YRSB19

iiSBE Forum of Young Researchers in Sustainable Building

July 1 2019 | Prague

Conference Proceedings

CTU
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Acknowledgement: This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS SVK 03/19/F1.

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YRSB19 – iiSBE Forum of Young Researchers in Sustainable Building 2019
1st July 2019, Prague, Czech Republic

Editors: Kateřina Sojková, Julie Železná, Petr Hájek, Jan Tywoniak, Antonín Lupíšek
Cover: Petr Hejtmánek
Published by: Czech Technical University in Prague
Processed at: Czech Technical University in Prague, Faculty of Civil Engineering, Department of Building Structures, Thákurova 7, 166 29 Prague 6
1st edition, Prague, June 2019, 263 pages
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ISBN 978-80-01-06610-2

Foreword

In an UN report Our Common Future, written by Brundtland Commission in 1987 is stated "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". It is clear that nowadays young people represent near future generation which could be threatened by global changes on the Earth.

28 years later (in 2015) UN adopted the Resolution: Transforming our world: the 2030 Agenda for Sustainable Development. This Agenda is a plan of action for people, planet and prosperity and should stimulate action up to 2030 in areas of critical importance for humanity and the planet. The principal goal is to end poverty, protect the planet and ensure prosperity for all.

There are specified 17 Sustainable Development Goals with 169 associated targets which are integrated and indivisible and balance three dimensions of sustainable development: economic, social and environmental. These new goals and targets came into effect on 1 January 2016 and guide the actions up to 2030. It is expected, that all stakeholders, all of us, will work to implement the SDGs Agenda within own countries and at the regional and global levels, considering national specifics and priorities.

These goals, targets and proposed solutions should be widely discussed in international group of experts, considering global measure of the problem and consequently regionally specific situation. Young researchers can bring new ideas on how to contribute to sustainable development targets.

YRSB19 – Young Research Forum on Sustainable Building is organized for the third time together with CESB19 conference. The idea to organize Young Research SB conference as a satellite event has been initiated and developed in iiSBE – International Initiative on Sustainable Built Environment.

We appreciate that doctoral students, as well as young researchers, who already finished their doctoral studies, can present their scientific achievements and discuss their approaches with colleagues from other teams and universities from different countries. The interaction will help to improve their research and create new cooperation, networks and friendships across the borders.

The proceedings consist of 26 papers from 21 countries presented on YRSB19 conference held on July 1st 2019 at the Faculty of Civil Engineering, Czech Technical University in Prague.

We would like to thank all the authors of the papers presenting results of their work in the field of sustainability. We also want to thank to Czech Technical University in Prague, Faculty of Civil Engineering for the support. A special thank is addressed to all members of the organizing committee. All above mentioned help and support were necessary for successful organization of the conference and publishing of the proceedings. We hope that it will help in dissemination of sustainable building techniques into everyday construction practice and will thus contribute to solution of SDG targets specified in 2030 Agenda for Sustainable Development.

We hope that conference YRSB19 will contribute to enhancement of knowledge in the field of sustainable buildings and built environment considering changing natural, as well as socio-economic situation in the world.

In Prague in May 2019

Petr Hájek
Julie Železná
Jan Tywoniak
Antonín Lupíšek

Contents

Keynote Address

Smart Building Skins Monitoring and Improving the Environmental Efficiency, Thermal Performance, and IEQ of Remote-Region Buildings in Australia

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Abstract

A sustainable building must address both environmental sustainability (e.g., energy use) and human sustainability (the well-being and productivity of its occupants). The standard industry response has been an increased reliance on the use of mechanical heating-cooling systems rather than passive design strategies aimed at reducing energy use and improving indoor environmental quality (IEQ) to maintain human well-being. These methods have come with a significant energy cost and pressure on the power supply system due to high peak loads. This trend is unsustainable, as climate projections for remote regions indicate hotter days in summer and cooler nights in winter, increasing the demand for energy and associated infrastructure. However, the performance of commercial and residential buildings in remote communities concerning energy use, thermal performance, and IEQ is unknown, meaning that these variables cannot be matched to the prevailing climatic conditions. This paper reports the initial results of a research project aimed at quantifying the environmental efficiency and human sustainability of remote-region buildings, based on which strategic interventions and design modifications can be made. A suite of instruments is currently monitoring variables related to climate, energy consumption, thermal performance, and IEQ at 10-min intervals for 12, 24 and 36 months in three buildings (in Wanarn community, Western Australia, Numbulwar community, Northern Territory and Halls Creek, Western Australia), other sites are being selected in different climatic zones. The data will allow the levels and patterns of climatic variables, energy use, and IEQ, and the relationships between them, to be quantified. BIM with energy/thermal simulation software will be performed using the data as constraints. The findings will be used to (i) Develop a series of key performance indicators for use by construction professionals regarding building performance; (ii) inform best practices for improving the energy-use efficiency, thermal performance, and IEQ of existing remote-region buildings; and (iii) informed design solutions for future buildings via simulations to optimize sustainability with respect to climate, environmental performance, and occupant well-being. Initial analysis of the data collected focused on energy load reduction, followed by the application of energy efficient solutions to match reduced load profiles. Preliminary emphasis was placed on designing the building skin to minimise external loads. The data collected was used as a baseline for energy modelling different orientations within several Australian climatic zones. The modelling provided energy load profiles on various areas within the three building structures. Hourly data profiles demonstrate times and places where loads exceed the established threshold for building heating, ventilation and air conditioning (HVAC) systems. This information enabled a design path for building improved thermal performance and personal comfort facilities using mechanical or natural methods. A new smart building skin technology has been developed and under trial now to determine its capacity to reduce energy use with the buildings and improve the environmental and social well-being of the staff working within the structures.

1 Method

In the past three years, the research has collected over 9 million bits of data at 10-minute intervals per year or a total of 27+ million bits of data in total and still collecting. The study is based on data obtained from instrumental monitoring devices installed at three building sites in different climatic zones within Australia. The research has received the following:

- Monitored climatic variables over a 12, 24, 36-month period, including temperature, humidity, and rainfall.
- Monitored IEQ metrics over a 12, 24, 36-month period, including volatile organic carbon (VOC) concentrations, humidity, temperature, CO_2, CO, formaldehyde, amongst other gases and substances.
- Site-assessed IEQ variables including lighting levels, air exchange, ambient sound levels, particulate matter, and airborne microbes.
- An occupant satisfaction questionnaire to augment the quantitative IEQ data, seeking information on aspects of IEQ, comfort, and human sustainability and productivity. The survey covers occupational profile, time–location data, time-activity data, building layout and furnishings, thermal comfort, air quality, lighting, acoustics, privacy and security, programmed spaces, energy-use patterns, and building sustainability features.
- Monitored energy consumption over a 12, 24, 36-month period, including totals and readings sub-monitored according to function and space within each building.
- Energy supply quality and variations over a 12, 24, 36-month period, including power outages (brown- or black-outs), power supply (grid, solar, other), and back-up.
- Building occupancy and operational profiles and variations over a 12, 24, 36-month period.
- An inventory of energy-consuming equipment in each building.
- Static built environment variables – building design and material characteristics, e.g., orientation, layout, material types and properties, passive sustainability features, air systems and ventilation, and insulation.

2 Research Outcome

A sample summary of the recommendations and findings of one site Numbulwar included the following:

- Local climate – External temperatures reflect the tropical location of Numbulwar and regularly exceed 35 °C. Temperatures were observed in a range of 17.5 °C to 46 °C and humidity levels between 25.9 % and 97.5 %.
- Energy Consumption – Every 3 °C rise in external temperature results in an additional 2kWh per hour increase in energy consumption to maintain indoor temperatures.
- Energy use intensity at 120 kWh/m^2/year is favourable to industry benchmarks of 167 to 306 kWh/m^2/year in the state of Victoria for similar businesses.
- Thermal Performance – Building skin and thermal envelope of the Numbulwar clinic are effective at dampening solar gain and conduction of heat.
- Internal Atmosphere – maximum recommended ambient concentrations of PM2.5 particles of 25 $\mu g/m^3$ were exceeded in isolation, and never for a whole day.
- Research through monitoring has proven that the corrugated iron used in remote building construction as the outer building skin envelop system has reached their limits of scale & cannot be "adapted" to create new active building surround systems and applications to provide intelligent building skins.

Lynx Building Envelop Technology System – One New Proposed Façade System for Trial [1]

The Lynx Building Envelop Technologies System is in preliminary testing at present. The new homes to be constructed in remote Australia will demonstrate the two façade systems.

- Frame Integrated Venting System (FIV)
- Double Skin Façade Cassette (DSFC)

The developer of the new technology Lynx is saying It's imminently possible with the aid of modern materials and construction systems to boost and improve the natural laws of thermodynamics to enhance the passive cooling and heating performance of our building.

Lynx is working on a high air cycle double cavity rain screen also acting as a façade framing system (Frame Integrated Venting) for this purpose. The vision for FIV technology is that it will be operated like the building skin and become the buildings HVAC System.

The Lynx FIV is a double cavity system with each cavity vented separately

The front 25mm cavity space vented through the vertical Frame Integrated Venting System and the rear 50mm cavity vented through the Horizontal Frame Integrated Venting System.

The objective is to use the first cavity to accelerate the stack effect and use the stack effect to generate enough kinetic energy to drive a façade integrated HVAC system for the veneer and the building. The designer suggests that the FIV will act to cycle air and reduce cavity temperatures, therefore, reducing the use of split air-conditioning units within the buildings consequently reducing the energy consumption.

Steel PV Roofing Cassette

The vision of building futurist is that building envelops will play a much more active role in the operation & functionality of the building. The concept is that building surrounds will function more like building skins, having sentience, with autopoietic like responses to many different inputs. Lynx now has the technologies required to innovate such building skins and realise this vision. The Lynx PV roofing cassette design has a transformative building envelop system & use, the first step towards the ultimate vision of active building skins.

References

[1] Gordon Andrew Geddes CEO, Lynx Systems Pty Ltd, www.lynxsystems.com.au

Innovative Materials, Products and Systems for Energy Efficient and Energy Positive Buildings

Industrial By-Products as Non-Conventional Supplementary Cementitious Material

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Abstract

The extensive efforts on reducing the carbon footprint of cement production have motivated the investigations on the use of supplementary cementitious materials (SCM) as additive and/or substitute in cement blends. However, previous studies were focused on limited types of SCM including natural pozzolans, ground granulated blast furnace slag (GGBFS) and fly ash – which could readily exhibit reactivity in cementitious systems. In this article, a review on the advances in the valorisation of novel industrial by-products (non-ferrous slag, municipal incinerator bottom ash, and jarosite waste) are presented to provide solution in reducing the volume of industrial landfills while creating greener materials for building applications. The second part of this paper demonstrates a case study applying exergy to compare the footprint of the flowsheets derived from the valorisation of industrial by-products as SCM.

Keywords: *green cements, slag, supplementary cementitious materials, bottom ash, jarosite, exergy, life cycle assessment*

1 Introduction

The use of green/eco-efficient cements incorporating supplementary cementitious materials (SCM) poses to be one of the promising solutions to promote sustainability in the building sector [1]. Green cements or eco-efficient cements [2] generally refer to cementitious binders produced through a more sustainable process utilizing materials or energy sources that would decrease the total environmental footprint of the final product relative to the more traditional system. Ideally, the substitute material incorporated has a lower carbon footprint than the cement component while maintaining a comparable or even a superior performance than the substituted binder formulation. On an industrial point of view, the economic advantage of a cheaper substitute along with a process suitable for upscaling and commercialization is among the critical factors in the definition.

A comprehensive review on traditional SCM is given by Snellings et al [3]. Among the numerous types described, only three materials are considered to take a major role as SCM in the market over the past 25 years, namely: granulated blast furnace slag (GBFS), fly ash and limestone [2]. However, despite recognizing the numerous types of traditional SCM and their seemingly growing acceptance on a commercial scale, their limited and often localized availability remains to be a main challenge impeding the green cement market. To answer these staggering needs for alternative sources, a promising approach of the Enhanced Landfill Mining (ELFM) concept [4] opens new pathways for potential types of novel SCM. In landfill mining, the high-value metal components are extracted from ancillary sources particularly pre-existing landfills. For the building sector, ELFM is a driver for novel construction materials and binder formulations. Typically, the metal-depleted by-products in the ELFM flowsheets [4] contribute a relatively low-cost stream of materials with major volume fraction. These could be good initial criteria for a mineral additive or a precursor to building materials: clean (metal-depleted), low-cost and high volume.

In this paper, the use of three landfilled industrial by-products (non-ferrous slag, municipal incinerator bottom ash, and jarosite waste) as non-conventional SCM is presented as a viable pathway for stimulating the green cement market. A review on the previous studies concerning the utilization of these by-products in the building sector is presented in the first part of the paper. The second part demonstrates a case study applying exergy to compare the footprint of the flowsheets derived from the valorisation of industrial by-products as SCM.

2 Studies on non-conventional SCM

Compared to traditional SCM, the chemistry and other properties of these landfilled by-products remain a challenge in their utilization as additive in cement blends. Whereas traditional types of SCM consist mainly of CaO, SiO_2 and Al_2O_3 similar to an Ordinary Portland cement (OPC), non-ferrous slags and jarosite waste are Fe rich. On the other hand, although municipal incinerator (MI) bottom ashes could have major proportions of CaO, SiO_2 and Al_2O_3, they typically have a much lower degree of vitrification as opposed to fly ashes (a traditional SCM) due to the slower cooling rate for the former. The chemical composition and the degree of vitrification are only two of the many factors considered to define the reactivity of residues and consequently their potential for valorization as SCM. A detailed discussion of these factors specifically adopted for slags is presented in the work of Chen and Brouwers [5].

Despite the striking differences in the properties of these landfilled industrial by-products compared to OPC and traditional SCM, it is important to note that in the concept of ELFM, these by-products are valorized as raw materials in a flowsheet which still require pre-treatment (extraction of valuable metals and hazardous components) prior to their possible utilization as building materials. This means that there is still a margin for engineering these by-products to induce or increase reactivity and likewise to reduce heavy metals and hazardous contents making them more suitable for building applications. Case in point, a zero-waste recycling scheme is presented in Hunt [6] providing elaborated flowsheets in the metals processing chain. In their paper, one of the flowsheets shows a lead-zinc ore processing that incorporates a slag fuming step (metal extraction by reduction to gaseous phase) for zinc recovery. To reflect this on an existing industrial application, an improved fuming process that yields a clean slag has been developed and is currently being further refined at Metallo-Chimique, for a combined metal and slag valorization [7]. This kind of zero-waste approach has given rise to the now commercialized “clean synthetic” slag (or fumed fayalite slag) of Metallo: Koranel® specifically adapted for sustainable building applications [8].This material will be the subject of the case study in the latter part of this paper to demonstrate an exergy analysis on its role as an SCM.

2.1 Non-ferrous slag

Among the wide variety of non-ferrous slags, copper, lead and zinc slags are some of the few generated in quantities that could allow viable utilization in building applications [9]. Non-ferrous slags are well dominated by Fe and Si existing as fayalite (Fe_2SiO_4) along with the other olivine group and spinel group phases [10]. Reactivity in cement blend is more often associated with non-ferrous slags having a summation of SiO_2, Al_2O_3 and FeO above that of the 70% percentile requirement for class N pozzolans. While their trace elements (As, Cd, Co, Cu, Cr, Mn, Ni, Pb, and Zn) content and sulfidic ore origin have previously triggered concerns on their weathering behavior and leachability that question their suitability to building applications [9,10]. Non-ferrous slags generally have high specific gravity (increases with the Fe content) and sharp angular particles. These properties are said to favor the soundness, stability and abrasion resistance of concretes incorporating these non-ferrous slags. However, at high replacement levels (>40 wt.%), the slow reactivity of slags in general yields slower strength development over time which is another impeding challenge on their valorization as SCM [9].

Alp et al [11] demonstrated the use of a metal-depleted copper slag recovered after flotation as an iron source in an OPC clinker production. This has been performed on an industrial scale as 100% substitute to the iron ore, constituting 2.5-6 wt.% of the raw meal. The mechanical performance of the standard mortars made with the clinker incorporating the clean copper slag was reported to be similar to a reference mortar without the slag. The leachability of heavy metals, Cu and Zn, was also reduced below the environmental limits in the crushed mortars made from the clinker incorporating the clean copper slag [11]. Similarly, previous studies [12,13,14] on the use of zinc and lead slags as SCM have demonstrated promising mechanical performance, along with other advantageous properties such as increased in gamma ray attenuation (capability to protect from radiation) [14] and suitability to high density special applications (such as noise barriers). In addition, a study by Penpolcharoen [12] highlighted an interesting role of a secondary lead slag's magnetic property in improving the mechanical performance of concrete blocks having 20 wt.% slag as cement substituent and simultaneously 100 wt.% slag as aggregate replacement. The study claims that the magnetic force strengthened the microstructure by magnetizing the water in the pore solution. An earlier study [15] explained that a complete hydration can be achieved when water molecules are preliminarily broken down by magnetic force, thus resulting to improved workability and compressive strength of mortars incorporating iron-rich slags.

2.2 MI bottom ash

MI bottom ash is generally categorized as a non-hazardous material coming from the incineration of municipal waste [16]. The composition of this residue can widely vary depending on the local source. In many cases it may contain pieces of plastics, stones, bricks, glass, ferrous and non-ferrous matters, and an assortment of other unburnt materials [17]. They typically display a porous microstructure in irregularly shaped particles that yields large surface area and a low specific gravity, consequently resulting to higher water absorption capacity versus natural aggregates [16,18]. Studies on its valorization as partial OPC and aggregate replacement in cement and concrete samples reported that its high metallic aluminum and bottle glass content can cause extensive spalling, expansion and susceptibility to alkali-silica reaction [16,19]. These support the need for pre-treatment (aging and chemical extraction [20]; pre-sorting, sieving and thermal treatment [17,21,22]) of the MI bottom ash to adapt its properties for cementitious applications.

The thermal pre-treatment procedures for MI bottom ash performed in previous studies [17,21,22] have highlighted the importance of vitrification of this SCM for cementitious applications. The paper by Ferraris et al [22] demonstrated that a maximum 20 wt.% substitution to OPC of a pre-treated Italian MI bottom ash could yield a comparable compressive strength after 150 days as the reference cement mortar containing no ash. The pre-treatment involved screening, magnetic separation, thermal treatment at 1450^{0}C and fine milling. The vitrification step is accounted for the inertisation of heavy metal ions and prevention of alkali-silica reaction throughout the 2 years span of monitoring [22]. A paper by Cheng [21] similarly demonstrated the benefits of combining sieving with thermal treatment to improve the strength of mortars incorporating pre-treated MI bottom ash originating from Taiwan. The decrease in total capillary porosity with the denser microstructure is attributed for the higher strength of mortars containing pre-treated MI bottom ash versus a reference mortar containing the raw MI bottom ash. However, a generally lower strength is obtained when compared to a pure OPC reference mortar along with observations of lower flowability, bleeding, increased shrinkage and higher total porosity [21]. Lastly, thermal treatment at lower temperature (550^{0}C) demonstrated in Tang et al [17] has proven to maintain the viability at 30 wt.% OPC replacement level using MI bottom ash from Netherlands. The key to mitigating the strength reduction in this study was the effective reduction of the metallic aluminum content in the MI bottom ash by a strategic sieving sequence; in parallel with the increased chemical activity brought by the reduction of organic matter content through thermal treatment [17].

2.3 Jarosite waste

Jarosite waste ($KFe_3(OH)_6(SO_4)_2$ as a pure mineral) is an iron and sulfur-rich by product of lead-zinc metallurgical plants, which high toxicity, acidity (pH ≈ 2) and heavy metals (As, V, Cr) content impose issues on its disposal and containment [23]. Previous studies have explored the viability of using jarosite as a substitute to aggregate in OPC-based concrete [24,25]; in combination with slag in pressed activated binders [23]; and as source of sulfate added to the raw meal during OPC and sulfoaluminate cement production [26,27]. As an aggregate replacement, the concrete samples formulated with 25% volume replacement displays appreciable durability and passes a toxicity characteristic leaching procedure citing chemical bonding and physical entrapment as the mechanism for its low leachability. Moreover, it is noted that at higher replacement percentage, the reduction of pH due to the acidic nature of jarosite could impose corrosion risk to reinforcement bars [24]. When pressed with iron slag, liquid activator and <5% OPC, an increased strength is attributed to the formation of amorphous gel hydrates, while heavy metals favourably show low leachability [23]. Meanwhile, as a raw meal substitute to gypsum in an OPC system, it is demonstrated that an optimum substitution of 20 wt.% will not affect the strength development of the binder [26]. The effect of different cations released by jarosite to the rheological properties of the cement are also discussed in Katsioti et al [26]. Lastly, as a raw meal addition for sulfoaluminate cement, the complete substitution of gypsum by jarosite shows to have no significant effect to the grindability, setting time, compressive strength and dimensional stability of cement pastes [27]. All these above mentioned results support the possible valorization of jarosite in cementitious formulations. In fact, a commercial product called Jarofix (50-75 wt.% jarosite with about 10 wt.% OPC and 2 wt.% lime addition) is being produced annually at 160,000 tons per year by CEZinc Refinery in Canada mainly for stabilization of waste [28]; and at 500,000 tons per year by Hindustan Zinc Ltd. in India with variations having soil and bottom ash additions for construction applications [29].

It is important to note however, that the most viable approach is to directly minimize creation of this waste by pre-treatment. As in the case of MI bottom ash, thermal pre-treatment has been proposed for jarosite waste to valorize the remaining metals and convert this residue to a clean slag. For instance, a commercial-scale process such as the Ausmelt TSL (Top Submerged Lance) technology has long existed for the recovery of zinc derived by fuming leaching residues such as jarosite [30,31] for the recovery of valuable elements such as In, Ge, Ag etc. In this way, jarosite can be converted to a slag with more suitable properties for building applications.

3 Case study on a non-ferrous slag as SCM

In this section, the impact of using a clean non-ferrous slag as an SCM has been evaluated through a simulation-based exergy and Life Cycle Assessment (LCA) perspective [40].

It must be noted, if the impact of including the cement flowsheet into the metallurgical one to generate a "zero-waste", a comprehensive flowsheet would need to be evaluated to understand what routes are the best. Fig.1 shows various options to deal with intermediates to produce slags, which can be used in various further downstream processes. In this analysis the SCM is a clean residue generated after a fuming process of the slags produced during non-ferrous metallurgy. For this analysis the SCM is produced in an arbitrary process, the footprint of which is not included in the analysis. Only the cement production is evaluated using exergy and environmental footprint.

The first indicator is exergy, which is a thermodynamic property based on the second law of thermodynamics. It is defined as the maximum work that a flow or a system can produce when it interacts with the environment, but also, the minimum work needed for producing that flow or system from the environment [32]. As exergy is always destroyed when a process is performed, it is a suitable property to evaluate the thermodynamic downgrading of the resources along an industrial process since energy and material flows can be measured with the same units (energy units) and thus integrated [33]. Irreversibility implies that every product of an industrial process will have an exergy cost (i.e. exergy destruction) i.e. an indicator of how many resources have been used to produce it [34]. As industrial processes can be very complex, with many interactions between units, recirculation, bifurcations, etc., a methodology that connects the irreversibility and the exergy cost of a product is required. This methodology, thermoeconomics [35–37] has been largely applied for the analysis of energy systems, but it can be applied to other different industrial processes such as industrial symbiosis [33, 38, 39] or metallurgy [40].

The second indicator is environmental impact. The LCA is a methodology for the environmental impact evaluation of the different stages of the life of a product, from raw materials to end-of-life [44]. This methodology has been already applied to evaluate the environmental impact of cement production processes [41–43]. Therefore, the combination of these two indicators is a good starting point to discuss the sustainability of an industrial process. This simulation-based approach has been already applied in process metallurgy e.g. in the assessment of the primary copper production and e-waste recycling [40,44].

