs, with 43% selecting to invest over 6000€. Investment decisions were influenced by the respondent's opinion on climate change and their occupational status, with employed residents who wish to save environmental and energy resources demonstrating strong support for RETs in monetary amounts greater than 6000€. Housing type also influenced the fraction of available backyard and roof area one would be willing to utilize for on-site RETs. The majority of Finnish residents living in single family homes and semi-detached homes indicated a strong support for installing RETs on their property (using greater than 25% of available area) and NIMBYism was not found to be prevalent among the sample population, with only eight respondents indicating they do not wish to install RETs on their roof or in their backyard. Respondents were in favour of receiving financial incentives, including tax deductions and investment grants, to support investment in RETs. 57 respondents ranked GSHP as the most reliable RET and 50 ranked SOLAR as the most reliable. Conversely, less than 10 respondents ranked either WINDS or WINDR as the most reliable.

In most cases, community level solutions for RETs can be more efficient than building specific solutions for several reasons, such as increased shared storage capacity, non-coincidence of power and heat loads, more professional supervision and management, and more flexibility to choose ideal location for production and promote idea of energy positive neighbourhood [75]. To promote growth of RETs, larger individual owner based subsidies should be introduced, especially for the detached houses which are not connected to a district heating network. These detached houses can then follow examples of renewable energy load matching as presented by Cao et al. (2013), for the case of a non-existent grid where energy is produced by photovoltaic panels and micro-wind turbines and stored in energy storage systems [76].

## Acknowledgements

Nusrat Jung was supported by a doctoral fellowship through the Academy of Finland Doctoral Program in Energy Efficiency and Systems (EES). We thank M.Sc. Maaria Laukkanen (www.eksergia.fi) for her valuable insight on applications of building-integrated RETs in Finland.

## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.renene.2016.07.006.

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**Supporting Information:** Nusrat Jung*, Munjur E. Moula, Tingting Fang, Mohamed Hamdy, Risto Lahdelma. Social Acceptance of Renewable Energy Technologies for Buildings in the Helsinki Metropolitan Area of Finland, *Renewable Energy*, Volume 99, Pages 813-824, 2016.

**Table S1**. Description of the web-based survey

| **Segment of survey** | **Content of the questions and multiple choices** |
|---|---|
| *Segment 1*<br>Background | Age; Gender (M/F); Decision on financial investment; Percentage of participation in collective decision making regarding financial investments (family structure); Educational background; Occupational status (employed, unemployed, student); Stakeholder group (industry, energy company, researcher, real estate developer, resident of Finland and doesn't belong to the mentioned categories). |
| *Segment 2*<br>Information of the home | Location of the residence; type of residence (single family house, semi-detached house, own an apartment, renting an apartment, student housing, other); Estimating the square meter of the residents backyard; Estimating percentage of roof area available for RETs; How is the residents home heated (electrical heating, district heating network, fuel oil boiler, natural gas boiler, wood or peat boiler, air to air heat pump, geothermal heating (e.g. ground source heat pump), other); If the interviewee has a green electricity contract from the power company and if any company has offered them green electricity - if yes than what percentage of electricity provided to their home is green? |
| *Segment 3*<br>Likelihood of investment | Opinion on climate change; How much would the interviewee invest on an environmentally friendly home (choices between 1,000-21,000 €, still under consideration, other); Choice of payback time for the selected amount of investments (choices between 5-30 years or other methods); Preferred type of incentives (feed in tariff, tax free, investment grant from the state, other); In order to reduce the environmental footprint of their home, which would be their preference (Reducing your heating/electricity consumption, producing energy from renewable energy sources which requires additional investment, renovation of heating ventilation and air conditioning systems, energy efficient windows, better materials to improve building performance) |
| *Segment 4*<br>Ranking of technologies | Ranking of RETs according to preferences from 1 to 8, where 1 is most favourable, where the choices were: solar electricity (photovoltaic), small scale wind turbine, roof mounted small scale wind turbine, solar heat (e.g. for heating space and water), solar thermal system (photovoltaic + solar thermal), combined heat and power (CHP) production based on renewable biomass (e.g. wood chips), ground source heat pump, CHP production based on community waste or peat, OR 'I am not familiar with the above technologies´, other technologies. Reliability of these technologies was asked in a separate question with possibility to select multiple technologies. |

**Table S2.** Energy consumption in households by energy sources in 2013 (Statistics Finland)

| Energy source | Share |
|---|---|
| District heat | 29% |
| Electricity | 34%: 62% heating of residential buildings and 38% household appliances |
| Wood | 23% |
| Light fuel oil | 7% |
| Ambient energy | 7% |
| Others | 1% (natural gas 0.5 %, peat 0.1 %, heavy fuel oil 0.1 %, and coal 0.005%) |

Statistics Finland, Energy Consumption in Households 2012, 2013. http://tilastokeskus.fi/meta/til/asen_en.html.

Aalto-DD 142/2018
VTT SCIENCE 182

ISBN 978-952-60-8108-3 (printed)
ISBN 978-952-60-8109-0 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

978-951-38-8660-8 (printed)
978-951-38-8659-2 (pdf)
2242-119X (printed)
2242-1203 (pdf)

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