Department of Mechanical Engineering

Advancing design criteria for energy and environmental performance of buildings

Nusrat Jung

Aalto University

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Advancing design criteria for energy and environmental performance of buildings

Nusrat Jung

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Abstract

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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

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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.

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Yours sincerely,
Nusrat Jung

Kitwe, Zambia
21 June 2018

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Appendices

Appendix A: Publication I: Extending Capabilities of BIM to Support Performance Based Design

Appendix B: Publication II: Reducing Embodied Carbon during the Design Process of Buildings

Appendix C: Publication III (with supporting information): Energy Performance Analysis of an Office Building in Three Climate Zones.

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 Extending Capabilities of BIM to Support Performance Based Design (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 (b) Expert interviews	Worldwide	Future directions for using BIM-based tools in conjunction with BPS-tools
Publication II Reducing Embodied Carbon during the Design Process of Buildings (Häkkinen et al., 2015)	How to calculate embodied carbon during design phases?	(a) Literature review (b) Building case study (c) Expert Interviews	Worldwide	Methodology to calculate embodied carbon during design phases
Publication III Energy Performance Analysis of an Office Building in Three Climate Zones (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 (b) Number of studied zones:160 (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 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 (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 Briefing	1 Preparation	2 Concept design 3 Generic design	4 Building permission tasks	5 Technical design 6 Preparation for construction	7 Construction	8 In use	9 Warranty period during use
Royal Institute of British Architects Plan of Work (RIBA, 2013)	0 Strategic definition	1 Preparation	2 Concept design	3 Developed design	4 Technical design	5 Construction	6 Handover and close out	7 In use
The American Institute of Architects Plan of Work (AIA, 2012)	0 Project brief	1 Concept design	2 Schematic design	3 Design development	4 Construction documents 5 Bidding	6 Construction	7 Commissioning	8 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.

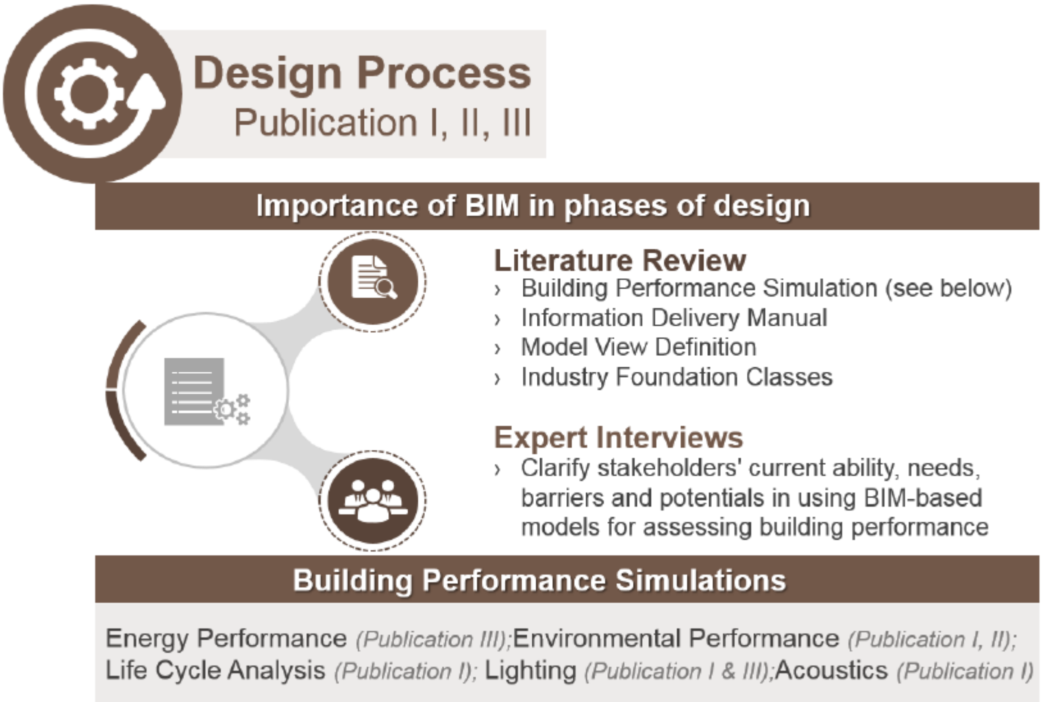

Figure 2. Scope of research questions for publication II on extending the capabilities of BIM to support performance-based design.

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.