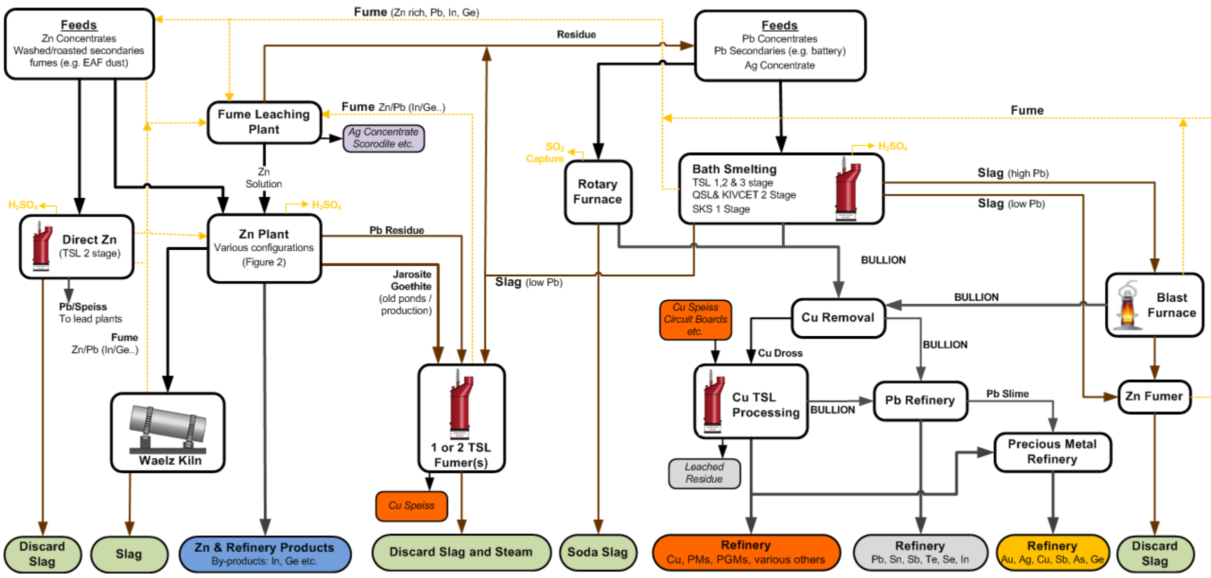

Fig. 1 *An integrated flowsheet used to recover zinc and lead from different slags and residues (e.g. Jarosite or Geothite) created during non-ferrous metallurgy, producing clean slags that can be used as building material or SCM [47].*

The dry cement production process has been simulated with HSC Sim (HSC Chemistry 9, Outotec [48]), from raw materials to cement (see **Fig. 2**). Through this simulation, the mass and energy balances have been performed, as well as the exergy values of all the streams of the cement plant were obtained. Subsequently the exergy and thermoeconomic analysis were conducted through the dedicated tool of HSC Sim based on the theory of the exergy cost [36] and symbolic Thermoeconomics [45]. The parameters of the exergy and thermoeconomic analysis used to evaluate the results of the simulation were:

- **Irreversibility:** Exergy destroyed along a unit or process.
- **Exergy cost:** The exergy cost of a flow is the quantity of exergy needed to produce it. Therefore, it is a cumulative indicator

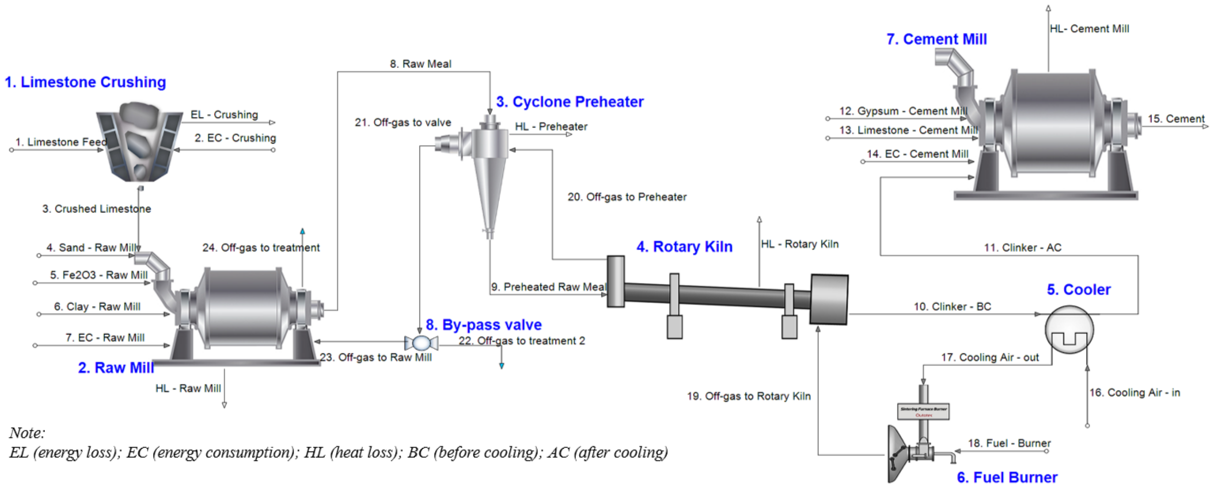

Fig. 2 *Flowsheet of the cement production process simulated with HSC Sim, showing the units considered and how they are connected between material and energy flows. This flowsheet would be linked to Fig. 1 to obtain a complete picture.*

Furthermore, as the mass and energy balances of the cement process have been performed through the simulation, the information required to perform the Life Cycle Inventory (LCI) of the process is also obtained. Using HSC Sim's LCA tool that links the results of the simulation with the environmental impact assessment (GaBi [49]), the process can be easily imported into GaBi to perform the environmental evaluation [44]. The indicators used to describe the process are:

- Global Warming Potential (GWP).
- Photochemical Ozone Formation (POCP).
- Acidification Potential (AP).
- Eutrophication Potential (EP)

Two cases (**Tab. 1**) for a fixed amount of cement produced of 100 t/h have been studied and compared (after normalization) through the indicators previously mentioned.

Tab. 1 *Formulations used for the two cases in this simulation*

in tons		Clinker	Limestone	Gypsum	Slag (SCM)	Sum
Case 1	no SCM	90	5	5	0	100
Case 2	with SCM	61.6	5	3.4	30	100

3.1 Exergy and thermoeconomic analysis

Despite the larger exergy destruction during the grinding of the fumed fayalite slag, the irreversibility analysis shows that the total exergy destruction along the process decreases around 30%, as **Tab. 2** shows. The reason of this decrease is the lower amount of material circulating through the raw mill and rotary kiln since a lower amount of clinker is required to obtain the 100t/h of cement.

Tab. 2 *Total irreversibility and exergy cost of the cement production*

	Case 1	**Case 2**
Total Irreversibility [MW]	79.8	56.2
Exergy Cost of the cement production [MW]	92.8	68.7

Furthermore, the exergy cost of the clinker is decreased around 32% when the slag is added to the cement mill. This drop on the exergy cost is due to the lower quantity of material circulating through the flowsheet, as exhibited with the irreversibility. However, as the slag must be grinded and added to the cement mill, the reduction of the exergy cost of the cement becomes 26% in total with respect to case 1.

Fig. 3 shows, that the main contributors to the exergy cost of the cement are the cyclone preheater and the rotary kiln, because of their heat losses, and the fuel burner due to the large amount of fuel required to perform the process. However, as the breakdown of the case 2 shows, the slag grinding has a considerable exergy cost. Around 3% of the cost of producing the cement is due to the electricity required to grind the slag.

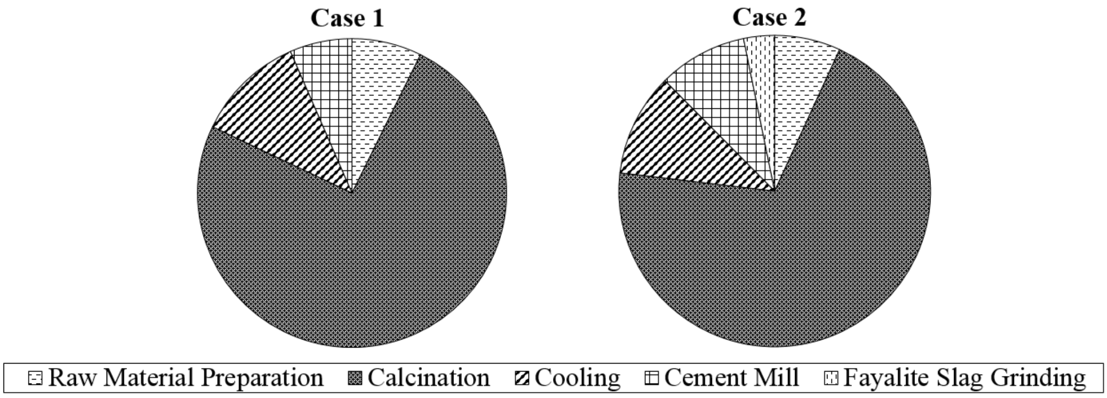

Fig. 3 *Exergy cost breakdown of the cement production (Note, the transportation cost for the SCM to the cement plant was not considered in this case study)*

3.2 Environmental footprint analysis

Tab. 3 summarizes the environmental footprint analysis of the two process routes. The GWP results obtained in this study are aligned with other LCA of cement processes. For instance, Moretti and Caro [42] reported a CO_2 emission for cements produced without SCM at around 960 kg CO_2 per ton of cement produced while the value obtained in this study for Case 1 is 1002 kg CO_2 per ton of cement. When SCM are utilized, values around 600-700 kg CO_2 per ton of cement are reported in literature, e.g. [41,42,46].

The results of this paper show that the environmental impact is decreased when fumed/cleaned fayalite slag is used as SCM. For instance, the Global Warming Potential is around 32% lower in the case 2 with respect to the base case. It is because the quantity of limestone required to produce the 100 t/h of cement is lower (32% less clinker required), thus, the emissions related to the calcination process decrease. However, as the slag must be grinded, the electricity production contributes more to the CO_2 emissions in the case 2, as **Fig. 4** illustrates. Nevertheless, the calcination process is still the main contributor to the carbon footprint constituting around 90% of the CO_2 emissions.

The other indicators, such as Photochemical Ozone Formation (POCP), Acidification (AP) and Eutrophication (EP) follow the same tendency as the GWP. The reason for this is that the use of slag in cement process decreases the specific raw material consumption. Therefore, the environmental impact generated to produce those raw materials, such as pet coke, limestone or sand, are lower. However, the contribution of the electricity generation to these indicators is higher than in the case 1 because of the extra electricity required to grind the slag.

Tab. 3 *Normalized LCA indicators of producing 1 ton of cement without including the larger flowsheet as depicted by Fig. 1.*

	GWP [kg CO_2 eq.]	**POCP** [kg NMVOC eq.]	**AP** [Mole of H+ eq.]	**EP** [Mole of N eq.]
Case 1	100	100	100	100
Case 2	68.4	73.9	74.3	75
% Reduction	**31.6 %**	**26.1 %**	**25.7 %**	**25.0 %**

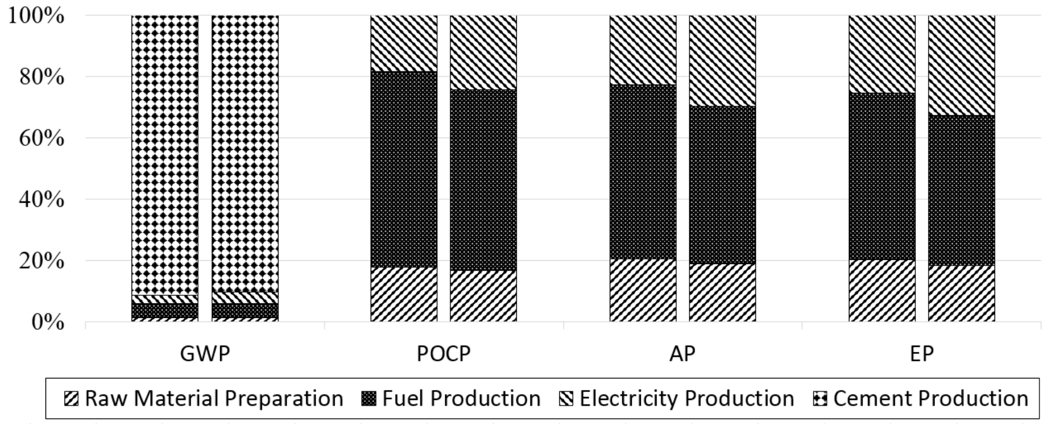

Fig. 4 *LCA Indicators Breakdown. Each indicator represents its breakdown for the case 1 (left column) and for the case 2 (right column)*

4 Conclusions

The use of non-conventional SCM derived from landfilled industrial by-products opens a promising pathway to promote sustainability in the building sector. It addresses the limited and often localized supply of traditional SCM while reducing the volume of landfilled industrial by-products. Previous studies presented in this review have demonstrated the viability and discussed the challenges in incorporating these non-conventional SCM to create green cements. In the second part of this paper, the case study presented shows the benefits of cement substitution with a non-ferrous slag as SCM both through exergy and environmental footprint analysis. The lower material circulation in rotary kiln during calcination is shown to greatly decrease the associated irreversibility and exergy cost of the process. The calculated Global Warming Potential from the LCA is reduced by 32% with 30 wt.% incorporation of SCM in an OPC-based system.

Acknowledgement

This research has received funding from the European Union Framework Program for Research and Innovation Horizon 2020 under Grant Agreement No.721385 (EU MSCA-ETN SOCRATES; project website: http://etn-socrates.eu)

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Experimental Study on the Optimization of Crushed Limestone Sand as Partial Replacement of Sea Sand in Concrete

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Abstract

Crushed limestone sand (CLS) is a by-product that is generated during limestone excavation. From an environmental perspective, it is beneficial to use CLS as a substitute for natural sand. However, due to the differences between CLS and natural sand, the application of CLS in conventional concrete is limited. The purpose of this research is to optimize an industrial concrete mixture containing CLS. In this research, firstly the influence of CLS on concrete was studied through literature review. Secondly, an experimental study was carried out by adopting the Bolomey's grading curve and the trial-and-error method. Workability of fresh concrete and compressive strength of hardened concrete were utilized as indicators. Trial results demonstrate that the reasonable ratio of sea sand to CLS (SS/CLS) is approximately within 1:5 ~ 3:3. When the SS/CLS ratio was 1:5, concrete with C25/30 compressive strength class, S4 slump class and qualified cohesiveness was developed.

Keywords: *crushed limestone sand (CLS), fines content, concrete mixture, workability*

1 Introduction

Sand is used as fine aggregate in concrete, usually accounting for 20% ~ 60% of the mass of concrete. The amount and properties of sand affect the workability, mechanical properties and durability of concrete. With the growing shortage of natural silica sand, effective alternatives are required. In this case, crushed mineral rock, crushed gravel and other by-products which meet the specifications of fine aggregate are considered as alternative sand. They are also known as manufactured sand, machine-made sand and artificial sand. The use of these by-products in concrete can significantly reduce landfill disposal and environmental pollution [1]. For example, Zhang [2] reported a case in which iron tailings, as a kind of waste at mining plant, can be used as fine aggregate for the production of concrete. When the ratio of water to cement (W/C) is 0.4 and the ratio of iron tailings to river sand is 6:4, the adjusted concrete has similar workability, compressive strength and volume stability to the concrete without iron tailings. In addition, recycling these by-products may reduce raw materials costs in certain regions, such as Rio Grande do Sul, Brazil [3].

Crushed limestone sand (CLS) is a primary type of alternative sand with a particle size of less than 4 mm (according to standard EN 12620). In Spain, France, Algeria and Argentina, CLS is mainly applied to road basements and landfill applications, due to these countries experience a large shortage of natural silica sand but rich in mineral resources [1]. In China, CLS is mainly used for roads, railways and dam construction in the southwest. For instance, as early as the late 1950s, CLS was applied to the construction of Xiuwen Hydropower Station on Maotiao River [4]. CLS is also popular in building construction presently, because the Chinese national standard (GB/T 14684) allows it to be utilized since 2002 [5]. On the other hand, the government is currently implementing strict regulations on river sand excavation, resulting in a shortage of river sand, so the building construction must begin to adopt CLS.

Although the feasibility of using CLS in concrete has been extensively studied for decades, the performance of concrete combined with CLS may vary widely. For example, it is difficult to achieve the high workability of CLS-containing concrete by using conventional mixture designs. This is mainly due to the fact that conventional mixture designs were proposed by using circular silica sand, while most CLS particles have an angular shape and rough surface texture. In addition, CLS has a large number of coarser particles retaining on the 2 mm sieve, as well as fines passing through the 63 μm sieve (according to standard EN 12620). For instance, CLS produced in Algeria consists of approximately 14% ~ 20% of fines passing through the 80 μm sieve (according to standard NF P 18-540) [6]. The poor grading of CLS can be corrected by mixing with fine natural sand [7]. The key question is which replacement rate should be adopted to approach an optimum performance of concrete. In this regard, a series of concrete mixture trials are recommended.

The purpose of this research is to use CLS to produce concrete with C25/30 compressive strength class, S4 slump class and qualified cohesiveness. This topic was put forward by a local concrete production company. The company was responding to the challenge of increasing CLS storage and a lack of sales. A promising solution would be using CLS to produce pre-mixed concrete. In this paper, firstly a review of the influences of CLS on concrete properties is presented, in order to provide some basic trends and potential optimization methods. Secondly, a case study of optimizing concrete mixture incorporating CLS is demonstrated.

2 Review on CLS

2.1 Strength

In general, the use of CLS tends to slightly increase the strength of concrete. For example, Carlos [8] conducted 13 concrete mixtures comprising three W/C ratios of 0.45, 0.55 and 0.65, respectively. The adopted CLS is from Shiga, Japan, and its particle size is less than 5 mm (according to standard JIS A 5005). The trial results showed that as the percentage of CLS increased from 0% to 100%, compressive strength, flexural strength and modulus of elasticity of concrete increased slightly. Since CLS has a higher density and hardness than mountain sand, the author inferred that CLS particles are more stable when the adhered mortar shrinks, which contributes to the strength and modulus of elasticity.

Li [9] also agreed with the impact of CLS itself on internal reinforcement. The author reported an experiment on 18 concrete mixtures comprising three W/C ratios of 0.32, 0.44 and 0.47, respectively, as well as six fines contents of 3%, 5%, 7%, 10%, 13% and 16%, respectively. The adopted fines have a particle size of less than 75 μm (according to standard GB/T 14684). The results showed that the ratio of compressive strength in prism to that strength in cube (f_c/f_{cu}) of concrete with CLS was higher than that ratio of concrete without CLS. The author stated that the flaky and wedge-shaped particles of CLS tend to increase the constraint on lateral deformation, which helps to increase the compressive strength in prisms.

Furthermore, Kim [10] observed that the fracture energy of concrete containing CLS was slightly higher than that of concrete containing only river sand through the wedge splitting test. The adopted CLS is from Donghae, Korea, and its amount of fines passing through the 75 μm sieve is only 1.68% of the mass of CLS. The author claimed that the fines might improve the cohesion between the cement paste and the aggregate, which was also Donza's point of view [11].

In summary, irregular-shaped coarser particles and a certain amount of fines may slightly improve the strength of hardened concrete.

2.2 Workability

In most cases, the use of CLS has a negative impact on the workability of fresh concrete. For instance, Donza [11] investigated the influences of three mineral crushed sand on concrete using a low W/C ratio of 0.30 and a large cement dosage of 530 kg/m^3. The adopted crushed sand are granite, limestone and dolomite, and their amount of fines passing through the 75 μm sieve are 10.7%, 10.6% and 13.3%, respectively. The results indicated that all types of crushed sand decreased the slump of fresh concrete, and required an increased dosage of superplasticizer to obtain the same slump. This view was also put forward by Park [12]. In addition, a considerable workability loss was observed after 20 minutes. The author claimed that the shape and texture of crushed sand is the cause of this phenomenon.

Safiddine [6] focused on the effect of fines passing through the 80 µm sieve on mortar containing CLS. The adopted CLS was firstly washed to remove fines, and then coarser portion was partially replaced by fines. Replacement rate varies from 0% to 20% in increments of 5%. Slump, spread flow, flow time, yield stress and viscosity were measured to characterize the workability and rheology of mortar. Test data showed that an increase in fines decreased the workability and the loss of rheology of mortar.

Since excessively high fines content often has a negative effect on the workability of fresh concrete, some researchers are trying to reduce the proportion of fines in CLS. Cepuritis [13] reported on an industrial case in Norway. Full-scale washing equipment was utilized to reduce the amount of particles with a size fraction below 0.25 mm. As a result, concrete with washed CLS displayed significantly better workability than concrete with unwashed CLS, in terms of slump and slump-flow. The author agreed that due to the large specific surface area of fine particles, excessive fine particles decisively decrease the flowability of fresh concrete.

However, CLS can also be used to produce concrete with high workability. Bouziani [14] realized this through a mixture design of self-compacting concrete (SCC). The adopted sand ratio is 0.5 and the paste volume is 360 L/m^3. The coarse aggregate has a maximum particle size of 10 mm, crushed sand of 4 mm, and river sand of 5 mm. The fines content of crushed sand is negligible and it is read from its grading curve. The mixture comprising only river sand has a slump flow of 74 cm, while the mixture comprising 20% river sand and 80% crushed sand has a higher slump flow of 77 cm.

In short, it seems that the shape and texture of particles, along with the fines of CLS are not beneficial for the workability of fresh concrete in most instances. In order to achieve high workability, a suitable mixture is demanded.

2.3 Fines content

Fines are the portion of an aggregate that passes the 63 μm sieve (according to standard EN 12620). Fines content is a crucial parameter for the influences of CLS on concrete properties. Li [9] reported that when cement dosage, W/C ratio and sand ratio are 410 kg/m^3, 0.44 and 0.32, respectively, a useful range of fines content is 3% ~ 7%. When the amount of cementitious materials and W/C ratio are 380 kg/m^3 and 0.434, respectively, the optimum fines content is 8%. In short, recommended fines content ranges are 10% ~ 15% for C30 concrete, 7% ~ 10% for C60, and less than 5% for C80 (according to standard GB 50010).

Menadi [1] studied the influences of 15% fines content on the durability of concrete incorporating CLS. The cement dosage, W/C ratio and sand ratio are 350 kg/m^3, 0.65 and 0.52, respectively. It was observed that the water penetration depth of concrete incorporating 15% fines was shorter than concrete without fines, regardless of cement type. This may be due to the fines that improve the pore structure of the interfacial transition zone (ITZ) in concrete. However, all concrete mixtures exhibited higher electric charge passed value, which indicated lower resistance of chloride attack. As a result, less than 15% of fines content is recommended when the concrete was exposed to the marine environment. However, Bederina [15] reported that approximately 14% fines content had a positive effect on mortar exposed to HCl solution, as well as in lime solution.

High fines content also has a positive effect on concrete in a few cases. For example, hydraulic roller compacted concrete (RCC) has essentially no slump, because of its small amount of cementitious material of only 120 ~ 160 kg/m^3. Whereby CLS can provide a sufficient amount of fines to increase paste volume in concrete. Wang [16] claimed that as the fines passing through the 0.16 mm sieve increased by 10%, the Vebe consistence (VC) increased by 4.6 s, and the unit water dosage increased by 7.5 kg/m^3. As fines content increased, the compressive strength, tensile strength and frost resistance increased. The Chinese standard [17] recommends the percentage of fines passing through the 0.16 mm sieve of 12% ~ 22% for hydraulic RCC.

In a word, the optimum fines content depends on the properties of raw materials and target performance of concrete. For ordinary concrete with a low compressive strength class, it seems that 15% is the maximum amount of fines.

3 Case study

3.1 Materials and methods

The raw material specifications used in this research are listed in Tab. 1. Both coarse limestone and crushed limestone sand (CLS) are produced in southern Belgium. Sieve tests were performed on 10 different samples of each aggregate. The average particle size distribution is shown in Fig. 1. Particle density and water absorption tests were performed on 5 or 10 different samples of each aggregate. The average result is shown in Tab. 2. The shape and texture of aggregates can be observed in Fig. 2.

Tab. 1 *Raw materials of concrete*

Materials	Specifications
Coarse aggregate	Limestone 4/25 mm
Fine aggregates	Crushed limestone sand 0/4 mm (CLS)
	Sea sand 0/2.5 mm (SS)
Cement	CEM III/A 42.5 Holcim Duinkerke
Water	Tap water
Water reducer (WR)	MasterPozzolith 390N con 40%
Superplasticizer (SP)	MasterGlenium SKY 576 con 15%

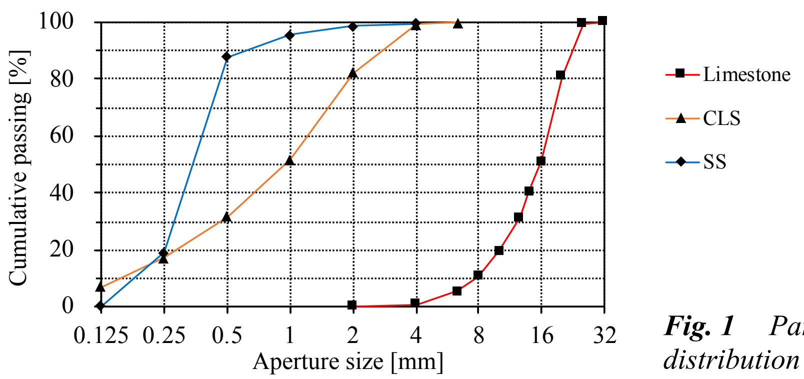

Fig. 1 *Particle size distribution of aggregates*

Tab. 2 *Particle density and water absorption of aggregates*

Aggregates	Particle density [kg/m^3]			WA_{24}
	ρ_a	ρ_{rd}	ρ_{ssd}	
Limestone 4/25 mm	2700	2660	2680	0.7%
Crushed limestone sand 0/4 mm (CLS)	2720	2660	2690	1.8%
Sea sand 0/2.5 mm (SS)	2660	2640	2650	0.5%

a) Limestone b) CLS c) SS

Fig. 2 *Photographs of the adopted aggregates*

Sieve test results show that the particles with a size fraction between 0.25 mm and 0.5 mm of SS are abundant, accounting for 68.76% of the total mass. The particles passing through the 0.125 mm sieve of CLS is 7.13%, which indicates the amount of fines smaller than 63 μm does not exceed the upper limit of 15%. Taking account of commercial cost, fines content is retained in this research.

In this case study, the Bolomey's grading curve was firstly adopted to check whether the sand ratio and SS/CLS ratio are reasonable or not. Secondly, the trial-and-error method was adopted to design the parameter level. The formula for the Bolomey curve is as follows (1). The least squares method is adopted to approach the grading of all particles to an ideal curve, as shown in Fig. 3.

$$P = A + (100 - A)\sqrt{\frac{d}{D_{max}}} \quad (1)$$

Where P is cumulative passing [%];
A is a constant [%];
d is size fraction [mm];
D_{max} is maximum size of aggregates [mm].

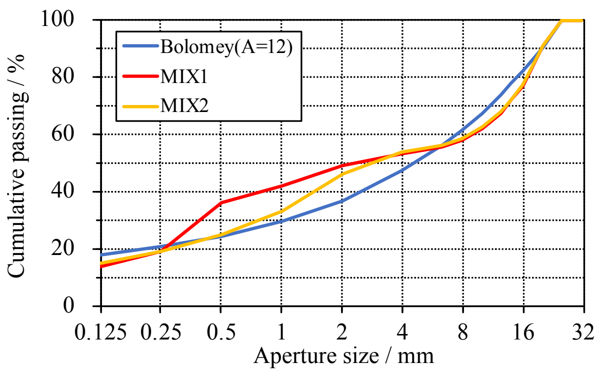

Fig. 3 *Optimization through the Bolomey's grading curve*

3.2 Experimental program and mixture design

A currently used concrete mixture containing CLS is from the local industry. However, the properties of hardened concrete are not stable enough. In this case study, the industrial mixture was repeated in MIX1. It turns out that there exists serious problems of segregation and bleeding of fresh concrete, as shown in Fig. 5. The lack of cohesiveness may lead to unstable concrete performance. In order to optimize this mixture, several indicators should be carefully considered, such as cement dosage (C), water to cement ratio (W/C), ratio of fine aggregates to total aggregates (sand ratio), ratio of sea sand to crushed limestone sand (SS/CLS), ratio of water reducer to cement (WR/C) and ratio of superplasticizer to cement (SP/C).