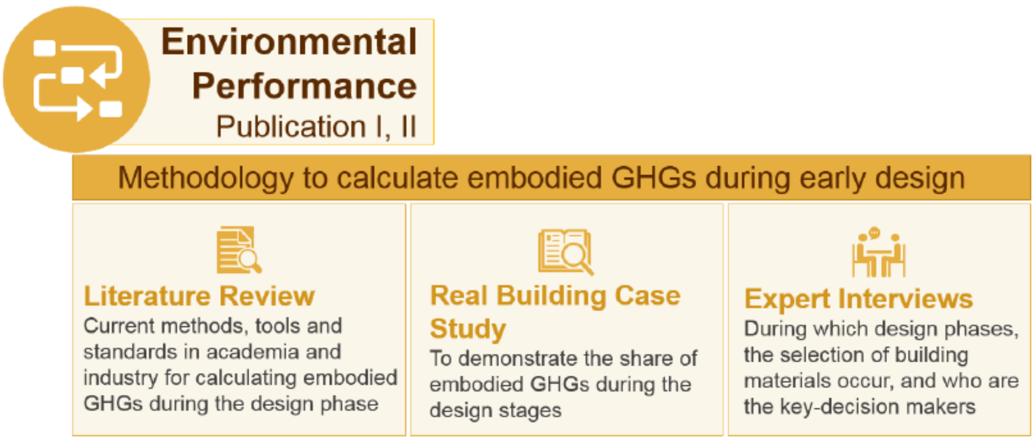

Figure 3. Scope for evaluating the environmental performance of buildings

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.

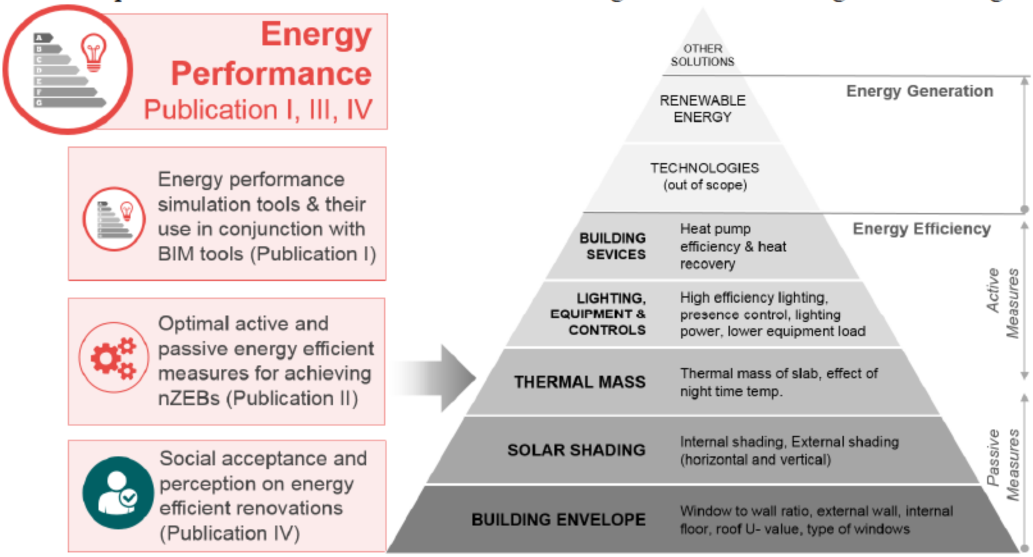

Figure 4. Scope of research questions for publication III on the energy performance analysis of an office building in three climate zones. Hierarchy triangle adapted from Botti (2015).

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.