According to the Bolomey's grading curve, calculated sand ratio and SS/CLS ratio are 47.3% and 0%, respectively. It does not seem necessary to use SS in this mixture, which is inconsistent with the treatment of CLS by mixing with natural sand [7]. In order to investigate how much SS should be mixed, seven SS/CLS ratios were designed, varying from 0:6 to 6:0, as shown in Tab. 3. As mentioned in the specifications, 0.25% and 0.325% are the minimum of WR/C and SP/C, respectively. Each mixture has 3 cubes for the compressive strength at 7 days of age and 6 cubes for the compressive strength at 28 days of age.

Tab. 3 *Mixture proportion and workability of MIX1 ~ MIX9*

Mixture	C [kg/m^3]	W/C	Sand ratio	SS/CLS	WR/C	SP/C	Slump [mm]
MIX1	295	0.57	46.2%	3:3	0.34%	1.220%	200
MIX2	295	0.57	47.3%	0:6	0.34%	1.220%	170
MIX3	295	0.57	46.2%	1:5	0.34%	1.220%	190
MIX4	295	0.57	46.2%	3:3	0.25%	0%	80
MIX5	295	0.57	46.2%	6:0	0.25%	0%	30
MIX6	295	0.57	46.2%	5:1	0.25%	0%	30
MIX7	295	0.57	46.2%	3:3	0%	0.325%	100
MIX8	295	0.57	46.2%	2:4	0%	0.325%	90
MIX9	295	0.57	46.2%	4:2	0%	0.325%	70

In order to significantly improve the workability of fresh concrete, three approaches are recommended: a). An increase in sand ratio tends to increase the cohesiveness and water retention ability of fresh concrete; b). An increase in cement dosage will increase paste volume and the consequent flowability of fresh concrete; c). Increases in WR/C ratio and SP/C ratio tend to increase the flowability of fresh concrete. These approaches were adopted individually or jointly in MIX10 ~ MIX17, as shown in Tab. 4. In order to consume CLS as much as possible, the SS/CLS ratio was fixed at 1:5.

Tab. 4 *Mixture proportion and workability of MIX10 ~ MIX17*

Mixture	C [kg/m^3]	W/C	Sand ratio	SS/CLS	WR/C	SP/C	Slump [mm]	Performance
MIX10	295	0.57	46.2%	1:5	0.25%	0.975%	160	Shear
MIX11	295	0.57	50.7%	1:5	0.25%	0.975%	160	Shear partly
MIX12	310	0.57	46.2%	1:5	0.25%	0.975%	220	Collapsed
MIX13	295	0.57	55.0%	1:5	0.25%	0.650%	90	Qualified
MIX14	295	0.57	40.0%	1:5	0.25%	0.650%	110	Shear slightly
MIX15	310	0.57	40.0%	1:5	0.25%	0.650%	170	Collapsed
MIX16	310	0.57	50.7%	1:5	0.25%	0.650%	160	Qualified
MIX17	325	0.57	52.8%	1:5	0.25%	0.325%	160	Qualified

3.3 Results and discussion

The results of compressive strength and density of hardened concrete are shown in Fig. 4 and Fig. 6. The photographs of the slump test of fresh concrete are shown in Fig. 5 and Fig. 7.

First of all, the differences in compressive strength among all mixtures are not significant, because their W/C ratios are constant and W/C ratio is a critical factor in concrete strength. MIX1, MIX4 and MIX7 have a same SS/CLS ratio and different dosage of additives. A comparison among them indicates that the mixture without additives would have a slump of less than 80 mm. In this regard, the company was likely to try to achieve the S4 slump class by using a large amount of additives, which caused segregation and bleeding problems.

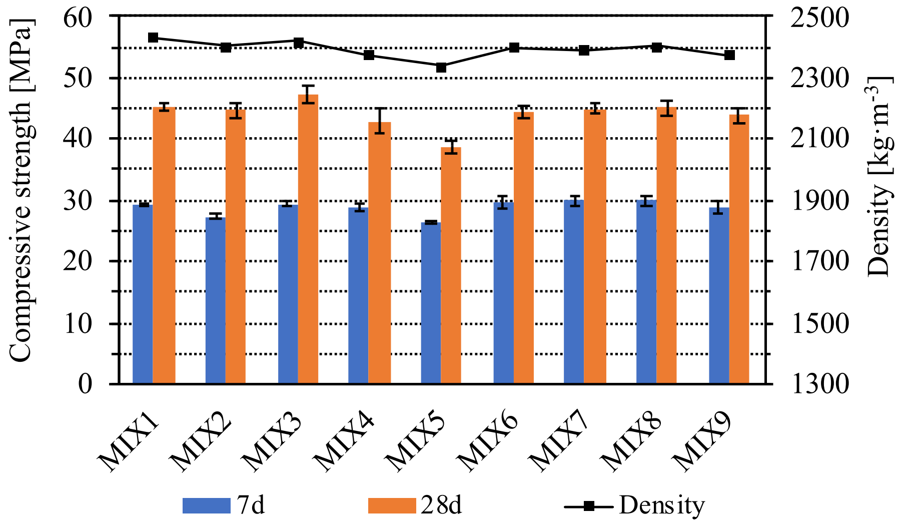

Fig. 4 *Compressive strength and density of MIX1 ~ MIX9*

a) MIX1_collapsed

b) MIX2_collapsed

c) MIX3_collapsed

d) MIX4_tend to shear

e) MIX5_true

f) MIX6_true

g) MIX7_true

h) MIX8_true

i) MIX9_true

Fig. 5 *Photographs of slump test of MIX1 ~ MIX9*

From the standpoint of compressive strength, all mixtures meet the C25/30 compressive strength class. Their density trend is similar to their compressive strength. MIX3 and MIX6 have higher compressive strength than MIX2 and MIX5, respectively. This trend is in accordance with the impact of CLS on concrete mentioned in the review [8] unless when the SS/CLS ratio is 0:6 in MIX2. The contribution of SS to correct the disadvantages of CLS may exceed the negative impact of SS-included particle grading. It should be noted that this 'negative' impact is inferred from the Bolomey's curve, while the Bolomey's curve is proposed by using pure natural sand. Anyway, the experimental results indicate that the joint use of SS and CLS tends to increase the compressive strength of concrete at 28 days of age.

From the workability standpoint, all mixtures are unqualified at all, so other parameters should be considered in the next step to significantly improve workability. MIX3 has a higher slump and better consistency than MIX2, indicating that a small amount of SS replacing CLS has a positive effect on workability. MIX4 has a higher slump than MIX5 and MIX6, indicating that the specific surface area of SS is higher than that of CLS. A large amount of SS tends to decrease the flowability of fresh concrete. While the slight slump increment of MIX5 to MIX6 shows an opposite trend, this may be due to the fines of CLS increase the paste volume and the flowability. MIX7 ~ MIX9 show the same trend as above. As a result, 1:5 ~ 3:3 is a reasonable range of SS/CLS ratio. The minimum dosages of additives may be not sufficient to realize fresh concrete with the S4 slump class.

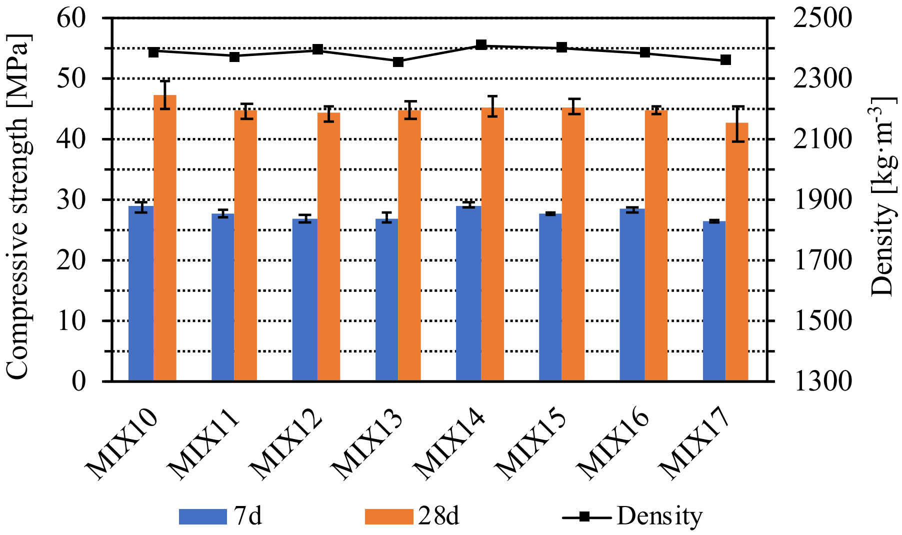

Fig. 6 *Compressive strength and density of MIX10 ~ MIX17*

a) MIX16_130 mm (with 0.325% SP) | b) MIX16_160 mm (with 0.650% SP) | c) MIX17_160 mm (with 0.325% SP) | d) MIX17_170 mm (with 0.650% SP)

Fig. 7 *Workability of target mixtures*

From the viewpoint of compressive strength, most of the mixtures in MIX10 ~ MIX17 have higher performance than MIX1 ~ MIX9, which confirms that a high dosage of CLS has a positive effect on the compressive strength of hardened concrete [8], while the density negligibly decreases.

From the workability viewpoint, as the sand ratio increase, the cohesiveness and the water retention ability of fresh concrete increase remarkably, and the cement demand increases relatively, but the flowability of fresh concrete and density of hardened concrete decrease slightly. When the sand ratio is 50.7% in MIX17, there is a noticeable decrease in compressive strength. Therefore, around 50% is likely the maximum sand ratio when the SS/CLS ratio is 1:5. Furthermore, the consistency tends to decrease rapidly with an increase in SP/C in MIX16 and MIX17, as shown in Fig. 7. There may be an upper limit to the workability of using these raw materials. A further method is to reduce D-max of coarse aggregate, which probably helps to reach the S5 slump class.

4 Conclusions

Crushed limestone sand (CLS) is a feasible alternative to fine aggregate for the production of ordinary concrete. Based on the literature review and an experimental study, it can be concluded as follows:

- The use of CLS generally has a positive effect on the strength of hardened concrete, but it has a negative effect on the workability of fresh concrete, due to its large amount of angular particles and fines passing through the 63 μm sieve.
- The joint use of sea sand (SS) and CLS tends to increase the compressive strength of concrete at 28 days of age. Circular and abundant particles with a size fraction between 0.25 mm and 0.5 mm may correct the disadvantages of CLS.
- The reasonable range of SS/CLS ratio is approximately 1:5 ~ 3:3.
- Concrete with C25/30 compressive strength class, S4 slump class and qualified cohesiveness was developed, when the SS/CLS ratio was 1:5.

Acknowledgment

This research was financially supported by the China Scholarship Council (CSC, File No. 201808110212). All raw materials were supported by Olivier Construct N.V.

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Analysis of accurate spatial use patterns within rooms for optimizing heating systems

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Abstract

Dwellings in Belgium are comparatively larger than in other European countries and their size is often not in line with the actual occupancy rate. In view of the impact of occupant presence and behavior on the actual energy consumption, knowledge of the effective spatial use is useful to develop more efficient and effective heating systems. This paper discusses the spatial use of three single family houses. The exact use patterns of the residents within the rooms were monitored for 9 consecutive days in autumn and winter 2017–2018. These data are combined with the residents' thermal comfort evaluation and their actions on windows and heating systems. It revealed that most rooms are completely heated whereas residents only use particular spots, use them for passing through or do not use them at all. These insights could be used to develop new heating systems, more adapted to the actual spatial use.

Keywords: *Effective spatial use, Standstill locations, Local heating, Energy efficiency*

1 Introduction

In order to achieve energy savings and reduce carbon dioxide emissions, renovation of residential buildings is directed by high insulation standards, air tightness requirements and energy efficient appliances and heating systems. The energy performance regulations cause a high material consumption and cannot always be executed correctly in older buildings. Simultaneously, the heating mode of dwellings remains equally in most dwellings, being central heating controlled by a single thermostat [1] that heats multiple rooms completely while residents do not use all rooms at the same time and, within a room, only use certain spots. This is especially the case in Flanders where 39% of dwellings is underused [2], i.e. dwellings are occupied by less residents than they were built for. As in Flanders, 50% to 75% of the total household energy consumption is used for heating [3], avoiding a mismatch between heating and effective use, is essential for energy efficient buildings. Adapting the heating system to the effective spatial use of the residents could save energy and thereby could be a relatively simple and low-cost energy saving alternative for the traditional cost- and material-intense renovation, especially in the case of large, underused houses.

A method to adapt the heating system to the effective spatial use could be by replacing the existing single-zone control system with a multi-zone system, such as Tado°[4], Eurotronic [5] and Honeywell Evohome [6]. These systems allow to control the temperature in each room individually. Studies [7, 8] have shown that such multi-zone heating has an energy saving potential of 11% to 33% in detached dwellings depending on several factors such as climate and building typology. Another method to adapt the heating system to the effective spatial use, is by implementing localized heating systems, such as heated chairs and infrared heating. These systems provide thermal comfort to the residents while the overall ambient temperature can be lowered [9-12]. Ghahramani et al. [13] have shown that lowering the ambient temperature from 21°C to 19°C in dwellings during the winter period can save 23% to 34%

of the energy consumption for heating. These localized heating systems could be applied at places where residents stay or sit for a longer time, only switching on when the resident is present at this location.

Today, most research on localized heating is focusing on office buildings that are characterized by mostly static activities. However, in order to develop more adapted heating systems. This paper presents the analysis of the spatial use of three single family dwellings during the heating season of 2017–2018.

2 Methodology

The spatial use, energy consumption and thermal comfort in three single-family dwellings **(Tab. 1)** in Flanders are monitored for nine consecutive days in autumn and nine consecutive days in winter, between October 2017 and February 2018.

Dwelling 1 is built in 1990, has a total floor area of 167m² and is occupied by one person who is working outside the house, thus is mostly not at home during the day at weekdays. The dwelling is heated by electric accumulation heaters in the living room and veranda, controlled separately by a manual thermostat located in the room itself, and by direct electric heaters in the other rooms. The resident turns on/opens the heater when he is in the room. However, the accumulation heaters in the living room are heated up during the night as the electricity tariff is lower then and they lose heat during the day, even when they are closed.

Dwelling 2 is built before 1945 and has a total floor area of 396m². The dwelling is occupied by 2 residents during weekdays and 5 residents during weekend days, which results in an area of 198m² per resident for weekdays and 79m² per resident during weekend days. In general, during weekdays, resident 1 is not at home during the day, while resident 2 is not at home in the afternoon. The dwelling is heated by a central heating system on fuel oil controlled by a single programmable thermostat in the office room combined with radiators and thermostatic valves. The residents frequently change the position of the valves of the heating elements when entering or leaving a room.

Dwelling 3 is built before 1945 and has a total floor area of 217m². The dwelling is occupied by 2 residents which results in 109m² per resident. Both residents are working mostly outside the house, and occasionally they work at home. The dwelling is heated by a central heating system on fuel oil controlled by a single programmable thermostat in the dining room combined with floor heating in the dining room and in the two bathrooms and radiators in the other rooms **(Fig. 1).** The valves of the radiators are only operated periodically.

Tab. 1 *Household and dwelling characteristics*

	Dwelling 1	**Dwelling 2**	**Dwelling 3**
Household size	1	2 adults + 3 children (only during weekend)	2
Occupation	Weekdays: morning + evening Weekend: variable	Weekdays: morning + evening (resident 1), before noon + evening (resident 2) Weekend: whole day (5 residents)	Week: morning + evening (occasionally working at home) Weekend: variable
Type dwelling	Detached	Detached	Semi-detached
EPC*	496 kWh/m²year	Unknown	370 kWh/m²year
Area per resident	167m²	79m² (weekend) 198m² (week days)	109m²
Construction year	1990	Before 1945	Before 1945
Heating system	Electric accumulation heaters (living, veranda) and electric heaters	Central heating on fuel, with radiators and electric heater in the work space	Central heating on fuel with radiators and floor heating (dining room and bathrooms)
Radiator valve operation	Often	Often	Periodically

* The Energy performance coefficient shows how much energy a building is using. The score depends on the insulation level and installations but does not take the occupant behaviour into account. Therefore, this score can be different from the real energy consumption

At the beginning of the case study, an exploratory interview was done with the residents. During the monitoring campaign, residents wore a tag, which is a small box that records their exact indoor position in the house 3 times per second [14], when they were at home and are awake. Residents were also asked to note, on pre-printed sticky notes, when they undertook actions on the building envelope (opening or closing windows/doors) and on the systems (changing the heating set-point, changing radiator valves). Additionally, residents got a text message each hour to fill in a right-here-right-now survey that questioned their thermal comfort experience, activity and clothing level at that moment. Separately from the data of the residents, also the air temperature was measured on one place in each room [15].

The unprocessed location data must be cleaned, processed and visualized to enable analysis of the spatial use patterns. First, errors as well as deviations caused by signal reflection by objects and persons need to be removed and corrected as good as possible to obtain more fluent movement line. In a second step, heat maps of the use intensity of the rooms over a certain period of time are calculated. These maps indicate how intense an area within a room is used and which rooms are not used or not used completely. However, these use intensity maps do not allow to distinguish between residents' circulation patterns and standstill positions. Therefore, in a third step, the data is separated into two groups: data when residents are moving and data when they are standing still in a certain location. These standstill positions are defined as places where residents stay for at least 60 seconds within a radius of 50cm. The average locations of the standstills are presented as bubbles on the floor plan with the size of the bubbles as a measure for the duration of the standstills. These bubble charts indicate the places where residents actually stay, in contrast to places where they circulate. These locations are checked with the spatial use indicated by the residents themselves during an exploratory interview.

3 Results

In the following subsections, the results of the monitoring campaign of dwelling 3 **(Fig. 1)** are presented, but, conclusions apply to all three cases. In Section 3.1, the spatial use is analyzed by means of use intensity heat maps and standstill bubble charts. The overall spatial use as well as the spatial use during specific periods of the day are discussed to detect inefficiencies in spatial use and identify zones with a high and low use intensity. Heating patterns and thermal comfort data are discussed in Section 3.2 resp. Section 3.3. By combining the spatial use patterns with the heating patterns and thermal comfort data (Section 3.4), inefficiencies in the energy consumption and opportunities to save energy by adapting the heating system are identified.

Fig. 1 *Floorplans of dwelling 3, ground floor (left), first floor (right).* *North*

3.1 Spatial use

3.1.1 Use intensity of the dwelling

In **Fig. 2,** the collected locations of the two residents during the entire monitoring campaign in winter are shown as use intensity maps. A higher use intensity results in a more red color. These maps show that some rooms are only partially used, and other rooms are barely used. Some places, mostly near furniture, are more intensively used than other places.

High use intensity places can be found at specific spots in some of the rooms. In the dining room, the piano and dining table are found as spots with a higher use intensity. In the kitchen, a high use intensity occurs at the kitchen table, but also at some places near the kitchen worktop. In the living room, the use intensity is more spread over the room, although the highest intensity is found in and around the couch. On the first floor, higher use intensity is noticed around the bed where residents load their tags every night. Also in the bathrooms, a higher use intensity is noticed. However, this is more spread out over the room and is less intensive than in other places. In the office space, a few spots near the desk are found. In one of the unused rooms (north side), a high use intensity is noticed, although this might by a measuring error as it is very close to the wall and might need to be related to locations in the corridor. During the interview, the residents also indicated that they did not use that room.

A low use intensity can be noticed in the center of the dining room. This room is frequently used as a connection to the other rooms. Almost the entire kitchen is used but many zones are characterized by a low use intensity which means that the residents only stay there for shorter periods. The living room functions as a connection with the first floor which causes extra circulation.

There are two reasons for the lack of localization data of the residents in some rooms. Firstly, the spatial use is only recorded when residents wore their active tag and they only wore it at home. This means that there was no spatial use monitoring in the carport and also less in the entrance, as when residents came home, they first had to put on the tag to start the recording. The second reason why no use intensity is recorded at some places or rooms, is that these places were effectively not used by the residents. These places are found at the northern and southern part of the living room and at the small staircase next to the kitchen. On the first floor, two rooms are unused as was also mentioned by the residents during the interviews. But also, at the southern part of the washing room, the northern part of the dressing and the western part of the office space, no spatial use was measured. When studying the use intensity map of autumn, a similar result is obtained.

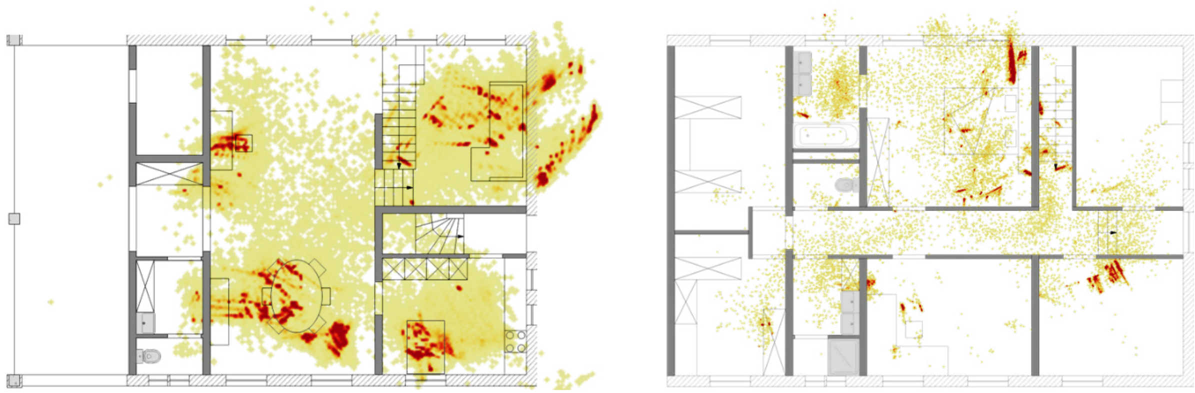

Fig. 2 *Use intensity of both residents in dwelling 3 during winter, ground floor (left), first floor (right).*

3.1.2 Standstill places

The standstills maps (**Fig. 3**) represent all standstills of the residents during the whole monitoring period. Each standstill is shown as a bubble with a radius that indicates the duration of the standstill. Many times the standstills occur at high intensity places because the location is plotted every second which leads to a higher use intensity. The standstill maps show that residents only use certain spots for a longer time inside a room. These spots can, similar to the use intensity, mostly be linked to furniture and activities in that room. If there are no standstills found in a room, it means that none of the residents stayed at the same place (±50cm) for longer than one minute.

In the dining room, standstills can be found at the piano and at the dining table. At the piano the standstills mostly have a duration of around 20’, while at the dining table the standstills have a longer duration (>60’). **Fig. 3** also shows that the piano is only used by resident 2, while the dining table is used by both residents. The standstills show that residents only effectively use these two spots in the dining room and the rest of the room for circulation. In the kitchen, two main standstill locations are found. Firstly, the kitchen table is a place where longer standstills (±25’) can be noticed, mainly due to eating. Secondly, shorter standstills (±5’) occur at the kitchen worktop. After the monitoring period, residents mentioned that they sometimes place their tag on the kitchen table instead of wearing it because it disturbed their activity. This could be the reason why less standstills occur at the kitchen worktop. In the living room, standstills are more spread over the room, however, most standstills occurred near the couch. These standstills near the couch mostly last for a longer time, similar to what was found near the dining table. Standstills outside the building are caused by measuring errors. At the first floor, short and longer standstills occur in the bedroom, next to the bed. Some of the standstills are due to loading of the tags and some shorter standstills occurred during the day. In the office room, only standstills of resident 2 occurred with a duration of 15’-30’. These standstills are only located at the desk which indicates that residents do not stay in the rest of the room. In the bathroom, next to the bedroom, mostly shorter standstills are noticed while the duration of the standstills in the bathroom next to the office space are mostly longer. Lastly, a few standstills are found in the laundry room. No standstills occur in the entrance, dressing room and the unused rooms. This means that the residents do not stay there for longer than one minute at the same place.

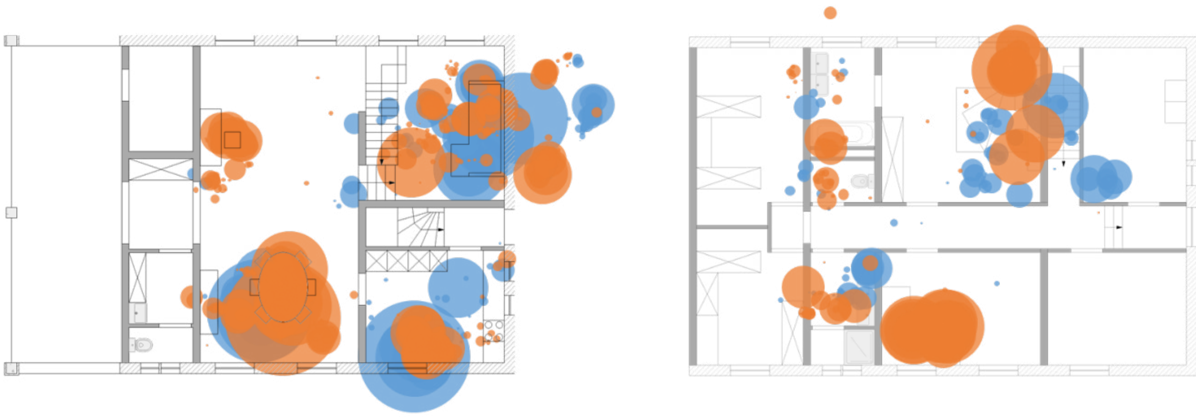

Fig. 3 *Standstills of resident 1(blue) and resident 2 (orange) in dwelling 3 during winter on the ground floor (left) and the first floor (right).*

3.1.3 Standstill during different periods of the day

Whereas in the previous paragraphs the spatial use over the entire monitoring period is discussed, in this paragraph the spatial use as a function of different time periods of the day, such as morning, afternoon, evening, is analyzed **(Fig. 4)**. However, the different days of the week are not seperated from each other causing that some standstills, e.g. office space, which occurred only during one day of the week, e.g. while working at home, are also shown in the figure. Although these maps show that some rooms are only used during specific periods of the day; e.g. in the dining room, before noon, relatively short standstills are recorded whereas in the afternoon longer standstills occur.

In the kitchen, before 7PM, standstills mainly occur at the kitchen table and none at the kitchen worktop. After 7PM, standstills are more spread which can be linked to cooking activities. The living room is barely used before 7PM. Standstills from resident 1 are noticed at noon when eating. After 7PM many shorter and longer standstills occur in the living room, which can be linked to activities such as watching television, relaxing, social interaction and eating. On the first floor, the office room is used during the whole day, however, when the standstills in this room are studied per day, they appear to occur only on one specific day and once during the evening on another day. This implicates that the resident was working at home at the desk in the office space only that day, while the other days the office room is not used. In the bedroom, standstills are shown over the different time periods, however, during the evening more standstills are noticed. The bathroom is mainly used in the morning, before noon and in the evening. During the day, both the bedroom and the bathroom are barely used.

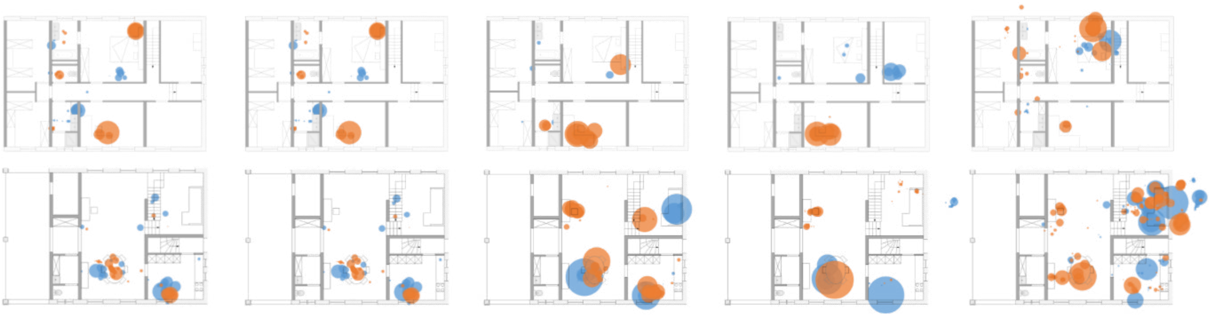

Fig. 4 *Standstills during different time periods of resident 1 (blue) and resident 2 (orange) in dwelling 3 during winter on the ground floor (under) and the first floor (above).*

3.2 Heating

As described in **Tab 1**, dwelling 3 is heated by a central heating system controlled by a single programmable thermostat which controls the water temperature of the heating system by a time clock and by a heating curve based on the outside temperature. Although a time schedule (**Tab. 2)** is programmed, residents also changed the thermostat manually to 'normal', 'setback' or 'program' (according to hours in **Tab. 2**) mode. During the monitoring period, the floor heating in the dining room and the bathrooms was switched on, and the radiator valves in the dressing, office room, and bedroom were opened.

Tab. 2 *Thermostat settings of dwelling 3 (according program mode during winter)*

Air temperature	**Mon.-Wed., Fri.**	**Thu.**	**Weekend**
Normal (nominal 20°C)	5h30 AM – 9h00 AM	5h30 AM – 11h00 AM	7h00 AM – 10h00 PM
Setback (nominal 14°C)	9h00 AM – 5h30 PM	11h00 AM – 5h30 PM	10h00 PM – 7h00 AM
Normal (nominal 20°C)	5h30 PM – 10h00 PM	5h30 PM – 10h00 PM	
Setback (nominal 14°C)	10h00 PM – 5h30 AM	10h00 PM – 5h30 AM	

When the indoor temperatures of dwelling 3 are analyzed while residents are present in the room **(Fig. 5)**, it can be found that the measured temperatures do not always correspond to the use intensity found in 3.1 and the activities in that room. E.g. an average temperature of 22°C is measured in the entrance hall, while residents do not spend much time there. In the kitchen on the contrary, temperatures are quite low (average of 15°C), whereas the use intensity is significantly higher. The data logger that registered the temperature in the kitchen was installed next to a window which could have slightly influenced the measurement, but the very low temperature in the kitchen was also mentioned by the residents during the interview. It was also found that the average temperature in the bedroom is higher than the temperature in the living and dining room, while in these latter rooms mostly a higher temperature is required.

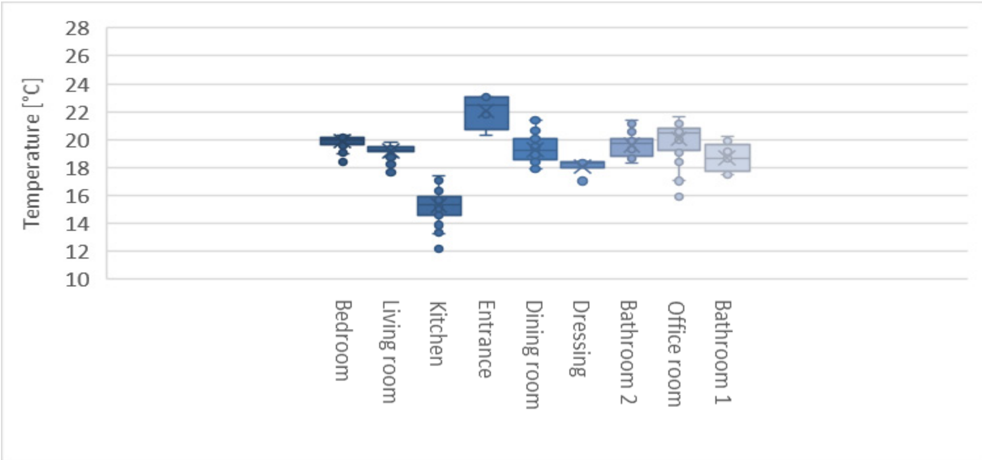

Fig. 5 *Air temperature per room while residents are present, measured in dwelling 3 during winter.*

Fig.6 shows the temperature of dwelling 3 during a winter day when the heating system is switched on at 7 AM, followed by temperature increase in most rooms. Especially in the office room, a fast temperature increase is noticed whereas analysis of the spatial use patterns and the survey revealed that residents did not use this room during the day. At 10h00 PM, the heating system is turned back to program mode, and the temperatures drops again. When studying the complete monitoring period, it is found that when the heating system is turned on, most rooms are heated simultaneously, although the reaction time in each room is different. Additionally, the heating is largely based on convection which means that the whole room is heated instead of certain spots. This does not correspond with the spatial use found in 3.1, which shows that the residents do not use all rooms simultaneously nor completely.

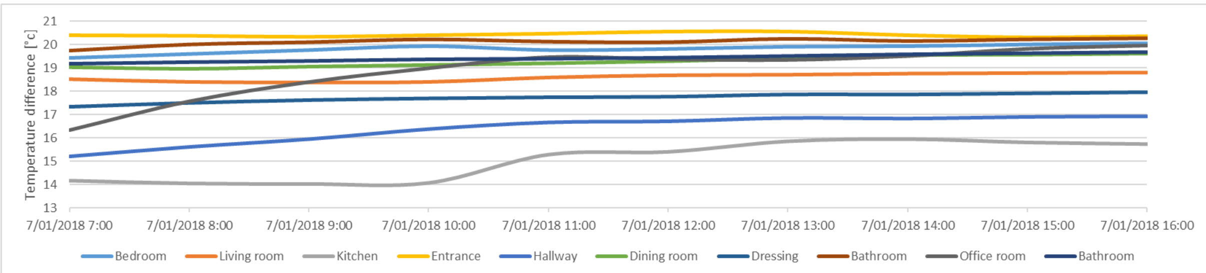

Fig. 6 *Air temperature per room, measured in dwelling 3 during a morning in the winter period.*

3.3 Thermal comfort parameters

Additionally, to temperature, thermal comfort depends also on other parameters such as: clothing level, activities, relative humidity and air speed. During the monitoring campaign, residents regularly had to fill in a survey in which they had to indicate their clothing level and activities. The residents also had to evaluate their feeling of thermal comfort on that specific moment.

3.3.1 Clothing level

Clothing has an effect on thermal comfort because it influences the heat loss of the resident. In dwelling 3, there are significant differences in clothing between both residents. Resident 1 wore mostly casual clothing (long trousers, t-shirt, thin sweater) during the heating season, while resident 2 mostly wore heavy clothing in winter and varying clothing levels in autumn. Both residents also used an extra blanket regularly (resident 1 in 26% and resident 2 in 10% of the responses), mostly while watching television and working at the dining table. It is possible that they used it as extra insulation layer to increase their thermal comfort or for coziness.

3.3.2 Activities

Activities performed by residents have an impact on the metabolic rate. When the internal heat production increases due to a higher metabolic rate, residents will adapt factors of the thermal balance (clothing, temperature) to preserve thermal comfort. When analyzing the activities of the residents from dwelling 3, active and passive zones can be found in the different rooms. The dining room is used for active activities such as cleaning the room, and passive activities such as playing the piano and working on the computer. In the kitchen, two different zones can be found; around the kitchen table more passive activities occur such as eating and social interaction and around the kitchen worktop more active activities take place such as cooking. The living room, office space and bedroom are rooms with mainly passive activities such as watching television, working on a computer or resting. The laundry room and bathrooms are used more actively for activities such as washing clothes or for personal hygiene.

3.3.3 Comfort experience

During winter, both residents perceived the indoor thermal environment mostly as comfortable (68% of the responses for resident 1 and 86% of the responses for resident 2). The measured temperatures could be related with the comfort experience of the residents, however, the exact temperature on that specific place has to be taken into account as well as the clothing level and the activities. Additionally, the perceived thermal comfort could also be linked to the rooms and to the behaviour of residents. For example, resident 2 wore warmer clothes than resident 1 which caused that this person perceived the temperature as more comfortable although they were performing the same activity in the dining room.

3.4 Energy saving potential by storytelling

In this section, the energy saving potential when adapting the heating system to the spatial use of resident 1 is highlighted for one day during the monitoring period (Monday 12th of January). In **Fig. 7,** the actual spatial use of resident 1 over time is combined with the actual setting of the heating system, actions on the building envelope and system that influence the room temperature and the thermal comfort experience. By studying these factors over time, actual moments where the energy efficiency could be increased can be found.

Around 7h15 AM, both residents woke up. At 7h20 AM, resident 2 manually turned on the thermostat to day mode. Meanwhile, resident 1 went to bathroom 2, where he stayed for a few minutes, and opened the bathroom window around 7h20 AM. Thereafter, the resident went back to the bedroom where he also opened both windows (7h31 AM). At 7h40 AM, the resident went downstairs, where he stayed at the dining table (1’) and then went to the kitchen table to eat. During eating (33’), the resident experienced a temperature of 15,2°C as slightly cool while wearing casual clothing. After eating, resident 1 went to the dining table where he stayed until 8h53 AM. Afterwards 8h53 AM, he went upstairs to close the windows in the bedroom and in the bathroom and then again stayed for a few minutes at the dining table. While preparing himself to leave home, the resident experienced a temperature of 22,6°C in the entrance hall as comfortable. When he came back home around 10h20 AM, he went directly to the kitchen where he walked through the room for a while. Thereafter, the resident went back to the dining room and stayed at the dining table until 12h30 PM. During this period, he also increased the nominal temperature of the heating curve to +5. While the resident was at the dining table, he responded the survey two times: The first time at 10h25 AM, he experienced a temperature of 18,9 °C as comfortable while working on the computer and wearing casual clothing. The second time (12h21 PM) he experienced a temperature of 19,1 °C as slightly cool while working and wearing casual clothing and an extra blanket. The difference in thermal experience could possibly be explained by the activity which took place before (coming home). At noon, the resident went shortly to the kitchen and then went to the living room to eat his lunch. There, he experienced a temperature of 18,4 °C as comfortable. After eating, the resident went back to the dining room to work and experienced temperatures of 19,6°C and 19,8°C as slightly cool. Around 6h30 PM, the resident passed through the kitchen for a couple of minutes and then went to the living room, where he experienced temperatures of respectively 18,9 °C, 19,2°C, 19,4°C and 19,6°C as comfortable while eating, watching television and working. At 12h46 AM, the resident passed through multiple rooms (living room, kitchen, dining room) while going upstairs, where he went to the bathroom and the bedroom. At 0h33 AM, the thermostat is turned back to program mode.

By visualizing a single day in detail, it can be noted that only certain places are used for longer times. In this case, the resident mainly stayed in the dining room during the day and in the living room during the evening and only used certain spots in these rooms. During the whole period the heating system was turned on. When comparing the actual temperature with the room usage, it can be noted that these do not always correspond to each other. E.g. in the office space, an average room temperature of 20°C was measured, while it was not occupied by one of the residents at all.

By visualizing a single day in detail, it can be noted that only certain places are used for longer times. In this case, the resident mainly stayed in the dining room during the day and in the living room during the evening and only used certain spots in these rooms. It also shows that during the whole period, the heating was turned on and the temperature rose in most of the rooms. When comparing the actual temperature with the room usage, it can be noted that these do not always correspond to each other. E.g. In the office space, the temperature rose during the day by the heating system, while it was not occupied by one of the residents at all.

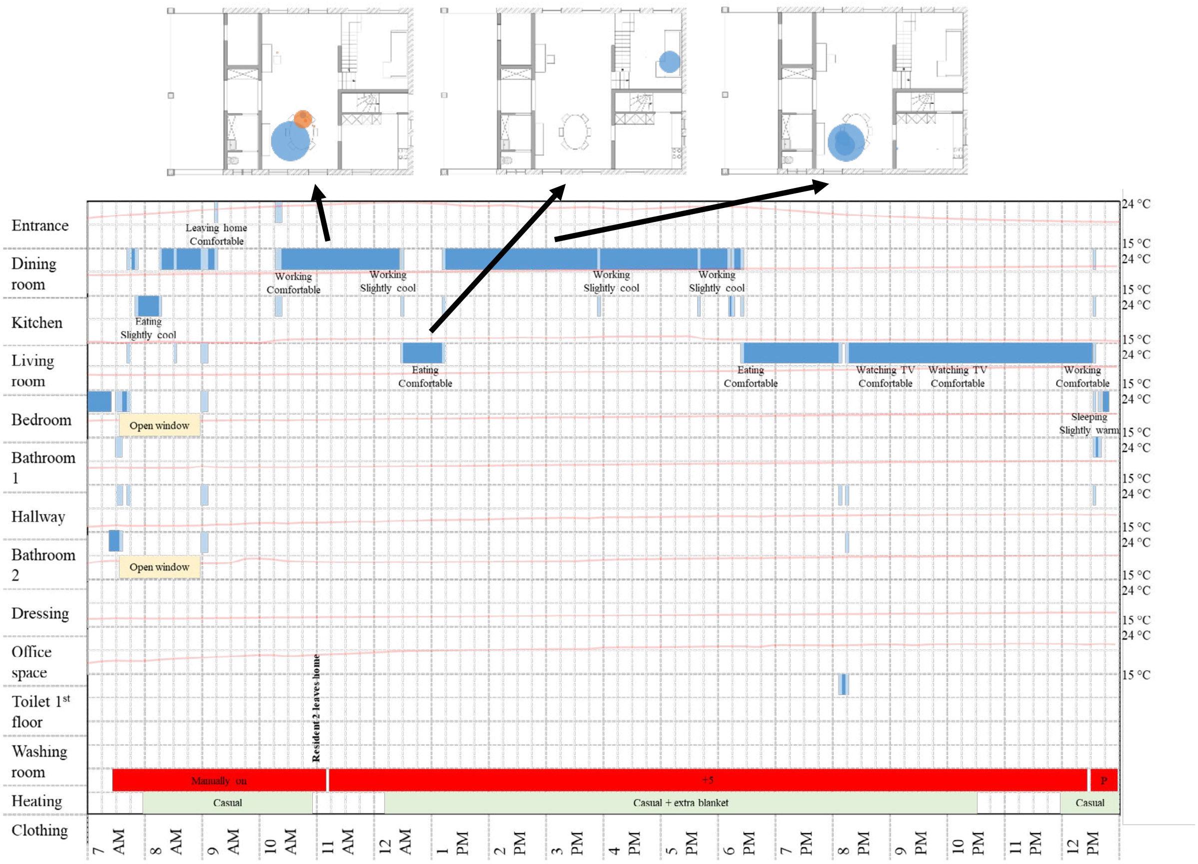

Fig. 7 Spatial use (circulation light blue, standstills dark blue) in combination with actions (yellow, red bars), clothing (green bars), activities, thermal comfort evaluation and indoor air temperatures (red lines).

By analyzing the spatial use, it is revealed that only certain spots are effectively used by the residents while the heating system heats several rooms simultaneously and completely. Energy could be saved by adapting the heating system more to the effective spatial use of the residents fe. by implementing localized heating systems while the background temperature is lowered. Localized heating systems, such as heated chairs, heated insoles and radiation panels, can be implemented at places where residents stay for a longer time, which are found by analysing the effective spatial use (fe. the dining table and the couch).

3.5 Conclusion

In this paper, the spatial use patterns of three single-family dwellings are analysed and combined with the heating patterns and thermal comfort data to detect inefficiencies in the energy consumption and to identify opportunities to save energy by adapting the heating system. The results of only one case are discussed, however, the conclusions apply to all three of the studied dwellings. The analysis of the spatial use shows that residents do not use all rooms nor the complete rooms, although the heating system will heat entire rooms simultaneously. Specific spots in the rooms are identified where residents stay for a longer time, such as the dining table, the kitchen table, the couch, the desk and the bed. Places which are mostly used for shorter periods of time and that are more spread around the room are the kitchen worktop and in the bathroom. In some dwellings, other frequently used places are found, e.g. in dwelling 3, the piano and the laundry room. Further research will focus on heating systems that are better adapted to the spatial use of the residents. It will be investigated if, by applying localized heating systems at the above identified spots, an effective energy saving can be reached while maintaining (or increasing) the thermal comfort of the residents.

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Decision-Support Tools and Assessment Methods for Sustainable Built Environment

Developing Indicators for Evaluating the Sustainability of Urban Areas

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Abstract

Urban development is often seen as vital when striving for sustainable development. A number of certification systems have therefore been developed around the world to support such processes. The certification system developed for a Swedish context is called Citylab, but it still lacks the important stage of follow-up on actual performance towards sustainability.

This paper presents some indicators by which Citylab can evaluate the sustainability performance of urban areas in a post-construction phase. The indicators were developed in collaboration with several working groups of experts and practitioners from the Swedish urban planning, real-estate and building sector. The work of the groups was guided by a list of indicators already used in different contexts and by a framework of principles for certification systems identified in earlier research. This process was intended to render the certification system and its indicators scientifically credible, practical, beneficial for the actors involved and capable of driving change.

Keywords: *sustainable urban development, certification system, indicator, Citylab*

1 Introduction

Urban development is often seen as vital when striving for sustainable development and there have been several local initiatives to monitor the sustainability of cities and communities, e.g. [1, 2, 3, 4]. In parallel, different certification systems have been developed for sustainable urban development, such as LEED for Neighbourhood Development, BREEAM Communities etc, see e.g. [5, 6, 7]. These multiple initiatives on developing and analysing indicators of sustainable urban development, together with more general literature [8, 9], have produced many important learning outcomes on how to conduct the practice. However, there does not seem to be a commonly used framework for how the development of new certification systems should be done.

For the Swedish context, a need for a certification system which supports urban development projects in their work with sustainability have been identified [10]. This need includes both what sustainability issues are important to consider and how to create a collaborative working process between different actors through the whole urban development process; from vision, to detailed planning, to construction and lastly follow-up and evaluation post-construction. To fulfil this need, a certification system called Citylab is under development with several parts already in place. Currently, Citylab mainly comprises a document with both voluntary guiding parts and mandatory certification requirements regarding the planning and construction phases. This document has been used in about

25 urban development projects in Sweden. However, this paper will report on the development of a new part of Citylab which focuses on follow-up and evaluation post-construction.

With the lack of a commonly used framework for how to design a certification system in a systematic and robust way, we developed a framework based on literature review and interviews with urban development practitioners in earlier work, see Lind et al. [11]. However, there is no objectively perfect certification system; on the contrary, it will always be built on subjective considerations [8, 4]. Therefore, the framework we developed earlier [11] does not stipulate exactly how a certification system should be designed, nor does it include a description of a step-by-step process. Instead, the framework highlights important considerations where transparency and thoughtful decisions are required in the development of a certification system such as Citylab.

The aim of this paper is to use the development process of Citylab to test the application of the framework for developing a certification system for sustainable urban areas.

The research questions are:

- How can a development process of a certification system be conducted, when using the framework?
- What are the key strengths and challenges when implementing the framework?
- How can a certification system, including its indicators, be designed based on the framework?

2 Background – a framework for certification systems

Our framework of important considerations [11] starts by defining three benefits a certification system must provide, see **Tab. 1**. First, it needs to be beneficial to the organisation using the certification for marketing purposes. Second, it needs to be beneficial to the practitioners using the certification system as a structure for the sustainability work. Third, it needs to be beneficial to the urban area becoming more sustainable through the work with the certification.

To provide these benefits, a certification system needs to fulfil three main principles, with several sub-principles, see **Tab. 1**. *Principle 1*: The certification system needs to be scientifically credible by being comprehensive, i.e. covering all relevant sustainability aspects. This needs to be done in an integrative way and with high validity and reliability. *Principle 2*: The certification system needs to be practical, by being intelligible for those using it, simple to conduct and focusing on issues that the target group can influence. *Principle 3*: The certification system should drive change by determining what is a good-enough level and guiding discussions regarding the issues among the stakeholders. It should also consist of different indicators to follow cause-and-effect chains and present the results in a way that enables action to be taken. To comply with these principles, stakeholder and public participation is an overriding requirement [11].

Tab. 1 *Framework of important considerations when designing a certification system for urban areas [11].*

Benefits to be provided	Principles to guide the development		Overriding requirement for compliance with the principles
	Principles	**Sub-principles**	
Beneficial for the organisation Beneficial for practitioners Beneficial for the urban area	Scientifically credible	Comprehensive	Stakeholder and public participation
		Integrative	
		Valid	
		Reliable	
	Practical	Intelligible	
		Simple	
		Influenceable	
	Driving change	Determining what is good enough	
		Guiding a discussion among relevant stakeholders	
		Including different kinds of indicators	
		Presenting the result in a way that enables action	

As noted in Lind et al. [11], some of these (sub-)principles are in conflict with each other. In this paper, we focus on some of these conflicts that affect the process more than others. The clearest conflict is between validity and influence (**Tab. 1**). Validity in this context means choosing indicators as close to the end problem as possible. To achieve high validity, one should choose e.g. an indicator that measures people's health, rather than features in the urban environment that are important to support people's health. However, urban planning has low influence over people's health and high influence over health-related features in the urban environment e.g. noise and greenery [11]. Throughout this paper, we present more examples of this conflict between validity and influence and discuss how to handle it.

Because of these conflicts, the (sub-)principles in the framework should not be seen as a strict template to follow, but rather as coordinates in a design space that allows for a variety of outcomes, depending on how the (sub-)principles are prioritised. This means that certification systems can be quite different from each other, but still follow the same framework. The crucial element is to be transparent and make thoughtful decisions about what (sub-)principles are prioritised, and why [11].

2.1 Four alternatives for Citylab, according to practitioners

To start exploring the relationship between the framework and the development of Citylab we previously conducted interviews with practitioners and identified four alternatives for the future certification system [11]. These alternatives are all focusing on a review and assessment post-construction, but they suggest different roles and functions the certification system could have. In short, the identified alternatives are:

1. **The sustainability performance:** The certification system review and assesses whether the urban area is more sustainable than other urban areas with regards to the activities going on in the urban environment.
2. **What was built**: The certification system review and assesses whether planned sustainability measures have been implemented in the urban environment.
3. **Learning outcomes**: The certification system review and assesses whether the stakeholders involved have drawn important learning outcomes from the project and identified what they will do differently when working with sustainability in future projects.
4. **Operation and maintenance**: The certification system review and assesses whether the operation and maintenance continue to strive for the sustainability objectives set in the planning phase.

The differences between the alternatives result in different prioritisation of (sub-)principles. Thus, when choosing the alternative to base the development of Citylab on, we will consequently start position the certification system in framework. In other words, choosing among the alternatives is also about choosing what (sub-)principles to priorities. These relationships between alternatives and (sub-)principles and what choices we made are further developed in section 4 below.

3 Overview of the working process for developing the certification system

The process of developing the certification system comprised several steps with broader involvement of practitioners and with work within the smaller project team, see **Fig. 1**. Having this practitioner involvement continuously throughout the project meets the overriding requirement in the framework, which is crucial in order to comply with several of the (sub-)principles, not least making the certification system practical, see **Tab. 1**. The remainder of this paper focuses on the parts of the process illustrated by boxes 2 to 6 in **Fig. 1**, with the content of each step explained in sections 4–6.

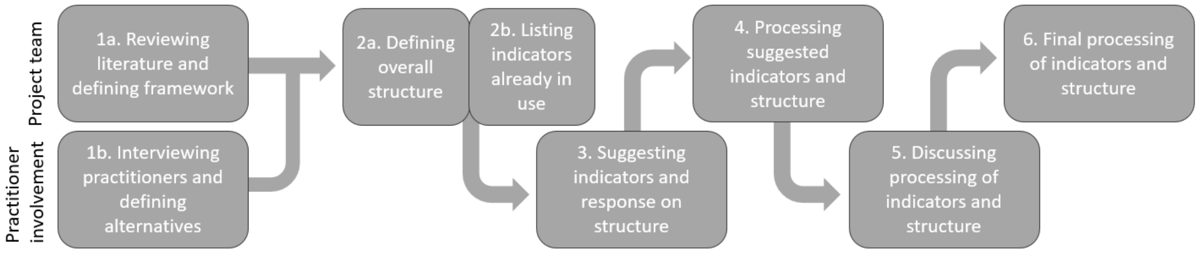

Fig. 1 *The process of developing Citylab certification system of urban areas post-construction, based on the framework. This paper focuses on box 2-6, box 1a and 1b see [11].*

4 Defining the overall structure of the certification system

The first step in developing the new certification system was to define the overall structure, see box 2a in **Fig. 1**, through a discussion about the relations between the (sub-)principles in the framework and the different alternatives (1-4) raised by practitioners. In other words, we started to position the certification system in the framework by prioritising the (sub-)principles. The discussion took Alternatives 1-4 as its starting point and resulted in Alternative 1, with its focus on sustainability performance in the urban area, being deemed the most attractive. The main argument for this was that we prioritised validity and thus the focus on the performance of the urban area regarding sustainability. This prioritisation was based on the current criticism that certification systems used today review implemented measures, rather than what effects these measures have on sustainability [6]. Thus, we decided that Citylab would focus on defining a good-enough level for the urban environment, rather than focusing on what the stakeholders involved have or have not done, which was the focus of Alternative 2-4. This choice was made with awareness of the shortcomings attached to Alternative 1, especially regarding the fact that stakeholders might have low influence over the issues included in the certification system [11]. Therefore, as we will show in this paper, the question of creating a good balance between validity and influence persists throughout the process of developing the certification system.