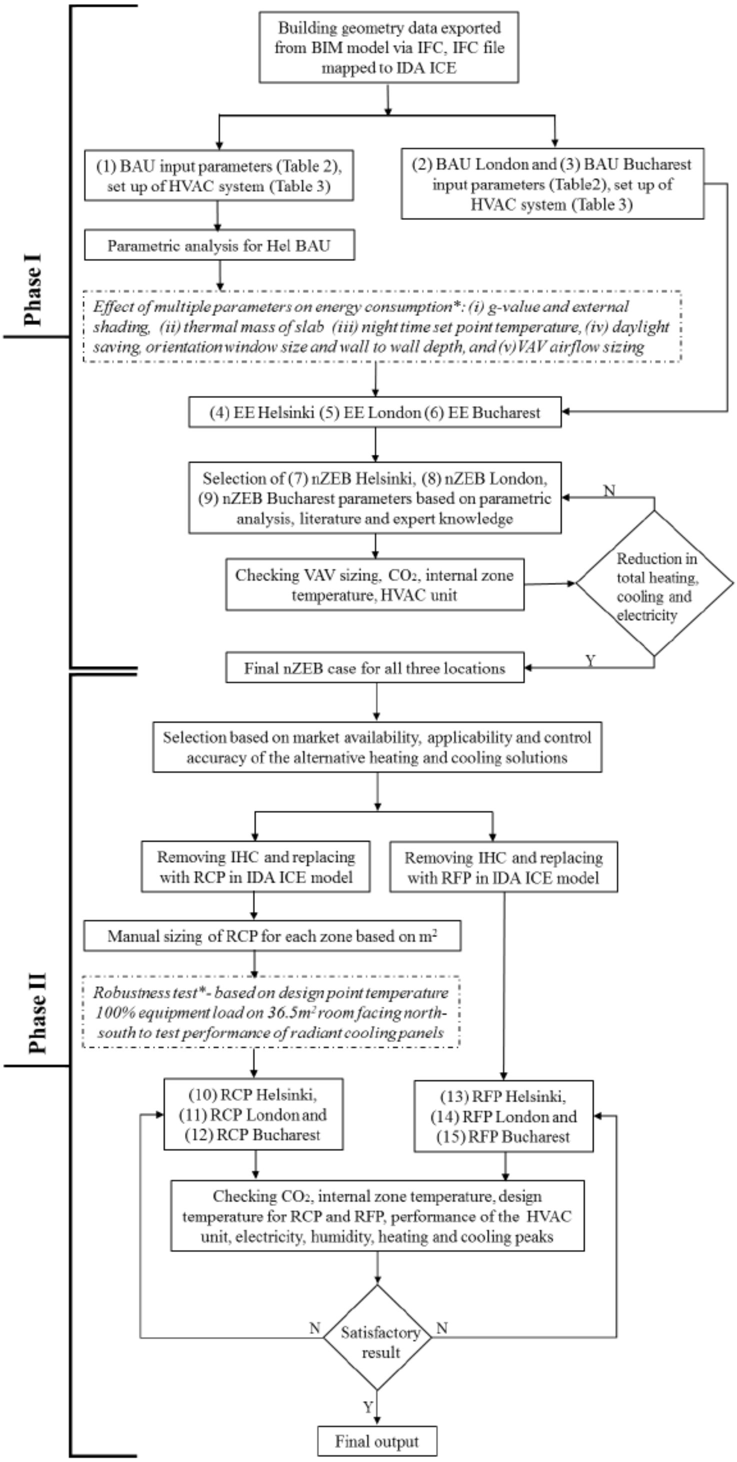

Figure 5. Simulation methodology. Original figure: Appendix C, Publication III, Figure 1, p. 1025. *Dotted lines represent the parametric analysis separately published in Jung (2013) and the robustness test, which are not discussed in this dissertation.

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).

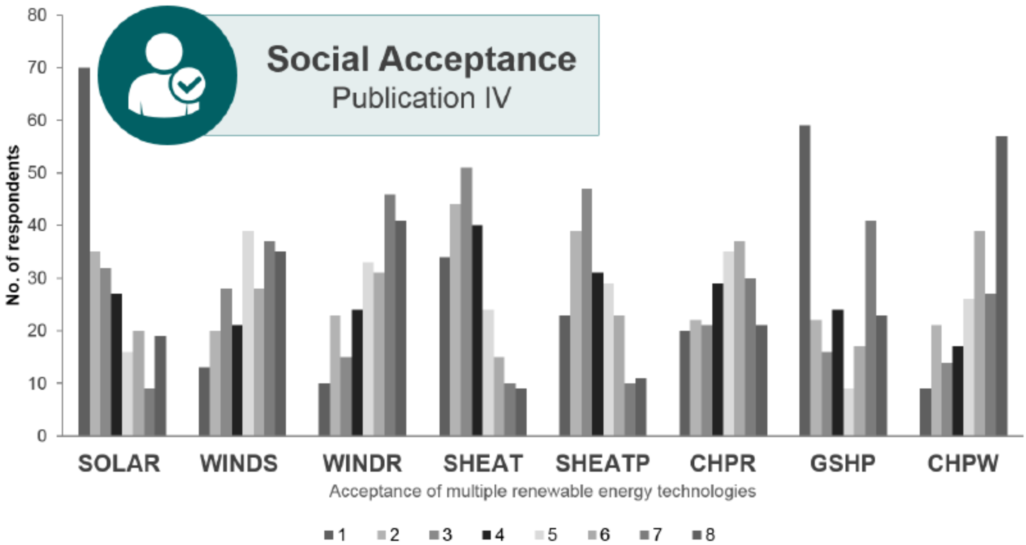

Figure 6. Ranking of the RETs before application of SMAA. Preference was ranked as most favoured and least favoured technology on a scale of 1 to 8.