Another sub-principle which seems vital to be aware of at an early stage of developing a certification system is how to be comprehensive and include sustainability issues of both local and global relevance. In our case, this was done by including two kinds of indicators in the certification system: indicators of general interest that all urban areas should use and site-specific indicators for each urban area which highlight sustainability issues of local importance. The site-specific indicators will not be comparable with those for other urban areas and the assessment must therefore focus on the process of deciding on the local indicators, rather than determining a good-enough level. The inclusion of site-specific indicators may also help fulfil other sub-principles (**Tab. 1**). Especially regarding better guiding a discussion between the different stakeholders and the overriding requirement of stakeholder and public participation, as such indicators need to be developed through collaboration and participation in each local context.

To comply with the sub-principle of including different kinds of indicators, Niemeijer & Groot [12] suggest including indicators that track all the parts of a cause-and-effect chains, i.e. driving force, pressure, state, impact and response (DPSIR). However, this may lead to quite many indicators and in turn make the certification system difficult to comprehend and expensive to use. As we prioritise the sub-principle of simplicity we therefore decided to not follow this DPSIR-approach. If an urban area performs badly in the certification, it may be relevant to use more indicators in line with what Niemeijer & Groot [12] suggest in order to understand the causes of that performance; but we don't see it as relevant to include it in the certification system.

The results of the assessment, with its performance-oriented indicators of both general and site-specific relevance, will be presented in a radar diagram or similar. By doing that we avoid having to aggregate all sustainability issues into one index, an aspect criticised in other certification systems [6, 8]. The most important reason for doing this, however, is to comply with the sub-principle of presenting the results in a way that enables action, see **Tab. 1**. It should be clear where new measures are needed, and thus being bad regarding one sustainability issue should not be hidden in an index.

5 Practitioners suggesting indicators

In the process described in **Fig. 1** we engaged practitioners from the urban planning and real estate sector in Sweden in working groups to suggest general indicators and criteria on how to develop site-specific indicators, see box 3 in **Fig. 1**. This was the most collaborative part of the project, with many practitioners involved, and detailed discussions were held regarding all different sustainability issue. Regarding this process we will, in this paper, focus on the preparatory work needed and main issues brought up for discussion.

5.1 Working groups for developing general indicators

5.1.1 Establishing the working groups

Four working groups involving in total of 22 practitioners were established, with the task of formulating general indicators to measure fulfilment of Citylab's sustainability targets in an urban area, see **Tab. 2**. The group members represented different member organisations within Sweden Green Building Council (SGBC), which operates Citylab, and were recruited through open calls on SGBC's website and newsletters. The practitioners mainly represented consultancy and architectural firms, but also development companies, one municipality, one real estate company, one university and the Swedish environmental protection agency.

Citylab's sustainability targets (**Tab. 2**) were an important part of the process as they framed the task of the working groups. They were developed prior our project, during 2015, through a process with broad stakeholder involvement, see [10], and define what an urban development project should strive for in the long run when working with sustainability. These targets were important in framing the work, not only to follow the existing structure of Citylab, but also to use it as an existing and used definition of sustainability aspects which are important to consider when working with urban development in Sweden.

Tab. 2 *Working groups divided according to Citylab's sustainability targets*

Group 1 sustainability targets	Group 2 sustainability targets	Group 3 sustainability targets	Group 4 sustainability targets
1. Good health and well-being	4. Safe and secure living environment	7. No negative impact on the climate	8. Resource management
2. Gender equality, equal opportunities and social cohesion	5. Good conditions for supporting a living		9. No negative impact on the environment
3. Participation and influence	6. Attractive city life		10b. Resilience and flexibility (with environmental focus)
	10a. Resilience and flexibility (with social focus)		

5.1.2 Preparing for the working groups

The instructions to the working groups were to select the most important aspects to measure through indicators (maximum of five) for each of their sustainability targets (**Tab.2**). This meant that the groups had to discuss how to comply with the first sub-principle (**Tab. 1**) of being comprehensive and at the same time comply with the sub-principle of simplicity by not including too many indicators. The groups were also introduced to the identified conflict between the sub-principles of validity and influence and were encouraged to discuss what they saw as relevant to measure regarding how to get high validity, but not too little influence. The groups were also asked to consider how to make the indicators intelligible and simple, while still having high reliability.

Beside the instructions for the work, the working groups were also given a list of indicators already in use today as support for their work (box 2b in **Fig. 1**). The reason for this was to make it possible to use data and methods to collect data that already exist. Using data that already exist would be a way to follow the sub-principle of simplicity, as it makes data collection cheaper. Using tested methods would be a way of fulfilling the principle of being scientifically credible, as tested methods would have had the opportunity to become more robust and get high reliability. Another reason for making the list of indicators was to follow the principle of being comprehensive by using international, national and local goals for sustainability as a starting point for the selection of indicators, thus being able to relate the chosen indicators to these overarching sustainability goals on different scales.

The indicators were found by going through about 40 different sources, ranging from an international scale, including UN Sustainable Development Goals, to national scale, including Sweden's Environmental Quality Objectives, and local scale, including monitoring of sustainability issues of municipalities and urban areas. In these sources, not all indicators had a clear connection to urban development, so some indicators needed to be excluded, e.g. average grades in elementary schools monitored by some local authorities. The result was about 1000 individual indicators, which were grouped into categories measuring the same or a similar aspect. Examples of such groups are 'parking space per resident' and 'energy use in buildings'. This resulted in about 100 indicator groups, which were presented to the working groups.

5.1.3 The work carried out by the working groups

All groups used the prepared list of indicators as a starting point for their discussions. By going through the list, indicators were eliminated in several rounds of discussion until there were about 3-5 indicators per target. However, the groups sometimes felt important aspects were overlooked in the prepared list and formulated new indicators. They also modified and combined indicators from the prepared list. To support the working groups and facilitate sharing of ideas between the groups, there was always at least one representative from the project team present at each group meeting. The representative had a passive role, asking questions to make statements and arguments more explicit and answer questions from the group members regarding the project. This made it possible to follow the discussions and understand the thoughts behind the suggested indicators.

Beside discussions on individual sustainability issues, two more overarching discussions were held in all groups. The first was on the balance between the sub-principles validity and influence (see **Tab. 1**), where Group 1 claimed that it would not be relevant to measure the health of the residents, even if that would mean high validity. Instead, their suggested indicators focused on what stakeholders have more influence over, i.e. possibilities in the outdoor environment to have a healthy life, such as good possibilities to use a bicycle and good access to services. Group 3, on the other hand, deemed it important to measure how the urban environment is actually used, and thus suggested indicators with high validity, but lower influence, such as how much drinking water is used and how much household waste is recycled.

The second overarching discussion held in the groups concerned whether it is relevant to determine a good-enough level (a sub-principle in **Tab. 1**) for all sustainability issues. The groups believed that there are issues which are important to measure in order to understand the urban area before new actions are implemented, but for which it is not relevant to set a common target level. Examples of this were mapping of ecosystem services and share of people living in the area who also work in the area. How the certification system handles these two overarching discussions and the associated indicators are described in section 6.

5.2 Working group on how to include site-specific indicators

A fifth working group focused on how the certification system could include demands on the process of deciding on site-specific indicators, including how the local community should be involved in such a process. However, that group needed more time and its work is therefore not described further here.

6 Processing suggested indicators to a final list

6.1 Categorising suggested indicators

In total, 45 suggestions for indicators were submitted by the working groups. Some were quite distinct and could almost be a final version, such as energy use per square metre, while some were formulated in more conceptual terms, for example regarding diversity and quality of public spaces. These suggestions were processed by the project group to identify overlaps and check whether they were in line with the agreed structure of the certification system and with each other, see box 4 in **Fig. 1**.

On comparing the suggested indicators, it emerged that they reflected the two overarching discussions brought up by all groups regarding the conflict between influence and validity, as well as the relevance of determining a good-enough level. Thus, some indicators had both high validity and high influence, for example energy use. Some indicators focused on features implemented in the urban area, leading to low validity but high influence, for example proportion of impermeable surface area. Other indicators focused on high validity but with low influence, for example regarding the economic situation of the residents. This last category of indicators was suggested to be reported only, and would thus not have a determined good-enough level.

6.2 Discussion of categorisation with group leaders

After categorisation of the indicators, the next step was to engage the two assigned leaders for each group in a workshop, see box 5 in **Fig. 1**. The workshop focused on the two overarching discussions and how different sustainability issues are suggested to be treated differently through the different kinds of indicators. It became evident that environmental aspects are often easier to measure on a performance basis, while social sustainability issues are often more difficult to measure if high influence is also valued. Thus, the certification system needs to have different tactics for measuring different issues. One suggestion was to determine a good-enough level for some indicators and to demand only that results of measurements be reported for other indicators, i.e. not demand a certain performance level regarding indicators with low influence. However, this means that indicators with a determined good-enough level will be biased and prioritised higher than indicators without such a level, even if the sustainability issues are equally important. For example, all urban areas would need to be energy-efficient, since that is easy to measure, but would not need to have qualitative green spaces, simply because that is difficult to measure with both high validity and influence. Another option discussed was whether the certification system should have good-enough levels at all, in order to treat all sustainability issues in the same way. However, the certification would then assess whether relevant information had been gathered, rather than assessing whether the urban area is sustainable or not.

Following this discussion, the working group leaders and the project group together made a priority list of the suggested indicators through a voting process using coloured dots on Post-it notes for each indicator. The prioritisation was based on both the most important sustainability issues for urban development projects and issues not handled satisfactorily in most urban areas in Sweden today. This was done to set a priority ranking for all the suggested indicators as a basis for the continuing work.

6.3 Final processing

As a last step in deciding on a final indicator list for the certification system, the project group conducted some final processing, box 6 in **Fig. 1**.

As a starting point for the final processing, the project group decided that the certification system would focus on determining the sustainability of urban areas and not on being a complete information base for future measures. Thus, we excluded indicators which the working groups suggested to include as a basis for measures to implement in the future rather than assessing the sustainability performance of the urban environment, e.g. indicators of the economic status of residents. Other indicators were excluded because they were judged to be more of a regional or even national nature and not the responsibility for an urban area or even a single municipality, for example supporting structures for selling locally grown food.

We also identified some sustainability issues that needed to be included since they are critical for urban development, but over which urban development has a low influence. Because of this low influence, we did not deem it relevant to determine a good-enough level for these indicators. However, these indicators still need to be compared against a benchmark, such as a mean for the nation or municipality. This is the case with e.g. a safe and trustful community. Determining exactly which indicators should have a good-enough level or not will be an important part of the next step of the project.

7 Final version of indicator list

The whole process resulted in the list of indicators presented in **Tab. 3**. This final list only stipulates the aim of each indicator and there is still work left to do regarding how the indicators will be used in practice, for example collection of data. In this regard, some indicators are still on a conceptual level and need to be concretised, e.g. how to evaluate meeting places for all and mixtures of dwellings. Some indicators need to be investigated to determine whether legal requirements make these indicators redundant, as is the case e.g. emissions of nitrogen and phosphorus, risks to drinking water supply and contaminated ground. Thus, the continuing process will also include iterations with regard to the framework in **Tab. 1.** The results of this future work will be presented in future publications.

8 Conclusions

In this paper, we have described how a development process may be conducted to apply in practice the framework we developed in previous work [11] for developing a certification system for sustainable urban areas. During the process, it became evident that some of the (sub-)principles in the framework are difficult to combine. The main conflict identified was between finding indicators with high validity and of high influence. Ultimately, the choice of (sub-)principle to prioritise will depend on the intended function of the certification system, but also on the differences between different sustainability issue. Some issues are easier to measure with high validity and high influence than others. Thus, it seems appropriate to describe the (sub-)principles in the framework as coordinates in a design space and that there are many possibilities for a rational design of a certification system. At the same time, using the (sub-)principles in the framework throughout the process made the conflicts clearer for the parties involved and it was possible to have a discussion on how to handle them. The process illustrated in **Fig. 1** was vital in this regard, since it went back and forth between practitioner involvement and the project group. This resulted in an iterative process using the (sub-)principles in several steps and steering the development of indicators, without all practitioners involved having to understand the framework in depth.

However, applying the framework have some weaknesses as it does not handle the challenge with sustainability being of a normative and subjective nature, as identified also by others, e.g. . Therefore, using the framework might not make the choices easier to make, but at least easier to identify and discuss within the development process and also clearer for those trying to understand the process from outside. As we value transparency in the development of Citylab, we see this as a major strength with the framework, and think it is essential to use in these kinds of development processes.

Tab. 3 *List of general indicators produced as a result of the development process and how they relate to Citylab's targets (target 3 is in focus for the development of site-specific indicators).*

Name of indicator	**Aim of the indicators: The aim is to promote urban areas…**	**Citylab's sustainability targets (Tab.2)**
Mixture of dwellings	…that support a diversity of inhabitants within the urban area and counteract segregation in the city at large.	2,4,5
Meeting places for all	… where everyone has the possibility to meet with and across group boundaries.	2,4,6
Functions and services	… where everyone has access to basic services.	2,5,6
Safe and trustful community	… which house a trustful community where people feel safe.	4,10a
Good acoustic environment	… with a good acoustic environment outdoor	1
Good air quality	… with good air quality outdoor	1
Healthy indoor environment	… with a healthy indoor environment (preferably certified buildings)	1
Sustainable travel modes	… where a high share of personal travel is by walking, cycling or public transport.	1,7,8,9
Household waste	… with little household waste going to energy recovery or landfill.	7,8,9
Low-energy buildings	… with buildings with low energy use.	7,8,9
Locally produced renewable energy	… where the energy used comes from renewable sources and to some extent is produced locally.	7,9
Climate impact	…with low climate impact (this indicator can be divided into many and/or incorporated into the two above).	7
Contaminated ground	… with no contaminated ground (naturally or purified).	1,9
Ecological and chemical status of water	… which include lakes, streams, coasts and groundwater of good chemical and ecological quality.	1,9
Biodiversity	… where the biodiversity and nature values are kept and developed from an ecosystem perspective.	9,10b
Closeness to green and blue space	… with such closeness to green and blue space that both cultural and regulating ecosystem services are utilised.	1,9.10b
Purification of stormwater	… where stormwater does not contaminate recipient waters.	9
Emissions of nitrogen and phosphorus	… with low emissions of nitrogen and phosphorus.	9
Flooding risk	… which will not be flooded during extreme weather events.	10b
Risks to drinking water supply	… with low risks of disturbance to drinking water supply.	10a

With Citylab as an example we describe in this paper how a certification system can be designed when using the framework, both in terms of the overall structure of the certification system and the indicators to use within that structure. A list of 20 indicators is presented as a final list to continue to work with. Work still to be done includes many details within each indicator, which means more choices that need to be related to the framework. The indicators also need to be tested by future users and iterated regarding whether the certification system as a whole is scientifically credible, practical and capable of driving change. However, based on the process described in this paper, we feel confident that the list presented complies with and balances these main principles quite well and will be a good basis for future work. Similar projects can hopefully apply and refine the framework in their future work in order to contribute to the overall discussion on how to measure sustainability in urban environments.

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Sensitivity Analysis in Building Simulation with Modelica – Dynamic Simulation

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Abstract

Sensitivity analysis helps to identify the key parameters that have a large impact on the building thermal performance. It can also be a tool to understand the characteristics of the model and simplify it in its development stage. The applied sensitivity analysis is dealing with parameters, which changes under consideration over time. The basic idea for this method was originally to investigate the key influential and less-influential parameters and then to use this knowledge for reducing the complexity of a residential building model to use it for an example for quarter simulations. The analyses were shown in two stages in this paper. The building and the heating system analyses. During the first stage the building separately were discussed and the local and global sensitivity analyses were discussed. In the second stage the heating systems, combined heat and power (CHP) units were discussed. The simplification process of building model is not discussed in this paper. This would be the discussed in the next stage during the ongoing research project "KWK plus el. Speicher [1]; English: CHP unit and battery storage". Furthermore, a comparison between measurements and simulation results for building and CHP system including buffer storage were presented.

Keywords: *CHP, Fuel Cells Modelica, Sensitivity Analysis*

1 Introduction

Energy consumption related to the building sector is a significant source of greenhouse gas emission and has become a major part of the total energy consumption worldwide. The rapid growth in population, various building services, and comfort levels ensure that this tendency will continue in the upcoming years. In this study building and heating technology will be discussed separately. In general, the focus on the consumed energy in building sector either when the power supply in building sector provided due to central power stations while heat energy generated due to local boilers or when both heat and power produced simultaneously due to CHP units. The CHP technologies used in the building sector are either internal combustion engine (ICE) or fuel cells technology. To study energy consumption in buildings sector, many simulation software have been developed such as EnergyPlus [2], TRNSYS [2], ESP-r [2], Dymola [2]. This type of simulation software is used for a wide spectrum of applications, such as space heating and cooling, ventilation and lighting and exploring the options for energy supply systems at the design stage. In most cases, the building model demonstrates the coupling between phenomena (e.g. interactions between occupancy, weather, building envelope and HVAC) through pairing of differently specialized sub-models and by using of a large number of diverse input variables.

Sensitivity analysis could play an important role in understanding the influence of controlled and not controlled input parameters on the output, which reflect how sensitive is to the changes of the defined parameters. Then to select the most appropriate to be considered, depending on the objective of the modelling.

Most of the input parameters of these models are associated with uncertainty due to simplifications and assumptions made in the models and lack of knowledge about the exact parameter values. Thus, sensitivity analysis of model parameters represents an important step in the modeling process in order to increase the certainty in the model results Campolongo, F. (2007) [3]. Saltelli, (2012), presents a comprehensive overview of different sensitivity analysis methods used in building energy analysis [4]. The different methods for sensitivity analysis of building simulation can be divided into local and global approaches. Local sensitivity analysis is known as one parameter at a time (OAT) approach. In this method, one input parameter is variable and others as constant while evaluating the output model Heiselberg et al., (2009) [5]. Another efficient method for energy consumption analysis in building simulation is global sensitivity analysis. In this approach, the whole variations of input can be studied but also the correlation between the parameters can be observed. This method is more complex than the local sensitivity analysis but it also reduces the computational costs in high dimensional expensive models. It consists five different methods, such as Regression method, Screening-based, Variance based, Monte-Carlo based and Meta-modelling approach.

In this study, both the local and global sensitivity approach were partially implemented to get the first impression and results of the final aim. Aimed result should have obtained from both of the approaches (local and global) which input parameters influence the most and which of the parameters need more attention during the design of a building model with less parameter. Moreover, the CHP model were developed. The same procedure to do the sensitivity analyses in a separate way were implemented.

2 Literature review and State of art

2.1 Building Library and Heating Systems in Modelica

The Modelica association created different types of free open source library beside the commercial libraries to explore various fields [6]. The libraries that deals with building and its heating technologies contain one-zone and multi-zone models, simulation models for heat / cold generation, storage, as well as distribution and delivery. Some of these building performance related libraries are introduced in Table 1. The foundation of most libraries is the Modelica Standard Library (MSL) including Modelica.Fluid, Modelica. Thermal and Modelica.Media which contains the components that can be used to model the basic physical phenomena such as heat flux through a thermal resistor, pressure drop or thermo-physical properties of fluids. Moreover, HVAC components such as static pipes, circulation pumps, and valves are included in the MSL.

Tab. 1 *Open source building performance analysis library in Modelica.*

Name	Description
A Modelica model library for building performance simulations	A Modelica model library for building performance simulations
ATplus	A free library for Building Simulation and Building Control, fuzzy control library included
Buildings	Modelica Buildings library
BuildingSystems	Modelica building system library
FastBuildings	Modelica library for low-order building modeling

In Dymola, the free open source 'AixLib' library is developed. The 'AixLib' library comprises various models for building envelops and HVAC components. In order to, perform different depths of energy analysis on building and city district scale, the building models include Low and High order models. The High order library in 'AixLib' provides standard models for one family dwellings (stand-alone house), single apartments and multi-family dwelling consisting of several apartments. The objective of this library lies in providing ready to use models for the dynamic simulation of building energy systems. Also because of the degree of flexibility in adapting or extending these models to one's needs. A library consisting of models for standard houses as such does not yet exist. Currently, the standard house models are tailor-made for the German market, it is also possible to adapt them to other markets. Moreover, the Low order library comprises of low order models for thermal building simulation using a bundle of simplifications. Here, the model deals with the number of capacitances to discretize thermal masses and to describe transfer effects and buffer storage. The order of the model is depending on the number of these capacitances. Additional simplifications of the models are made for the consideration of long-wave radiation exchange, outdoor as well as indoor radiation exchange. In 'AixLib', various connectors of the Modelica Standard Library (MSL) are used, e.g. Modelica.Fluid and Modelica.HeatTransfer. The HVAC model comprises components for the heating system, using water as medium and ventilation systems using moist air as a medium [7]. In this research, the library was used because it is an open source library and the connecting components in the building model are quite similar with the model from the library created in GWI. It will help to combine both libraries and that can be shared with the Modelica association to perform in depth study regarding building model.

The considered heating system in this paper is CHP systems. CHP units are installed with a buffer storage to reduce on-off cycles and to increase the self-ratio heat usage generated by the CHP units. Modelling of heating systems is an essential part for building simulations, which are different complexity stages modelled. In the mentioned building libraries in Table 1 includes different types of storages. For the ongoing research project, the needed Buffer storage includes domestic heat water in addition to the space heating part, which is due to coil heat exchanger implemented. The buffer storage in AixLib were used in this work. The adopted models of the buffer storage and CHP unit were developed and validated. The modelling efforts will be described in the next chapters.

2.2 FMI (Functional Mock-up Interface)

Functional Mock-up Interface (FMI) is a standard independent tool which supports both model exchange and co-simulation of dynamic models using a combination of XML-files and compiled C-code. This platform was initiated by Daimler AG with the main purpose of improving the simulation model exchange between suppliers and Original Equipment Manufacturer (OEM). It is supported by over 108 tools and mostly used by automotive and non-automotive organizations throughout Europe, Asia and North America [8].

3 Building and Heating System Model

3.1 Building Model

To perform the local sensitivity analysis, the One Family Dwelling model from Dymola was used. For the global sensitivity analysis, the model from Dymola was exported to Simulink through FMI (Functional Mock-up Interface). In order to give an overview of the model architecture, Figure 1 illustrates the floor plan of the One Family Dwelling (OFD).

The objective of using this model from the open source library is to implement the different combinations of building setups to perform the local and global sensitivity analysis. All the pre-set parameters in the models are based on typical values derived from data by the German Federal Statistics Office and expert consultations [9].

In the mentioned simulation, the default One Family Dwelling with a developed hydraulic distribution system were used. In order to investigate the total energy consumption due to the change in various input parameters, a simple pump was added to the building model. For a typical one family dwelling in a German building standard, a general assumption is that the heat is distributed in a water circuit. To evaluate heat consumption, there exists a radiator model which calculates the convective and radiative heat flows transferred to the room depending on the hot water flow and radiator type. Different types of radiators can be defined by specifying the design parameters, such as, length, height, nominal power at standard flow, return and room temperatures. The radiators for different rooms are showed in the diagram, where each room has different radiators type.

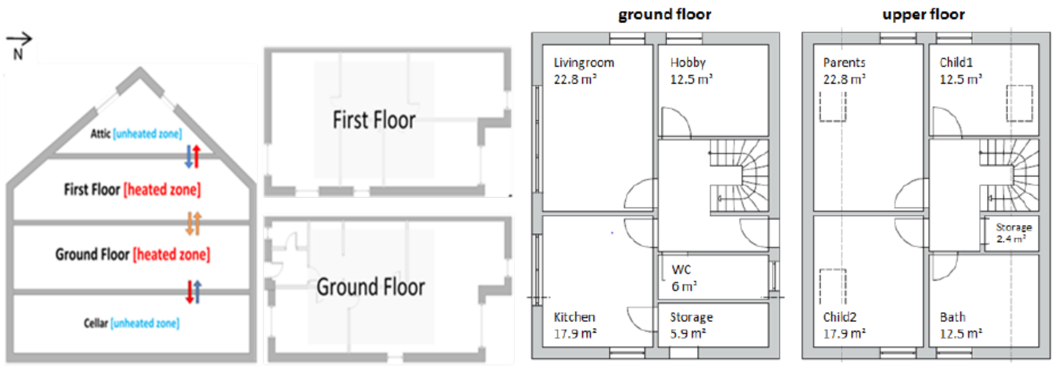

Fig. 1 *A schematic drawing & floor plan of the selected One Family Dwelling in Aixlib.*

3.2 Heating System

The central devices for modelling a CHP system for building energy supply are buffer storage, back-up boiler and CHP Unit. The current version of AixLib library contains five different storage models with different degrees of complexity. After comparing each model with the necessary requirements, the model named "Buffer storage"; was chosen. This model, Figure 2, offers the possibility to simulate any number of layers, two upper and two lower hydraulic connections, two selectable heat spiral coils, one selectable electrical heating rod and a high degree of parameterization. The described partial models were all validated according to own measurements.