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.

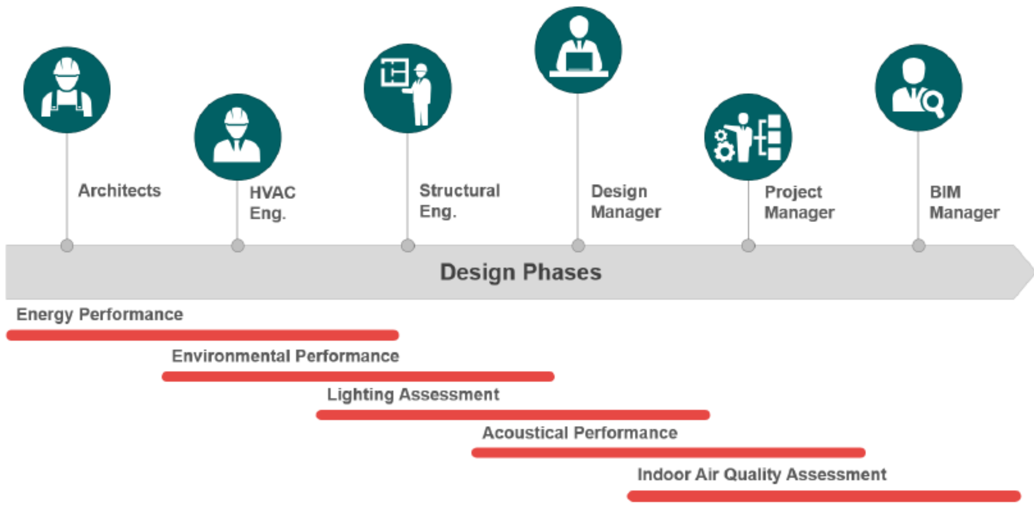

Figure 7. Roles of expert interviewees and the evaluated building performance criteria. See more on quantitative and qualitative results of the interviews in Appendix A, Publication I, Jung *et al.* (2018b), p. 31-34.

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.

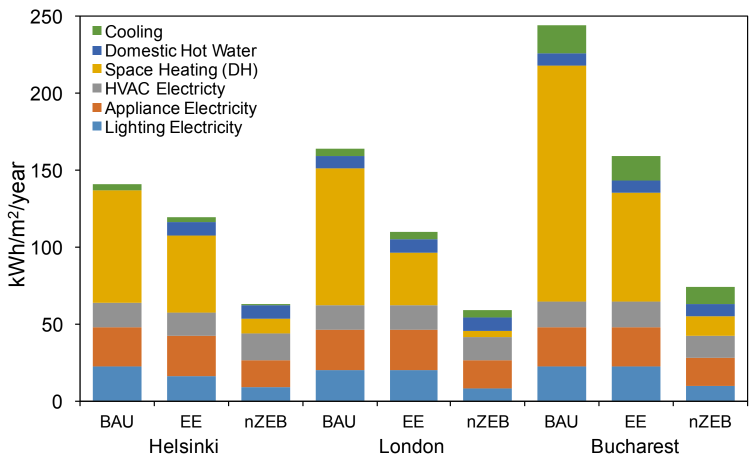

Figure 8. Delivered energy demand for BAU, EE and nZEB for three climate zones. Original figure: Appendix C, Publication III, Figure 4, p. 1029.

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.

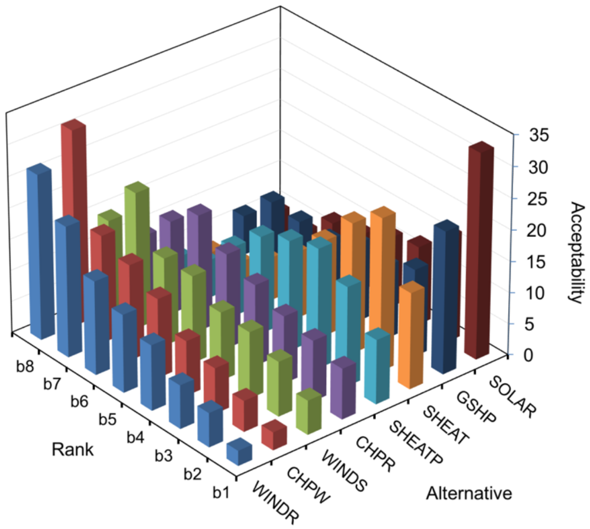

Figure 9. Acceptability ranking indices for the RET alternatives, showing the variety of possible preferences and their acceptability ranking. Original figure: Appendix D, Publication IV, Figure 6, p. 820.

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_2eq 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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