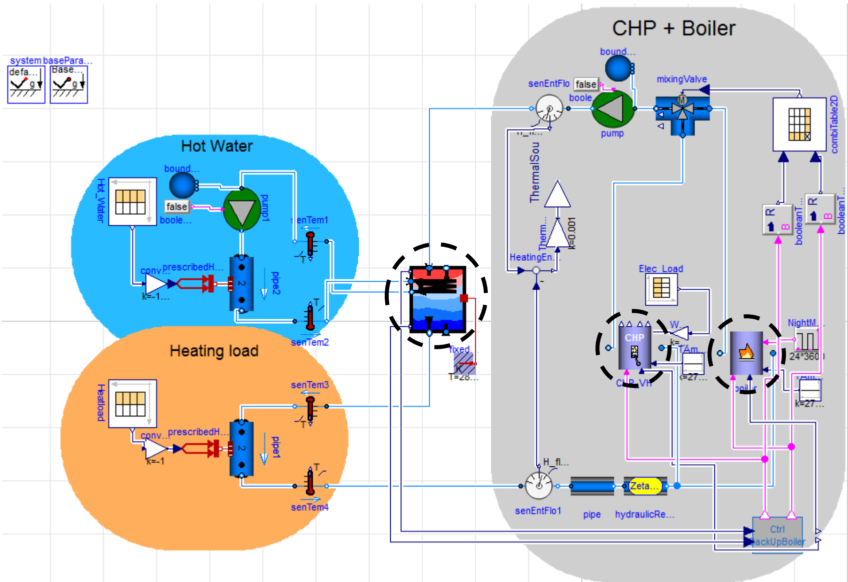

Fig. 2 *CHP system Model Modelica.*

The CHP model is a parameter-based model and could be electric- or heat- driven. For the electric driven, a table load profile must be linked, whereas for the heat-driven version, a set temperature can be selected. However, since the model also has the option of controlling the system externally with an on/off switch, this variant was chosen to switch the CHP system on or off on the basis of the buffer storage temperature. Especially for this purpose a regulation was modelled in this work. This is followed by the validation of the buffer storage. The circled objects in Figure 2 from left to right are the buffer storage, the CHP Unit and the back-up boiler. As can be seen, the buffer storage has many hydraulic connections, which include both flow and return of the heat supply as well as heat consumption (as shown in the blue and orange areas on the left in figure 2). In addition to hydraulic connections, CHP Unit and buffer storage are also connected to connections to the control unit, which can be found in grey at the bottom right.

4 Comparison between simulation and measurement

The comparisons results used to observe the trend of thermal characteristics and to find out whether the simulated data from the One Family Dwelling are realistic as the Reference building from the project. Before implementing the sensitivity analysis method, a comparison between a One Family Dwelling from 'AixLib' and a Reference building from a project was completed. The heating system but also buffer storage model were also checked according to the measured data. The main objective of this comparison was to investigate the thermal characteristics of the building model and validating the storage model. The heating was checked comparing to measurement as further step. The methodology of the comparison is represented in this section and the results are discussed in the later part. Moreover, a good description of the characteristics of a Reference building is very important. The Reference building was built in 1904 and was completely refurbished in 1988. The geometrical and thermo-physical properties of the Reference building are summarized in Table 2.

Tab. 2 *Open source building performance analysis library in Modelica.*

Area/Direction	North	East	West	South
Wall m^2	29.8	67.4	29.8	67.4
Window m^2	8	X	X	1.4
Door m^2	X	X	2.4	X

For the One Family Dwelling, the geometrical characteristics of each room were taken from the Reference building. However, the U-value for windows, doors and also the wall layers were also taken from Reference building. For the One Family Dwelling the weather data was different and it was taken from TRY_2010. The other values for the parameters for both buildings are represented in Table 3 [10].

Tab. 3 *Pre-defined values of parameter for both building*

Parameters	Unit	Values
Infiltration	ACH (h^{-1})	3
Transmittance of window	W m^{-2} k^{-1}	1.5
Transmittance of door	W m^{-2} k^{-1}	4.5
Set temperature	k	Upper-floor: 292.3k Ground-floor: 293.5k

Figure 3 represents the comparison and total heat demand between the One Family Dwelling and Reference building. From the bar chart, it can be seen that the total heat demand during winter season is higher than the summer season. For example, during the summer (July) the total heat demand by the Reference building was 100 kWh and during the winter (January) it was 650 kWh. It is because during the summer season the occupant's do not need heating system in their daily life, except the domestic heat water. Whereas, during winter to deliver hot water and to keep a comfortable indoor environment for the occupant's the radiator needs to provide more energy. The bar chart of the One Family Dwelling also represents the same thermal characteristics. However, from the comparison it can be seen that there is a difference between the total heat demand for both of the building. Although the dimensions and parameter values for both buildings were the same, but the weather data for the One Family Dwelling was different from the Reference building. Another reason behind this difference is that the occupant's behavior in the One Family Dwelling was not studied accurately like the Reference building due to some limitations in the model. Furthermore, according to the theoretical knowledge, the change in total heat demand throughout the year is showing the same trend for both the One Family Dwelling and Reference building.

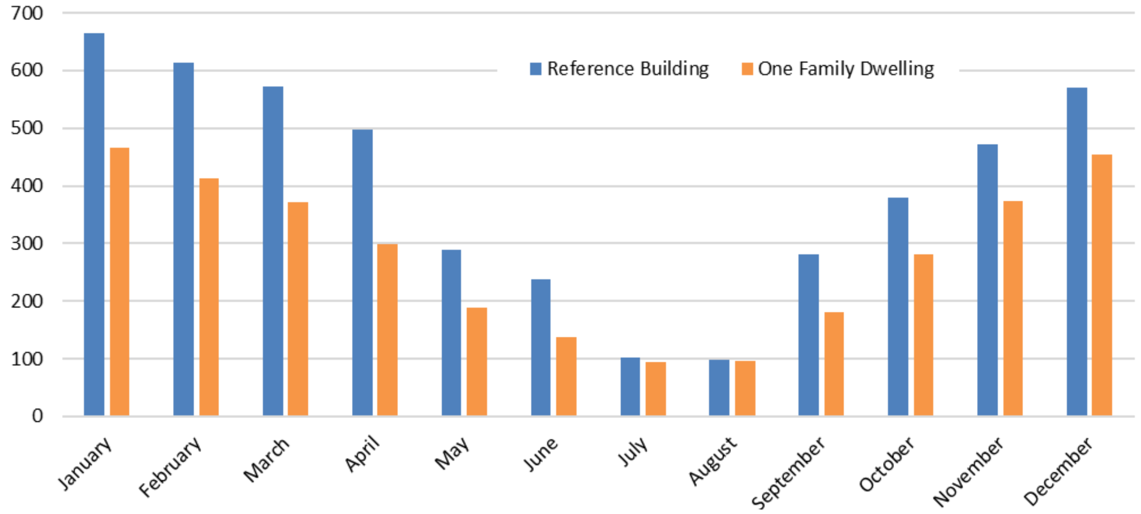

Fig. 3 *Comparison between Reference building and One Family Dwelling.*

Additionally, according to the measurement efforts done at GWI, it is possible to use the measurements results for the validation of the buffer storage model. The 295 l multifunction buffer storage from Vaillant "allSTOR VPS 300/2" [11] was equipped with ten steel threaded sleeves to monitor the temperatures in 10 layers. These sleeves located from outside to the middle of the tank. The threaded sleeves were equipped with Platinum resistance temperature detector (PT-100) [12]. The measuring point was located at 10 positions, as described in Figure 4.

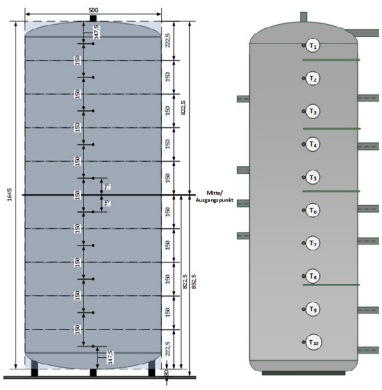

Fig. 4 *Measuring points and layers.*

The first series of measurements shows complete charging process, Figure 5, (to approx. 70°C) from a cold state (approx. 17°C) with a micro-CHP system. Here, the incoming energy quantity is known from the mass flow and the flow temperature. A second series of measurements shows the behaviour of the buffer storage during self-discharge (starting temperature approx. 73°C) after complete separation with hydraulic systems. The important ambient temperature has also been measured. These two measurements are to be simulated in Dymola using the "Buffer Storage" model.

The allSTOR VPS 300/2 was parameterized according to the manufacture technical data. For the ambient temperature, the mean temperature of the measured ambient temperature was set. The results of the measurement and simulations are illustrated in Figure 5. Although ten sensors were installed and measured, only 5 of them were represented in Figure 5. This is to make it more clearly to the reader. The lowest and upper measured values were included in Figure 5. The differences in the behaviour between measured and simulated profiles can be explained as a typical behaviour in simulations a one-volume models in Modelica as described in the master thesis in [13] has described. Additionally, the mean temperature of the buffer storage was calculated with a resolution of 5-seconds and the RMSE (Root Mean Square Error) equation 1 was formed. The RMSE was then compared with the mean temperature level of the measurement series.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(f(x_i) - g(x_i)\right)^2} \tag{1}$$

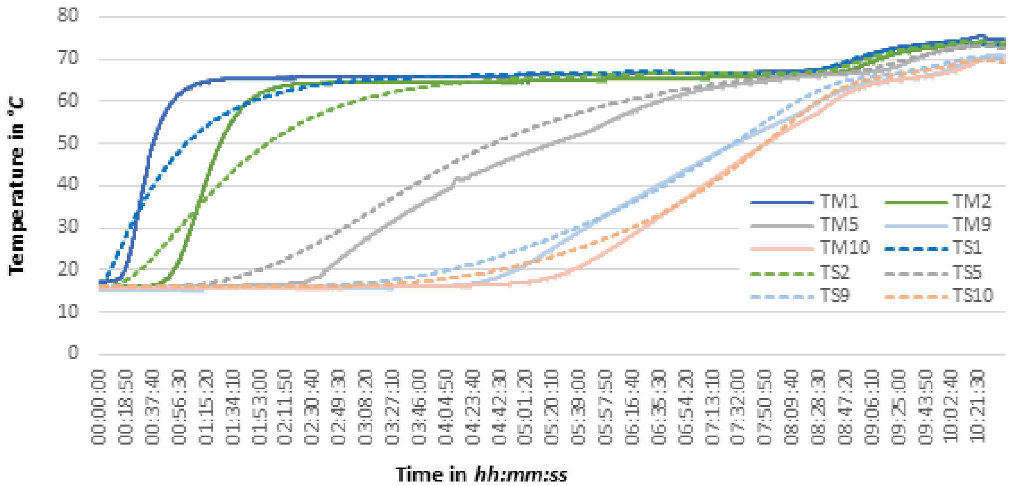

Fig. 5 *Comparison between measurements and simulations profiles for validation storage model*

Tab. 4 *Validation storage charging process results*

Hours	5	10
RMSE	0.7784 °C	0.8834 °C
Mean temperature	30.6766 °C	46.5261 °C
Deviation	2.54 %	1.90 %

In Table 4 it can be seen that the simulation at the beginning (5 hours) still has a higher deviation due to the inertia but this decreases in the further course and largely compensates itself. During simulation and measurement both charging processes are completed after approx. ten hours and over this time the mean temperature deviation is only 0.89°C or 1.9%. The simulation describes the measurement with sufficiently good accuracy.

Tab. 5 *Validation of storage unloading process results*

Hours	12	24	48	68
RMSE	0.706 °C	1.681 °C	2.998 °C	3.5998 °C
Mean Temperature	69.452	66.015	60.277	56.5671
Deviation	1.02 %	2.55 %	4.97 %	6.36 %

Table 5, show the results of the free-discharge process. This does not show a large deviation by comparing the simulation and the measurement. However, the difference becomes larger as the measurement progresses as the temperature drops faster than the simulation, Figure 5. An explanation for this could be the thermal bridges due to the 10 installed temperature sensors. Furthermore, these sensors made holes in the origin insulation and thus a source of heat loss.

Furthermore, the validation of CHP model is discussed in this work. In order to investigate whether the model shows a meaningful and realistic reaction to given heat load curves, the plausibility of the model is checked. For this purpose, data from the project "100 KWK-Anlagen" are used, in which CHP systems were examined in detail in real operation for the supply of residential units. Thanks to complex measurement technology, a large amount of data is available over a long period of time. The model should be adapted as exactly as possible to an object in order to compare the simulation results with the measured data. This object was chosen because it has a Stirling engine from Brötje. For this CHP system including the associated buffer storage and boiler, there are many detailed manufacturer specifications regarding hydraulic circuitry, plant control and temperature-related power drop, which makes modeling the plant considerably easier. For a complete consideration eleven summer days, eleven transition days and eleven winter days were considered in each case in which the plant ran. The object under consideration can be characterized as in Table 6:

Tab. 6 *Data reference object and heating system*

Building data		System data	
IWU Typology	RH_H	CHP-Technology	Stirling engine
Inhabitants	3	Manufacturer	Brötje
Av. electrical demand	5.115 kWh/year	Model	EcoGen WGS 20.1
Av. heat demand	16.216 kWh/year	Power CHP	1 kWel/5.4 kWth
Heat transmission	Radiator, floor heating	Heating-Storage volume	774 l

These results can be compared with detailed measurement data (5min resolution) of the object.

An important criterion of a CHP system is the correct supply of the heat demand. This depends on the inertia of the system (the heat accumulator reacts as a buffer). Since in the investigated case the heat accumulator should have the same behaviour with correct parameterisation, a similar heat production is expected. The simulation results and the comparison to the measurement are shown in Table 7:

Tab. 7 *Validation heat demand*

Time period	Measurement in kWh_{th}	Simulation in kWh_{th}	Deviation in %
Summer	121	120,89	-0,1
Transition	326	317,69	-2,6
Winter	906	897,36	-1,0
Cumulative	1353	1335,94	-1,3

Overall, the deviation between measurement and simulation is very small. Due to missing data, the drinking water profile from summer was adopted for winter and transition, so the deviation in transition is greatest, as the warm drinking water has a greater influence there. In the winter the heating load has a clearly higher value. As can be seen from Figure 6, the heat production between simulation and measurement is largely identical in all three periods considered.

The largest optically deviation here takes place in the transition period, as was already the case with the consideration of the absolute heat quantity. Particularly in winter, it is easy to see how evenly the jumps in heat production between simulation and measurement occur. It can be said that the model corresponds very well to reality in terms of heat production. Despite the estimated domestic hot water consumption, the cumulative production quantity is largely the same for simulation and measurement. Times and performance also correspond. There are minor deviations, but these are negligible relative to the existing uncertainties.

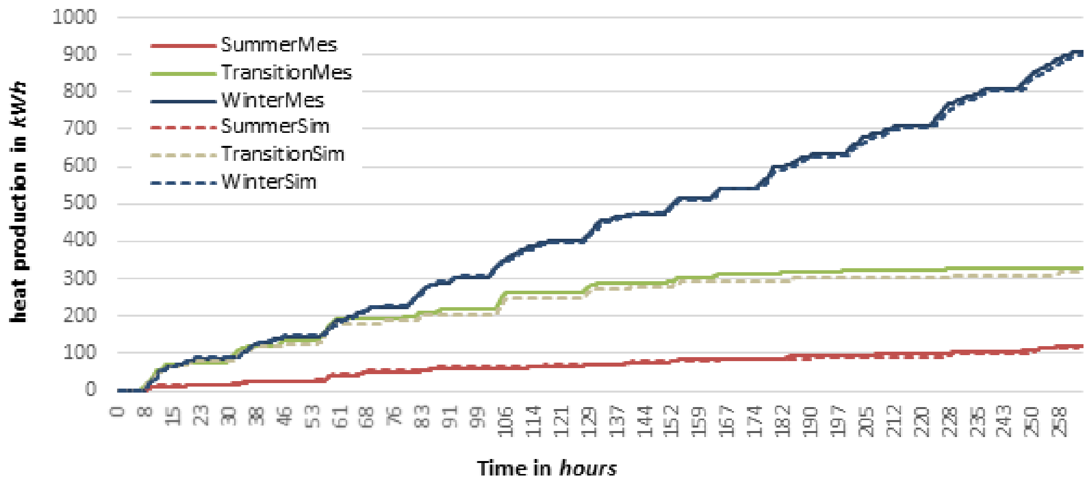

Fig. 6 *Cumulative heat production CHP-System*

4.1 Costs for Electricity Production and Demand Primary Energy

Electricity generation costs consist capital expense and operating expense including maintenance costs, fuel costs, and revenues from heat & electricity generation and fed-inn process. The annual costs can be calculated as in described in eq. 1:

$$X = (capital\ expense + maintenance\ costs + fuel\ costs - electrical\ revenues - heat\ revenues) \cdot \frac{1}{E_{el}} \quad (2)$$

The capital expense consist buying the entire system as well as installation costs. The considered described period is over 10 years.

$capital\ bound\ costs\ C$:

$$C = (unit\ costs + installation\ costs - subsidies) \cdot a \quad (3)$$

$$with\ annuity: a = \frac{q^n(q-1)}{q^n-1}\ ;\ q = 1 + \frac{interest\ rate}{100}\ ;\ n = 10\ years \quad (4)$$

Data and information about unit costs and installation costs used for the analyses were provided due to the unit's manufacturer. The maintenance costs of the Stirling engine were obtained from field trial [14]. For the considered unit the capital costs of all plant parts, the installation and the costs for 10 years maintenance amount to approx. 24,0000 €, is assumed to become a maximum subsidies of 4968.50€ from the "KWK-Gesetz; in English: CHP Act" the total annuity is 2,346.28 €.

Fuel costs were calculated based on the average gas prices in 2018, which lays by 6.14 Cents/kWh natural gas [15]. The heat revenue describes the avoided costs for the heat generated by the CHP unit. This means that required costs for primary energy if the heat produced due to another device, in this case is a condensing boiler with an efficiency of 98%. Electricity revenues consist both self-used and feed-into grid parts. The considered CHP system need 11.809 cents/kWh for the part fed into the grid. According to CHP Act 2018 each self-used 1 kWh_{el} is subsided by 4 cents. The feed-in kWh_{el} is by 8 cents.

The considered primary energy consumption the total energy consumption in the building. Therefore, the electrical energy consumption from the grid and the fuel consumption (natural gas) are calculated with diverse primary energy factors. The primary energy factor is the ratio between the primary energy required and the final energy delivered. The primary energy obtained are natural gas and electricity. It is 2.8 for the German electricity mix and 1.1 for natural gas [16]. The fed-in electricity was detracted as described in equation 5. The $primary\ energy\ consumption$ (PEC) in the analyses applied in this work is calculated as in eq. 5:

$$PEC = E_{el,fromGrid} \cdot 2.8 + (E_{gas,CHP} + E_{Br,Boiler}) \cdot 1.1 - E_{el,FeedingGrid} \cdot \left(\frac{1.1}{\eta_{total,CHP}}\right) \quad (5)$$

The PEC as well as the capital bound costs are used in the local sensitivity analysis where the heat demand is changed.

5 Local Sensitivity Analysis

Local sensitivity analysis is a simple and effective approach to investigate the thermal characteristics of building simulation. It is a one at a time (OAT) technique and the effect in the energy consumption of a building is investigated by one single parameter and doing this for other in step. There are several parameters associated with the building simulation. However, in this paper, five uncertain parameters were studied for both analyses. To perform the local sensitivity analysis in Dymola, one parameter was kept as variable and the other uncertain parameters were kept as constant in their reference value. The reference values, Table 8, for the parameters were obtained from various literature review and German standard described in One Family Dwelling model. However, the range of the parameters is defined as ±15% of the reference value.

Tab. 8 *List of parameters and assigned uncertainty ranges for local sensitivity analysis*

Parameters	**Unit**	**Ranges [Reference Value]**
Infiltration	ACH	2.12 – 2.87 [2.50]
Ventilation	h^{-1}	0.42-0.57 [0.5]
Internal Temperature	k	290.15-296.15 [293.15]
U-value	$W\ m^{-2}\ k^{-1}$	0.85-1.15 [1]
Wind Speed	m/s	2.12-2.87 [2.50]

Some of the parameter values are out of range based on the standard theoretical value but still it was chosen to observe the effects of each parameter in the total heat demand. In order to implement the local sensitivity analysis, the parameter values can be changed manually in each simulation. However, in this way, the simulation time will be very high. To reduce the simulation time, some 'functions' and 'scripts' were created for these five uncertain parameters. A Modelica script file is a convenient call to simplify the use of them. The script facility makes it possible to load model libraries, set parameters, set start values, simulate and plot variables by executing script files. However, everything that can be done in a script file, can also, be performed by using a function instead. In Modelica, a function is mainly a 'black box', acting on values given to it and returning outputs. There are many advantages of using functions for scripting over writing script files directly. Some of the advantages are discussed below:

1. A function is saved as a Modelica file and can be part of a library structure whereas a script file is always stored in a separate file.
2. The functions can be made generic by defining the necessary inputs the user has to set before calling the function. However, in script file all parameter values must be hard coded. The change of the parameter values can only be done by changing the source code of the script file, which increases the simulation time.

5.1 Results – Local Sensitivity Analysis

The local sensitivity analysis for the One Family Dwelling have been summarized in Table 7 and it is represented in Figure 7. On the horizontal axis, the change in yearly energy demand and on the vertical axis, the percentage of change from the parameters reference value.

The ratio of change from the reference value represents the greater influence in the total heat demand. From Figure 7 it can be seen that when the parameter values are increased and decreased from its reference value they are influencing the total heat demand of the building. When the internal set temperature is increased by 5% and 15%, the total heat demand due to the change in this parameter was 30000 kWh and 36160 kWh. The increase in U-value is also affecting the total heat consumption. It is because when the U-value of the building increases the heat exchange between the outdoor and indoor environment as a result, the radiator needs to provide energy to keep a comfortable environment for the occupants. On the contrary when we decrease the value of the parameter the effect in total heat demand decreases as shown in Figure 7.

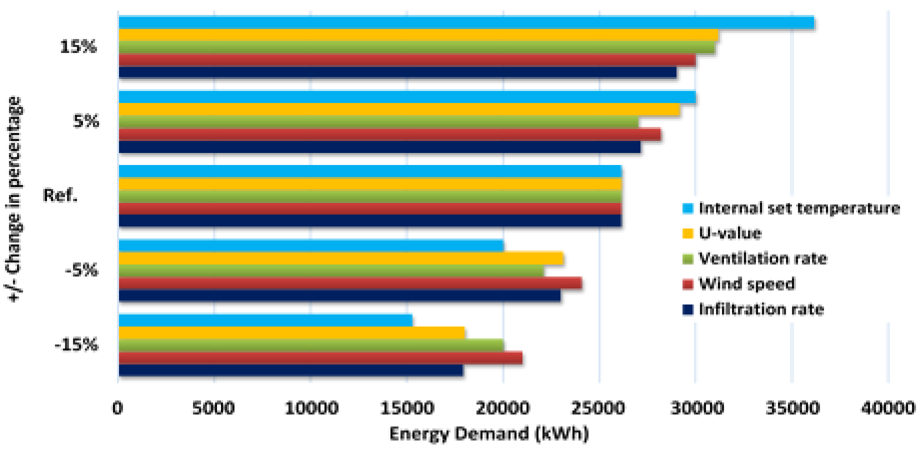

Fig. 7 *Local sensitivity analysis to investigate the influential parameter*

When the parameter values were decreased the most influencing parameter was internal set temperature. It can be identified by observing the ratio of change from the reference value and decreased value of internal set temperature. The other parameter, for example, due to the decrease in ventilation rate the total energy consumption was 22084 kWh. Whereas, when its reference value was used the total energy consumption was 26128 kWh. So, the change in effect for the total energy consumption is not that much high. To summarize this plot, it can be said that the effect in total

Energy consumption was high due to the change in internal set temperature, whereas the less influential parameter is the infiltration rate.

Local sensitivity analysis does not require sampling methods to generate a large number of inputs which makes it easier to implement compared to global sensitivity analysis. As a result, it is easier to find out the influential and non-influential parameter in a building system. In this study, the most non-influential parameter is wind speed which can be simplified while developing the model. On the other hand, the influential parameter ventilation rate can be optimized to develop a calibrated single zone One Family Dwelling in quarter simulation. Table 9 shows the result of the local sensitivity analyses.

Tab. 9 *Local sensitivity analysis of five uncertain parameters*

Parameter	Yearly Energy demand (kWh) -15%	Yearly Energy demand (kWh) -5%	Yearly Energy demand (kWh) Reference	Yearly Energy demand (kWh) 5%	Yearly Energy demand (kWh) 15%
Internal set temperature	15280	20000	26128	30000	36160
Ventilation rate	20000	22084	26128	27000	31000
Wind speed	21000	24075	26128	28184	30000
U-value	18000	23112	26128	29143	31172
Infiltration rate	17915	22989	26128	27130	29000

Based on the sensitivity analysis for building parameters, a local sensitivity analysis with the CHP system is to be carried out, which deals with the effects of the influencing parameters on the building. The effect of the parameters is to change the heat demand in the building. Therefore, the CHP system is now to be operated with modified heating requirements in order to investigate its ecological and economic impact. Analogous to the previous local sensitivity analysis, the output parameter (in this case the heating load) should be changed by +5%, +15%, -5% and -15%. The full load hours at the same time the electrical energy produced by CHP, the primary energy requirement of the building and the electricity production costs are determined as key factors for the evaluation as seen in Figure 8. The full load hours are not visible because it has the same values as electrical energy production. All results react to a percentage change in thermal load with a smaller change. An increase in the heat load by 15% only leads to an increase of 4.58% in full load hours, thermal and electrical production and 7.58% in primary energy demand. An increase in the heat load naturally also influences the boiler, which is why the increase in the heat load is only partially covered by the CHP system. The changes in full load hours, electrical generation and thermal generation are the same, as the ratio of these three variables remains the same in the simulation.

The primary energy reacts more strongly to an increase in heat demand than to a decrease, as can be seen. A possible explanation for this is that the CHP unit reaches its limits at some point and most of the heat has to be covered by the boiler. However, the boiler has a smaller primary energy utilization, since no electricity is produced.

As expected, the electricity production costs react with a reduction when the heat demand increases, as the CHP unit runs longer and becomes more economical with longer running times. However, the costs decrease at the beginning (between -15% and -5%) faster and then decrease slower proportionally. This could be due to the fact that electricity demand does not increase and that more electricity has to be fed into the grid when production increases. If the share of own use no longer increases from a certain point, but is only fed into the grid, a proportional behaviour occurs in which the increased fuel costs and the feed-in tariff are offset.

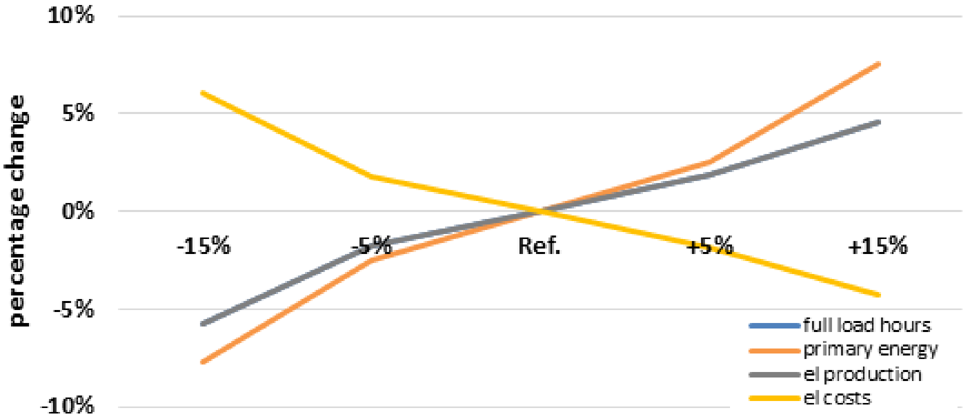

Fig. 8 *Results of change in heat demand*

5.2 Global Sensitivity Analysis

In the presented research, a global sensitivity analysis was also used to investigate the influential parameter. The main objective of using both the sensitivity analysis is to find out the efficient method for the analysis of energy consumption in building simulation. In a global sensitivity analysis, the input parameters are varied together to observe the overall effect of the output. The key difference between the local and global sensitivity analysis is that in this method, a large number of sample data are generated for the model evaluation. In Dymola, there is no function or script available to generate samples of data from the parameter value. As a result, it is not possible to perform the global sensitivity analysis directly in Dymola. The Dymola software developer 'Dassault Systemes' created an interface in order to resolve this problem. The interface is known as FMI (Functional Mock-Up Interface) [17]. Functional Mock-Up Interface (FMI), provides the opportunity to any modelling tool to generate C code or binaries; demonstrating a dynamic system model which may then be seamlessly combined in another modelling and simulation environment. The FMI specification describes two exchange formats; 'FMI for model exchange' and 'FMI for Co-simulation' [17]. The 'FMI for model exchange' defines the interface for simulation code modules that must be shared with a common, central, solver. This provides a uniform numeric solution and reliable centralized simulation error control. The 'FMI for Co-simulation' describes the interface for code modules with embedded numeric solvers, as used by the generating tool. This method gives the opportunity to embed dedicated solvers for the modelled application and enables compatibility with simulation in the authoring tool [17]. Furthermore, the 'Dassault Systemes' develops an 'FMI kit for Simulink' which enables to import/export model between Dymola and Simulink in order to perform the global sensitivity analysis.

In this study, 'FMI kit for Simulink' is used to perform the global sensitivity analysis. The One Family Dwelling (OFD) model was compiled and exported from Dymola to Simulink by using FMI in the first step represents a functional mock-up interface to export a model from Dymola to Simulink. After exporting the model, an FMI block from Simulink library was used to represent the complete model of One Family Dwelling including all the associated parameters. In the next step, the five uncertain parameters were defined and the 'heat demand' variable from the model was used as the output from which the influential parameters were investigated. To define the five parameters, the reference values were used from the literature review.

6 Results – Global Sensitivity Analysis

The global sensitivity analysis was performed in Dymola-Simulink interface to investigate the influential parameters from the One Family Dwelling. The ranges for the uncertain parameters were kept as similar as it was in the local sensitivity analysis. A large number of random sample was generated from the ranges in order to explore the parameter space and perform the evaluation accurately. However, to visually analysing the effect of parameters on the 'heat demand', a statistical analysis was performed in the final step. In Figure 9 a tornado plot is generated which represents the influence of the parameter based on their ranking. The tornado plot shows results from high to low in the order of which parameter most influences the requirement. The statistical values range from -1 to 1, where the magnitude indicates how much the parameter influences the output, and the sign indicates whether an increase in the parameter value corresponds to an increase or decrease in the model output. From the tornado plot, it can be seen that there are three different methods of data representation. The 'Correlation' method defines how the model parameters are correlated with the heat demand. However, the 'Partial correlation' describes how the five chosen uncertain parameters are related to the model output. In this method, the other parameters in the building model are neglected.

The 'Standardized regression' explains how the parameters are linearly influencing the total heat demand. From Figure 9 it can be seen that the most influential parameter is the internal set temperature and the less influential parameter is infiltration rate of the building. The correlation effect of the internal set temperature and ventilation rate are inversely proportional to the total heat demand. It means if the value of the parameter increases then the correlation effect decreases. Infiltration rate of the building has no correlation effect with the output whereas wind speed and U-value are directly proportional to the heat demand. The magnitude of internal set temperature for both standardized regression and partial correlation effect is higher than any other parameter. If the ventilation rate and infiltration rate increase, then the partial correlation effect of the total heat demand decreases. However, the U-value has no partial correlation effect whereas if the wind speed increases in the building than the partial correlation effect increases. The linear relationship between the parameters and the model output is represented by the standard regression effect. The standardized regression effect of internal set temperature, ventilation rate, and infiltration rate are inversely proportional to the total heat demand. It means that the linear influence of these parameters to the total heat demand decreases when their value increases. Both the local and global sensitivity analysis is used to investigate the parameters influence on the model output. In this study, both methods were used to observe their advantage and disadvantage. The parameters ranking is similar for both local and global sensitivity analysis. In spite of that, the global sensitivity analysis is computationally more efficient and reliable than the local sensitivity analysis.

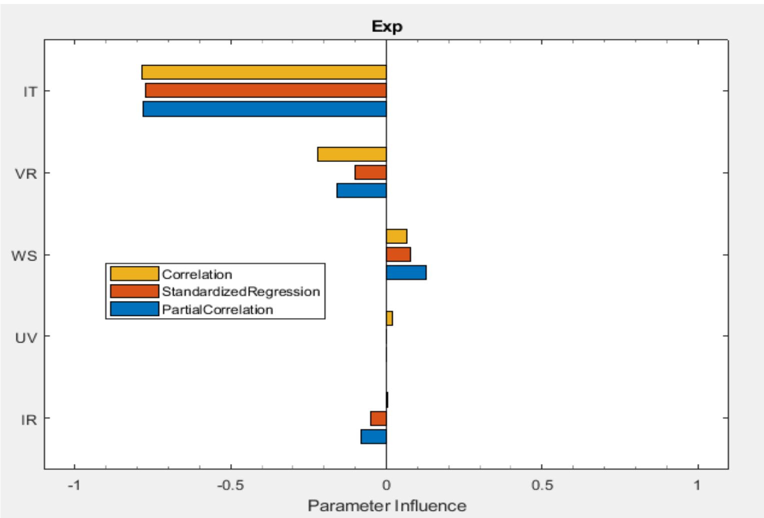

Fig. 9 *Ranking of influential and less-influential parameter*

7 Conclusions and Outlooks

In this paper, both the local and global sensitivity analysis have been studied. The main aim is to define the influential and less-influential parameters which can be used for the simplification of the residential building. In a residential building, there are various parameters available that are associated with it. The impact of these parameters can be studied by using the local sensitivity analysis and different types of global sensitivity analysis. Dymola was used as the building simulation software. All the simulations were performed in a multi-zone One Family Dwelling. Among all the parameters associated, the five uncertain parameters were chosen to see their influence on the total energy consumption because they are properly described in the model and mostly important for the retrofitting of the building.

From local sensitivity analysis, the result shows that the internal set temperature was the most influential parameter in the building. The comparison between the reference and 15% increase/decrease in internal set temperature indicates that when the set temperature is high the radiator needs to provide more energy especially during winter. As a result, the total energy demand increases. However, during summer the heat demand decreases due to the less energy production from the hydraulic system. The other four parameters also represent the same linear characteristics, for an example, when the air exchange between the outside and inside environment of the building is high, the radiator needs to provide more energy in order to keep a suitable thermal condition, during winter. Although, during summer, the radiator provides less energy due to the increase in air exchange. It is because of the air exchange the internal condition of each room remains appropriate for the occupants. To perform the global sensitivity analysis, both Dymola and Simulink have been used. In addition to that, the co-simulation with a functional mock-up interface (FMI) was used. It is a very essential interface through which the building models from Dymola can be exported to other supporting software such as, Python, MS-excel etc. In a global sensitivity analysis, a random number of samples were generated and also evaluated based on the output of the imported Dymola model. The evaluated tornado plots also illustrate the same ranking of the parameters like the local sensitivity analysis. However, from the tornado plot, it can also be observed that whenever a parameter value increases whether it will increase or decrease the total heat demand. Compared to local sensitivity analysis, the global sensitivity analysis provides more information like the correlation between the parameters. It also reduces the computational cost in high dimensional expensive models and provides faster simulation run than local sensitivity analysis. The comparison of the One Family Dwelling represents the similar heat demand characteristics as the reference building. It also ensures the reliability of the result that we achieved from the One Family Dwelling. To sum up, both the local and global sensitivity analysis helps to identify the influential parameter which can be used to modify a residential building and decrease the complexity of energy analysis in the quarter simulation.

The results related to the CHP system are the first link in a more detailed sensitivity analysis using different technologies. Yet, it should first show that the model is suitable for investigating various parameters at CHP system. In addition to the heat load the user behaviour (i. e. electricity demand and hot water) should also be considered with different technologies in the future. Future research works are needed to investigate more parameters associated with the buildings and CHP systems. In this way, it will be efficient to create a database of influential and non-influential parameters for the building and heating technology, which can be optimized while developing new systems. Moreover, it will reduce simulation run and cost for the simulations.

Acknowledgement

Grateful acknowledgement is made for financial support by the Ministry of Economy, Innovation, Digitization and Energy – "progres.NRW programme" – of the state North Rhine-Westphalia of the state of North Rhine-Westphalia in Germany.

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Development of a Green Maintainability Design Decision Support System

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Abstract

The concept of green maintainability (GM) provides the building sector with an exciting opportunity to transform itself with highly maintainable and sustainable buildings. It spans throughout the building project delivery process and overarches different building systems. This paper illustrates the development process of a decision support system (DSS) to objectively measure and aggregate GM factors in a complex building project.

The objective of the current manuscript is to develop the framework for a capable DSS to assess green maintainability of facility designs with relative ease, and the proposed research design is of a case study nature. Resource-centric constraints such as time, cost and environmental performance are considered with the GM factors to critically assess the ease of maintenance, maintenance productivity, safety and sustainability of design decisions. This study makes an attempt to promote green maintainability among building professionals to advance the lifecycle sustainability of built environments.

Keywords: *Green maintainability, Decision support system, Building maintainability, Sustainability*

1 Introduction

For asset-intensive industries such as the building industry, maintenance shares a significant portion of its operational cost and it is gaining increased awareness that improved maintenance performance can be used to add value to the business process [1]. The knowledge of service lives of built assets enables the building industry to minimize maintenance and environmental costs while improving safety [2]. Therefore, building maintainability is vital to transform the real estate industry towards being more productive, reliable, and sustainable, ultimately reducing the building life cycle cost [3], [4]. To this extent, building maintainability is established as an effective tool in the maintenance of building elements with ease and at a lesser life cycle cost for higher productivity, which has received considerable attention in recent years [5]. While maintainability of buildings aspires to identify common maintainability problems and make recommendations of good industry practices to the design professionals at the project outset; the maintenance costs and maintainability considerations, on the other hand, are not anticipated from the standpoint of the design. Resulting in buildings that are difficult to maintain i.e. more labour intensive and costly in their operational stages.

It is further held that building designs can achieve optimal performance throughout its operational stages when principles of sustainable construction and facilities management (FM) are infused into them at early design stages. This and the recent developments in green FM has paved way paving way for the concept of green maintainability [6], [7]. Green maintainability is defined herein as using maintainability and sustainability considerations to achieve green FM [8]. This involves taking measures at the project outset to minimize project risk and cost factors while improving building performance and environmental indices, i.e. reducing negative environmental impact, and resource consumption. These five green maintainability objectives are entwined with the outcomes of sustainability, viz. health, safety and well-being, productivity, resource stewardship, and high performance. Therefore, this concept can bring building projects the benefits of sustainability in terms of the social, environmental, and economic aspects [9]. However, it is found that while building professionals are aware of the benefits of adopting maintainability principles in their designs, the knowledge transfer from FM to the design professionals is both impeded and insufficient to drive the changing paradigm [10]. Whilst the concept of green maintainability can address issues in sustainable and maintainable building operations, the awareness among building professionals to incorporate those principles in their decision-making processes are not evident. The lack of use of this concept can be thereof attributed to a decision-making problem. Decision support systems (DSS) can be used to overcome such problems. Such a system is equally important for designers, builders, and FM alike; as sustainability and maintainability considerations should be applied throughout the lifecycle of a building.

This paper discusses the preliminary findings of an on-going research. It begins by briefly describing the concept of green maintainability and how it factors in to create more sustainable and maintainable buildings. Building on this concept, the rationale to conduct green maintainability assessments is then discussed; followed by stating the requirement of decision support systems to achieve this paradigm. The steps taken to develop a decision support system to this effect is then discussed, including the modelling framework as well as the process flow with identifying the key inputs and outputs; leveraging on the extensive insights gained by analyzing standard benchmarks pertaining to design, construction and maintenance of buildings.

2 Method

The lack of consideration given to the concept of green maintainability during initial stages of a building project may be attributed to a lost opportunity in avoiding both physical and functional performance lapses in building systems. This raises the need to identify sources of defects with significant attention to design detailing, materials, construction quality, and environmental factors. To improve green maintainability of buildings over its lifetime, the underlying risk factors of buildings' usage and performance must be identified and factored.

The current manuscript sets about to identify the research gap in green maintainability, such that a framework can be developed to facilitate effective design support in building projects to allow green maintainability considerations to be incorporated into facility design. Consequently, the research objective is to develop a capable tool to assess green maintainability for easy adoption and effective assessment of facility designs for downstream maintenance issues. This is carried out by building upon existing building and maintainability modelling research through recent literature. The methods proposed for this research are based on previously published work.

As previous work on maintainability decision support systems (DSS) are comparatively new concepts in practice, and application of DSS are rare; quantitative methods are in an unfavourable position to gather rich data from a unique and small sample. Therefore, data collection and analysis of the current study takes a qualitative method under an inductive approach. This will develop the hypothesis to be tested in the following stages. Qualitative methods are well recognized for its capability to study complex situations [11]. In particular, qualitative methods in Information Systems (IS) research emphasizes the applicability of interviews as a data collection mechanism which can be used in such problems [12]. The richness of qualitative data gives the opportunity to confirm the research question as well as inform possible solutions.

The research is structured with an extensive desk study on literature to identify the green maintainability indicators and to learn the industry best practices related to green maintainability. During this stage, 416 national and international standards pertaining to design, construction and maintenance good practices were considered to compile the green maintainability scoring system checklist. A case study approach is taken to determine the interrelations between maintainability indicators and their relative importance. As case studies are considered to be effective in building science research; especially in issues concerning operations, maintenance and maintainability [9], [13], [14].

3 Results and discussion

This paper expresses the current work on green maintainability to develop tools to improve green maintainability. Lapses in green maintainability in current practice can lead to a myriad of performance issues resulting in higher maintenance budgets, lowered productivity and even increased safety risks of end-users; as green buildings are falling short from expectations during operations and maintenance stages due to the lack of implementation of green FM and building maintainability. This can be linked with the vast information gap between building users and design teams. Exasperated by the lack of satisfactory knowledge in maintainability scoring, and lack of tools to operationalize green maintainability. Based on these gaps, it is apparent that there is a clear gap between existing building operation and maintainability strategy implementation. Therefore, it is imperative to link the environmentally sustainable design with the design for maintainability principles, in order to, achieve objectives of building operations to tackle the rising energy costs and scarcity of resources. The need for incorporating sustainability with principles of maintainability can be highlighted with the challenges posed by fast dwindling finite resources aggravated by the increasing global population, and the need to achieve efficient building operation with reduced resource usage, that can, in turn, improve profits, especially in times of economic downturn. In this sense, buildings need to be designed for sustainable operation, which effectively balances the economic value and the generation of the maximum value for all parties involved, the well-being of people and their activities, and its environmental impacts. Factors relating to green maintainability that was identified from literature were scrutinized through a series of expert opinion surveys, to derive the GM factors; classified into four green maintainability goals (see Figure 1). Out of the experts (6), equal representation from FM industry (3) and building science academia (3) was achieved, to bring in the practical aspects alongside the theoretical arguments.

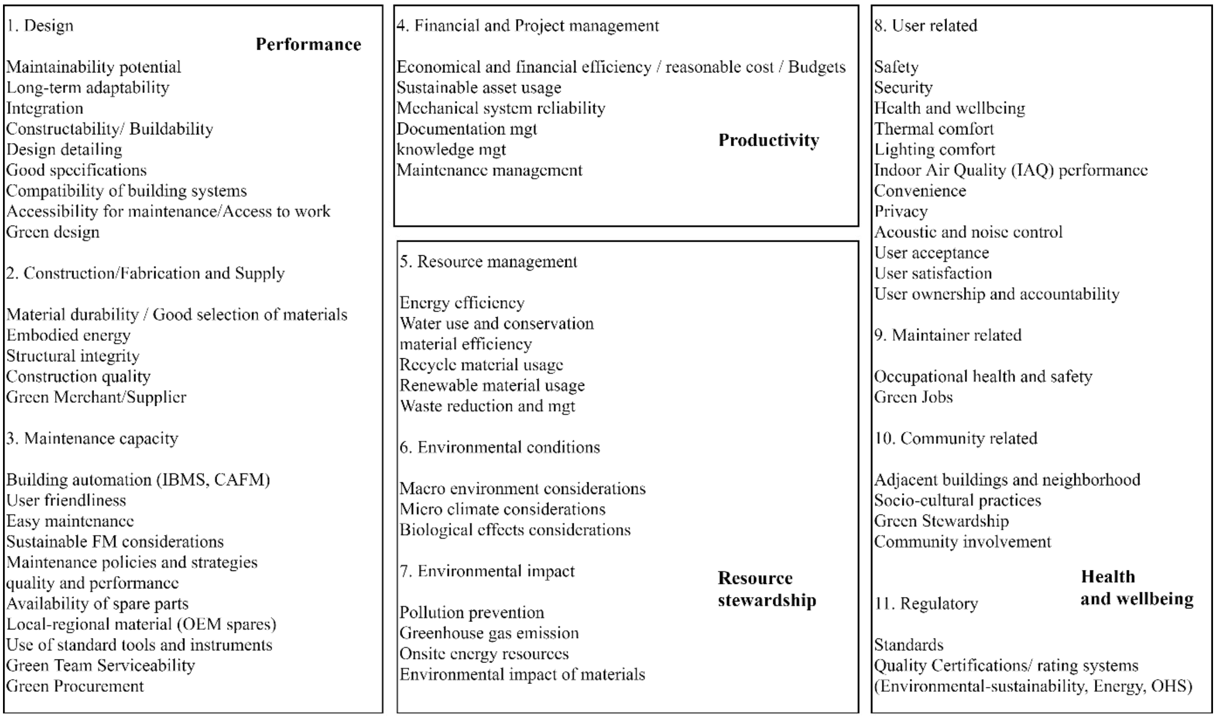

Fig. 1 *Conceptual framework for a green maintainability decision support system*

3.1 Decision modelling and opportunities for green maintainability

Decision modelling is sought out as a potential solution to overcome the gaps identified in the earlier section. Building professionals such as architectural designer, planners, and engineers; in projects and facilities management has been traditionally using decision support tools. Mostly dealing with constraints of cost, quality and time for project management tasks [15]. Modelling provides the decision makers with an understanding of the system and enables forecasting without any impairing the system or having to let things run its course. However, the current models are unable to adapt to the highly dynamic and interactive nature of the operations they model which intensifies the uncertainty of their results. On the other hand, building projects are heterogeneous in nature making the problem of modelling them unique from the manufacturing and industrial systems where a high level of control is available.

Different authors have taken various approaches to decision making modelling pertaining to design, construction, and maintenance. It is identified that different approaches were used to forecast component conditions at a given time; i.e. using deterministic, probabilistic or stochastic prediction models [16]. Different linear and polynomial models, as well as mathematical functions and probability distributions, have been developed using deterministic approaches. However, due to the nature of highly variable data in building systems, a deterministic approach is not suitable to model buildings [17]. Finding that it is too complex to develop a single model to fit the overall building dynamics, a multi-scale and multi-model approach can be taken to address these problems [2]. Where the multiple models would use existing data to model a building, and multiple scales to consider interlinks between building, products and materials aspects into account.

Decision support systems, on the other hand, are used to aid decision makers under circumstances where sufficient knowledge and informed alternatives do not exist. Where perfect knowledge is unavailable, such systems are useful to systematically analyse problems to find suitable solutions [18]. Hence, in case of implementing green maintainability of buildings, as a key initiative to create more maintainable and sustainable buildings; such tools can be of paramount importance to aid the decision makers.

Upon reviewing the state-of-the-art it is identified that the current building grading and maintainability assessment systems are received by the construction industry with reluctance and not being adopted in the industry due to various issues, i.e. high complexity, fuzzy nature of weighting criterion, maintainability scores not being reflected in tangible monetary terms [19]. Green maintainability, on the other hand, refers to maintainability and sustainable design with sustainable FM in mind; which altogether adds even further dimensions of complexities and uncertainties. The challenge, therefore, is to develop models or tools for the building domain that considers these limitations. Current knowledge must, therefore, be updated to overcome this challenge to transcend human-centred decision making by developing new methods and guidelines. Such models can then be used in outlining project requirements with all parties; enabling clear communication between all parties starting from the schematic design phase of a project, while ensuring all project priorities are considered, and delivering a platform to discuss impacts of value engineering decisions.

3.2 Measuring the impact of green maintainability

A decision support framework is proposed to this effect with the ability to systematically quantify the green maintainability of design alternatives and derive the lifecycle savings based on the design decisions. The proposed framework aspires to close the information gap between design professionals and the FM by promoting inclusiveness of all building stakeholders. The designers can greatly benefit the use of such a decision support tool to evaluate their design choice (i.e. to discern their designs which in turn reflects possible maintenance defects or environmental issues). Whilst the design team uses the decision support system initially, the ultimate beneficiaries will be the owner, developer and FM teams who reap the benefits of improved green maintainability.

The conceptual framework for modelling green maintainability of building designs is presented in Figure 2. The proposed framework uses building design features that come from the design team as model inputs. The characteristics of these design features are then classified and rated such that the cost of these design decisions can be obtained as model outputs. The cost of design decisions can be seen as the maintainability impact; quantified as a maintainability cost. This cost can be categorized into the cost of labour, materials and environmental interactions relating to the cleaning, repair and replacement activities derived from the particular design features.

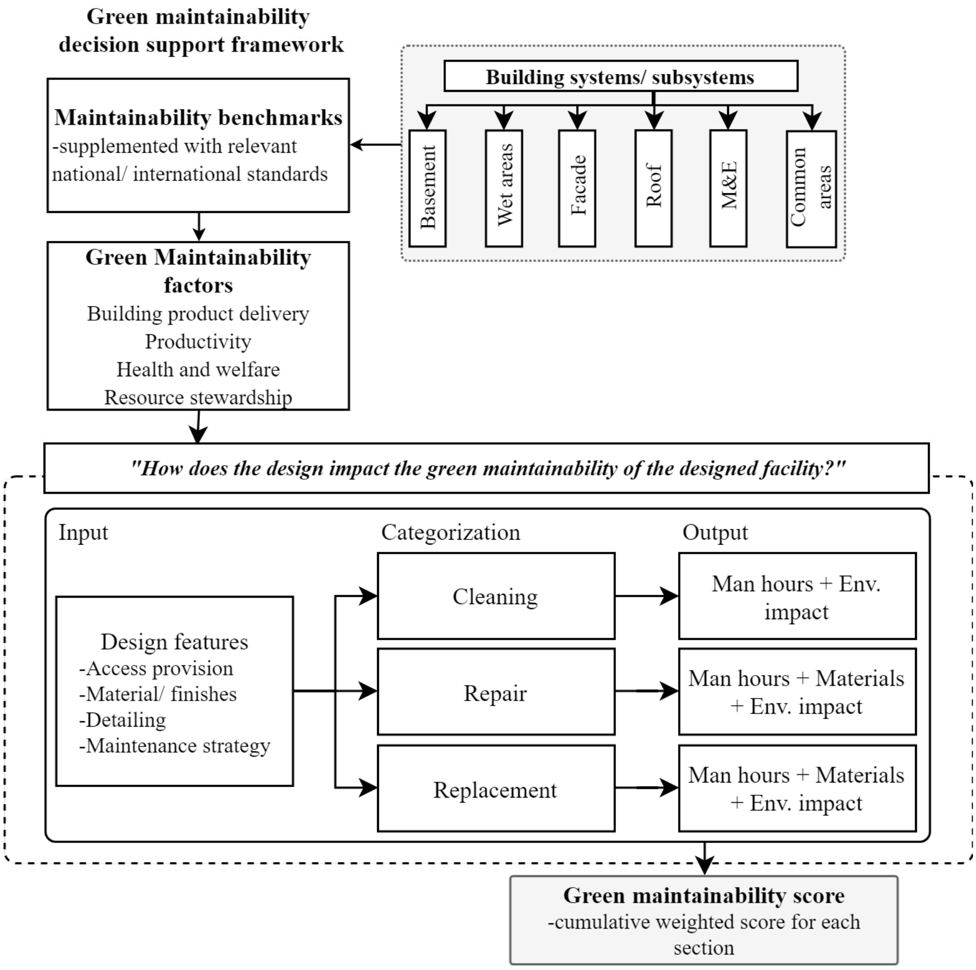

Fig. 2 *Conceptual framework for a green maintainability decision support system*

Green maintainability benchmarks pertaining to building design, construction, and maintenance are identified in the development of this framework. These benchmarks correspond to different building systems and subsystems, such as basement, façade, wet areas, roof, common areas, and, mechanical and electrical systems. See Figure 3 for the hierarchy of these building systems and components. Upon aggregation, a weighted additive process can then be used to accumulate the green maintainability costs throughout the whole building. Such a protocol for grading a building will deem this decision support system a 3rd generation performance-based building rating system, therefore, being greatly beneficial for construction projects in aiding informed decision making among varying alternatives. Referring to the industry best practices relating to green maintainability; a green maintainability scoring system checklist was compiled consisting of 1372 green maintainability benchmarks across 6 building subsystems and 65 sub-components. An excerpt of such benchmarks relating to basement design, construction and maintenance are presented in Table 1. This checklist is then used to carry out the instrumental case studies, focusing on maintenance activities (i.e. cleaning, repair, and replacement) of each building system; systematically investigating all factors affecting the efficiency, economy and environmental transactions of maintenance activities relating to improving green maintainability.

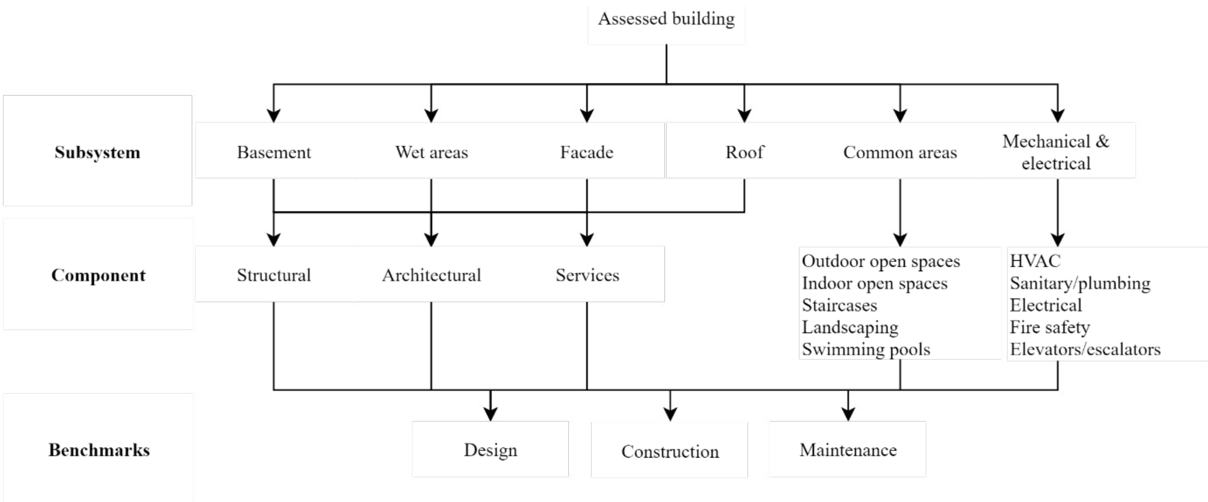

Fig. 3 *Hierarchy of building subsystems and components leading up to the standard benchmarks*

Tab. 1 *Excerpts from GM benchmarks relating to basements*

#	Subsystem	Component	Sub-component	Phase			Variable	Standard/benchmark	Measure
				Design	Construction	Maintenance			Yes (1) No (0) N/A(99)
B1	Basements	Structural	Concrete	1			Specify admixtures (e.g. water reducing agent, pozzolanic products, pore refiner, etc.) to reduce permeability.	BS EN 1504-9: 2008	1
B2	Basements	Structural	Concrete	1			For moisture control in special areas with a high-risk of water penetration, an electrochemical treatment can be specified	BS EN 1504-9: 2009	0
B3	Basements	Architec-tural	Joints		1		Slow down the drying of concrete to avoid plastic shrinkage	BS 6093:2006+A1:2013	1
B4	Basements	Architec-tural	Joints		1		Carry out sealant application in movement joints when joint gap is at the mean trending to the maximum	BS 6093:2006+ A1:2013	0
B5	Basements	Services	Service penetra-tions	1			Pre-plan, group and box out service penetrations to minimise penetration through waterproofing	BS 8102: 2009, SS CP 82:1999	1
B6	Basements	Services	Service penetra-tions	1			Provide additional reinforcement to counteract concentration of shrinkage stress especially at corners of openings	BS 8102: 2009, SS CP 82:1999	1

This study directly addresses current industry challenges which are predicted to escalate in the future due to the rising resource limitations and the rise of complex operations and maintenance issues emanating from more intricate building designs and systems that are built at present; achieved by way of highly maintainable building designs to eradicate predictable maintenance problems.

To this end, building design professionals can use the proposed framework during the concept design and detail design stages, by tallying the maintainability costs for the design features they wish to integrate into the building. To illustrate how the proposed framework can be implemented for a certain design feature, the simplified process of the proposed DSS is illustrated in Figure 4. The proposed DSS is modelled upon the basis of three pillars; previous building maintainability research, identified factors of green maintainability and the standard benchmarks for building projects. The latter is used to frame the maintainability scoring system checklist; which acts as the input to the DSS, which the design professionals can easily use. It is intended to provide a foundation of best practices and recommendations to the design teams to integrate green maintainability in their design alternatives; rather than being prescriptive in its effectuation. These inputs will then be classified according to the constraints set out by the client and optimized according to the multiple objectives of green maintainability. The resource-centric constraints such as time (i.e. schedule), cost (i.e. budget) and environmental performance (e.g. a sustainability budget) can be taken into account within this DSS to assess the different design alternatives brought forth by the design teams, derived from their inputs.

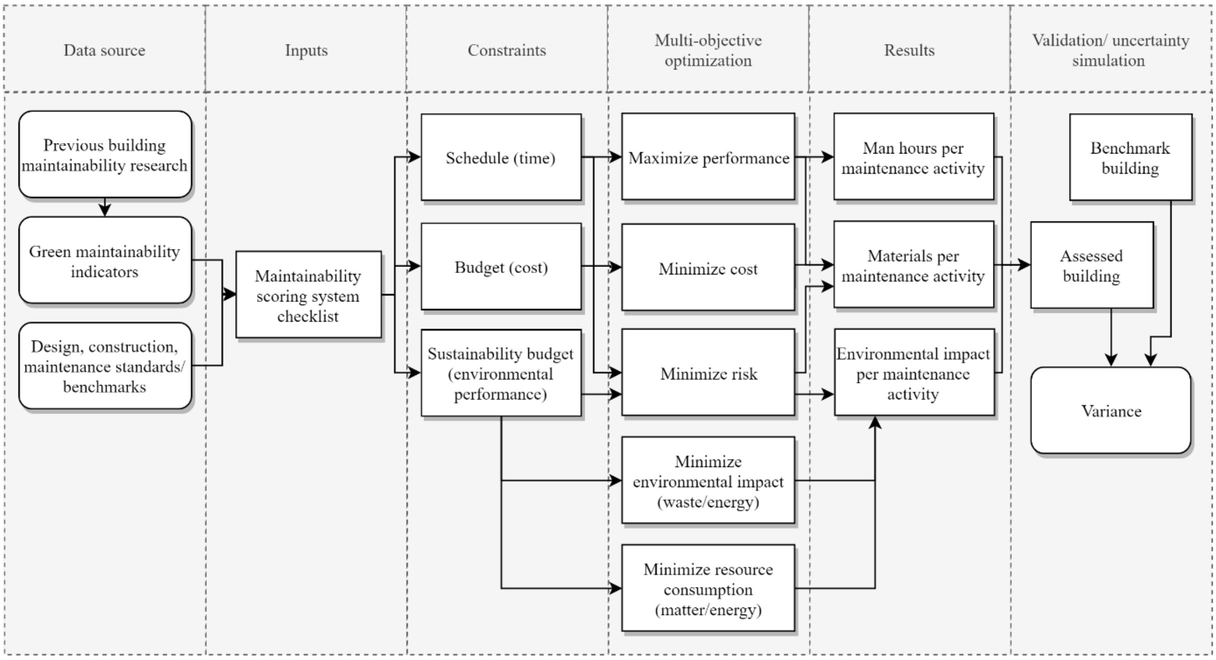

Fig. 4 *Simplified steps of the proposed green maintainability DSS*

Through classification, the green maintainability impact concerning maintenance activities resulting from each component is accounted as a cost, with reference to the direct maintenance cost (incurred for manpower and utilized resources), as well as the indirect environmental cost. The environmental cost is obtained from the environmental impact and waste/emissions generated during the maintenance activities. The proposed DSS, therefore, uses a multi-model approach to predict the temporal degradation of façade and the resultant implications on maintenance processes (including environmental impacts). The integration of environmental cost components is used as an indicator of green maintainability. Hence, it provides a holistic green maintainability forecast for the alternatives considered by the designers. The resultant composite cost will be compared with the results for a baseline building such that comparisons can be drawn against an ideal design in terms of the building benchmarks. Finally, the results will be validated by running sensitivity analysis to cater for uncertainty.

4 Conclusions and future work

Green maintainability is grounded on the need to attain sustainability performance throughout the lifetime of green buildings. Based on the literature review, it is hypothesized that green maintainability of buildings can be improved by implementing green maintainability strategies through maintainability scoring in early design stages to ensure life-cycle sustainability in buildings. This gap is attributed to improper decision making during design stages. This paper proposes a conceptual DSS to derive potential impacts of design alternatives to interlace principles of sustainable construction and building maintainability into building projects. The current paper lays out the rationale and method for the proposed DSS to be developed. Such a system can mitigate a facility's maintenance issues and operational defects. This leads to a reduction in the facility's lifecycle costs and lifecycle environmental transactions, helping it achieve lifecycle sustainability.

The current research seeks to improve facility design processes with capable tools. To attain this goal, the on-going research work deals with gathering qualitative and quantitative data from multiple case studies. The green maintainability modelling based on this framework will be done in relation to existing maintainability scoring systems and be factoring in the identified green maintainability parameters. Currently, there is no specific rating tool or technological solution on maintainability and only a handful of superficial guidelines globally. In this context, the proposed DSS framework is a novel and comprehensive attempt to incorporate green maintainability into the building delivery process. Furthermore, it is envisaged that this conceptual DSS can be adopted globally in any locality by simply defining the respective maintainability benchmarks for that locality.

Acknowledgement

The current study did not operate from any sort of external funding sources.

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Evaluation of Life Cycle Assessment Tools for Assessing the Potential Environmental Impact of Renovation Measures

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Abstract

Life cycle assessment (LCA) is used to evaluate the potential environmental impact of different processes and services, including in the construction and real estate sectors. This study compares three LCA tools that have been specifically developed for use in the construction and real estate sectors with a fourth that is a general LCA tool. An LCA is performed for a case study of a multi-family building where a heat recovery system has been installed. The main aim of the study is to assess the advantages and limitations of using simplified LCA tools to perform an LCA in the construction sector. This study includes a comparison of the potential environmental impact in the different tools for the case-studied building and shows differences in the results of the different tools due to the differences in their configurations and the available databases on environmental impacts.

Keywords: *LCA, ventilation system, heat recovery system, refurbishment, multi-family building*

1 Introduction

The European Union has set a goal to reduce carbon emission by 40% by 2030 (from the base level in 1990) [1]. With the construction and real estate sectors having been found to be among the greatest contributors to CO_2 emissions, there is potential for improvement in these sectors. In Sweden, the construction and real estate sectors are responsible for 18% of the greenhouse gas (GHG) emissions [2]. The Swedish National Board of Housing, Building and Planning has identified the implementation of mandatory climate declarations for buildings as a possible way to both increase awareness of the environmental impact of our buildings and gather data on appropriate levels on emissions for future regulations [3]. The climate declaration for buildings should then be performed with a life cycle perspective. The use of the life cycle assessment (LCA) method for assessing GHG emissions has increased in the construction and real estate sectors [4].

LCA is a standardised method (SS-EN ISO 14044:2006/A1:2018) [5] that has been studied in previous research on renovation [4], [6]–[8]. The standard for LCA provides overall guidance on performing an LCA [9]. The standard does not specify which tool to use, so there is a high level of adaptability and flexibility in each specific case. To be able to compare results from LCAs, the standard specifies a high level of transparency.

To assess the environmental impact of individual building components/elements, environmental product declarations (EPD) can be used [10]. EPDs are standardised and verified environmental assessments published through databases such as the international EPD system, EPD Norge and Institut Bauen und Unwelt e.V. The number of EPDs is continuing to increase, but there are still areas relevant to the building industry where EPDs are limited, for example building services components. The information that can be found in an EPD for a building component is usually for the product (A1-A5) and waste treatment (C3) stages.

The most commonly included stages when performing an LCA for a renovation project are the product and the user stages [4]. Vilches (2017) found that construction and demolition have less impact on a renovation project than the product and user stages. More recent studies have found a change in the distribution between these two stages compared with before. With more energy-efficient buildings, the environmental impacts have decreased for the user stage and increased for the product stage, due to the decreased energy demands of the buildings and the increase in the amount of material used.

This study aims to evaluate the challenges and limitations of performing an LCA with simplified LCA tools as well as the tools' potential for use in further studies on assessing environmental impacts.

2 Method

Three simplified LCA tools are compared and evaluated with a more general and complex LCA tool. The four tools in this study were chosen because they are all open access and free to use. The analysis of the tools was performed considering different aspects. The analysed aspects were the included data (accessible data), environmental categories and renovation measures; transparency of calculation and input data; presentation of results; uncertainty analysis of input data; and adaptability.

The tools were also used for a case study of a multi-family building that had undergone a renovation in which heat recovery was installed in the ventilation system.

2.1 Life cycle assessment tools

The three simplified tools that were evaluated were chosen because they had been developed for use in the construction and real estate sectors. The comparison was between the simplified tools BM, Beceren and RenoBuild and the general tool OpenLCA. The comparison evaluated the possibilities and limitations of simplified tools.

2.1.1 BM

Byggsektorns Miljöberäkningsprogram (BM) was launched in Sweden in the beginning of 2018. This tool was developed by the IVL Swedish Environmental Research Institute as a simplified method of performing an LCA [11], [12]. The tool was developed with the aim of supporting and spreading the implementation of LCA in the construction and real estate sectors as well as to be complex enough to be able to compare different alternatives for construction from the perspective of environmental impact.

The tool is free to use and available to download from IVL's webpage [13]. A user manual and one-day courses are also available.

2.1.2 Beceren

Beceren was developed in 2008 with the aim of supporting the formulation of goals and evaluating renovation measures from the perspective of energy use, potential impact on climate change and life cycle cost [14]. The tool is an Excel file that has been further developed in subsequent research projects and tested in case studies. The main developments have been performed by researchers at the Royal Institute of Technology (KTH).

The tool is free to use and available to download [15]. There are some help texts in the tool for the user, as well as a user guide.

2.1.3 RenoBuild

RenoBuild was developed in research projects carried out by the Research Institutes of Sweden (RISE) [16] [17]–[19]. The tool is an Excel file and has been evaluated in different case studies. It was developed as an early decision support tool for integrating the three aspects of sustainability – environmental, economic and social – in the decision-making process before a renovation. The three different parts of the tool are linked together in order to evaluate different renovation measures from the perspective of sustainability. In this study, only the environmental part was included. The tool is available in two different versions, one that is adapted to multi-family buildings and the other to school buildings, with the former being used in the study.

The tool is free to use and available to download from RenoBuild's webpage [20]. The webpage has user guides as well as some help texts in the tool.

2.1.4 OpenLCA

OpenLCA was developed, and is maintained, by the company Green Delta. The software is an interface that links different databases of potential environmental impacts of products and services with different methods of assessing the environmental impact of these [21]. It is also possible to build up a product or service in the software using different raw materials and specifying their emissions and impacts.

The tool was first developed to assess the environmental impact by performing an LCA, but it is also possible to include economic and social aspects.

OpenLCA is a free software product that can be downloaded from Green Delta's webpage [22]. Free databases are also available both for the potential environmental impact of products and for different environmental assessment methods. Other databases are available to purchase for the software, e.g. EcoInvent, GaBi, JRC and Ökobaudat. A guide, videos and some different courses are available for users to learn more about the tool.

In this study, the free database JRC European Commission is used for the material, and the GWP is calculated using the ILCD 2011 midpoint v.1.0 method.

2.2 Case study

The four tools were evaluated for their usability and LCA results using a case study. An LCA for the case study was performed in all four tools. The aim was to use the same set of input parameters in the different tools. Depending on the required input data and limitations of the tools, the input parameters could differ. Some generic data valid for the construction sector are available in the applied tools. In this study, the generic data are used to evaluate the adaptation or simplification made in the tools.

2.2.1 Functional unit

The functional unit for this study is 1 m^2 of heated floor area of a multi-family building that fulfils the Swedish building code requirement for a time period of 20 years.

2.2.2 System boundaries

The potential environmental impact assessment of the energy-efficient measure includes the following life cycle stages (according to EN15978): 1. production of the additional material for the building (air handling unit, supply ducts; A1-A3) and 2. the operational energy reduction of the building (B6). The study does not include the potential environmental impact of workmanship, any materials related to the installation stage (A5), or waste treatment (C3).

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHREA), the expected lifespan of fans and dampers is about 20 years, and diffusers, grilles and ductwork have an expected lifespan of 27-30 years [23]. In this study, the lifespan of the installed air handling unit (AHU) and new ductwork as well as the existing ductwork are assumed to be 20 years. After 20 years, it is assumed that the ventilation system will need a major renovation or to be replaced to prolong its lifespan.

2.2.3 Building

To evaluate the different LCA tools, the renovation of a multi-family building built in 1969 in Sweden was used as a case study. The building has eight flats and is split over two floors with a total heated floor area (A_{temp}) of 919 m^2 [24]. The building had a mechanical exhaust ventilation system before the renovation. The renovation, performed in 2016-2017, included the installation of a mechanical balanced ventilation system with heat recovery (MVHR). The existing exhaust duct system was retained while a new supply duct system was installed together with a new air handling unit (AHU) with a heat exchanger. No other measure was performed on the building at the time of the renovation.

The renovation was followed through a research project that evaluated the potential energy savings of the installation of heat recovery in the ventilation system [25].

2.2.4 Input data

The information about the case study comes from the research project [25] and the building owners. The input data used in the LCA tools are presented in Tab. 1.

Tab. 1 *Input data for the case study*

Input	Case study
Area	919 m^2
Number of flats	8 units
Assumed lifespan after renovation	20 years
Heat source	District heating of waste incineration [26]
Energy demand before renovation	131 kWh/m^2
Energy demand after renovation	99 kWh/m^2
Dimensioned airflow	322 l/s (1158 m^3/h)
Renovation measure	From mechanical exhaust air ventilation to mechanical supply and exhaust air ventilation with heat recovery with an expected lifespan of 20 years
Added material (due to the renovation)	Supply air duct system, approximately 3150 kg of steel ducts (including silencer, reducer/expander, plug, T-branch, straight ducts and bends) with an expected lifespan of 20 years
	Central air handling unit (AHU) with heat recovery and fans with an expected lifespan of 20 years
	Supply air device with an expected lifespan of 20 years

3 Comparison of the different tools

The evaluated aspects included for the different tools are presented in Tab. 2. In the general LCA tool OpenLCA, the data used for potential environmental impact can be accessed from different sources such as EcoInvent, GaBi or the JRC European Commission databases. The simplified LCA tools developed for use in the construction and real estate sectors include some input data on environmental impacts. In Beceren, this information can be accessed by visualising hidden tabs in the Excel-based tool. In RenoBuild, the CO_2-equivalent emissions for district heating and primary energy factor (PEF) are linked to an external source in the tool and can be changed. The potential environmental impact of the amount of materials and length of transportation are set as default values in RenoBuild but are not visible to the user. In BM, there are approximately 120 EPDs linked to the tool, with data on the potential environmental impact of different materials. The environmental impact of some services can also be added in the tool, such as of construction work. All materials have a default value for climate impact with transportation of materials based on an average, depending on the weight and distance, from the industry in Sweden. This default value can be changed by the user of the tool. The user can also import their own materials and services either by stating the potential environmental impact or by importing an EPD into the tool.

Tab. 2 *Generic information and comparison of the different LCA tools*

Tool	BM	Beceren	RenoBuild	OpenLCA
Included data/accessible data (Source for LCI)	Database with approx. 120 EPDs for products, with the possibility of importing additional EPDs. Includes generic values for additional materials.	Data included in the tool with generic values for the potential environmental impact of different materials and services.	Data included in the tool with generic values for the potential environmental impact of different materials and services. PEF factor and GWP for district heating have default values but can be changed.	Possible to link to several different databases for both products and environmental impact categories. All data can be changed/adapted.
Included environmental categories	Global warming potential (GWP)	Global warming potential (GWP)	Global warming potential (GWP), Primary energy demand (PED)	Possible to import different databases with environmental impact categories.
Included renovation measures	All measures need to be added manually.	Included renovation measures: - insulation of the building envelope - change windows/doors - thermal bridges - change of ventilation system - low-pressure taps - heat exchanger in the wastewater system - change to LED lights - change to low-energy kitchen appliances - installation of solar energy - installation of wind energy Not possible to add any others	Included renovation measures: - change of heat source - change circulation pump in the heating system - insulation of the building envelope - change windows/doors - change ventilation system - change of heating system - change electricity wiring Not possible to add any others	All measures need to be added manually.
Transparency of calculations	Based on EN15978. Characterisation factors are not visible.	Possible to see hidden tabs and make own alterations in the tool to, e.g., potential environmental impacts.	Information such as characterisation factors and potential environmental impact is not visible.	Visible in the different impact assessment categories in the databases.
Transparency of input data	Used values are visible and changeable in the tool.	Default values for the calculation of the building's energy use, potential environmental impact for different materials and energy sources. The default values can be changed to be project specific.	The default values for potential environmental impact for different materials are not visible. Default values for district heating and PED factor.	The tool is transparent but relies on the users to enter some important information. Emissions are visual and changeable.
Presentation of results	Table and graphs as an environmental declaration in an Excel file. Results are specified in the life cycle stages: A1-3, A4, A5, A5.1, A5.2, A5.3, A5.4, A5.5.	The results are presented in tables and graphs in Excel and give the values of the total energy demand and total global warming potential.	Presents the GWP and PED (values and restoration time) in tables and graphs in relation to a reference case in which no renovation is performed. Specified results: production, transport, user stage and waste treatment.	Results are presented in several different ways in the software such as: geographically, inventory, impact etc. Single case or comparative. Results can be exported to Excel.
Uncertainty analysis in input data	Uncertainty analysis can be performed manually by changing different input data and manually documenting the outcome.	Uncertainty analysis can be performed manually by changing different input data and manually comparing the outcome.	By using different alternatives for the renovation measure, some uncertainty analysis can be performed manually in the tool.	Possible to consider uncertainty in both method and input data. Possible to use Monte Carlo simulation and the developed uncertainty system Pedigree.
Adaptability	Limited to life cycle stages A1-A5. Possible to add EPDs.	Adaptation is possible in the hidden Excel tabs.	Possible adaptation of some default values.	High possibility of adaptation (open source).

4 LCA for the case study

The tools have different ways of specifying the input values for an LCA. In this study, the differences have been identified in relation to the relevant input data for the case study, where heat recovery has been installed in the ventilation system. The required inputs for each of the tools are presented in Tab. 3.

Tab. 3 *Differences in input data requested by the tools*

Input parameter	BM	Beceren	RenoBuild	OpenLCA
Building	Mandatory information: - building type - closest geographical location from given options	Mandatory information: - closest geographical location from given options - building year - building type - ventilation system - energy source (heat and electricity) Possible to enter more project-specific information	- heated floor area (m^2) - number of flats - heat source	Not adapted to the construction and real estate sectors. The functional unit needs to be quantified, e.g. heated floor area (m^2).
Added material	- duct system	- specified a change from exhaust ventilation to exhaust and supply with heat recovery	- AHU - duct system - supply air devices and dampers	- steel for the supply duct system
Air handling unit (AHU)	Not included due to limitations in the available database.	No option to specify	- central AHU - dimensioned air flow (m3/h) - km of transport by lorry, boat or train	Not included due to limitations in the available database
Supply system	- number of kg of duct - default (construction and real estate sectors) value for transportation	No option to specify	- number of kg of materials - expected lifespan - km of transport by lorry, boat or train	- number of kg of material of which ducts are made
Supply air device	Not available in the database	No option to specify	- expected lifespan - km of transport by lorry, boat or train	Not included
Energy	Not included	- amount of energy in kWh - district heating (Stockholm)	- amount of energy in kWh - district heating consistent with waste incineration	- amount of energy in kWh - process steam from waste incineration

Fig. 1 presents the results of the potential environmental impacts from the four tools separately for the product stage (A1-A3) and the user stage (B6). The results presented in Fig. 1 depend on the differences in the input parameters presented in Tab. 3.

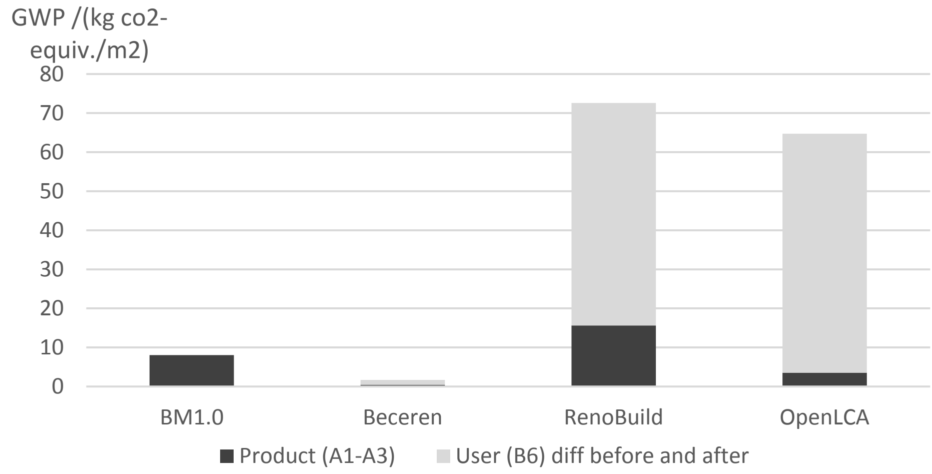

Fig. 1 *Results of the potential environmental impact of the installed system in the case study using the four different LCA tools*

5 Discussion

The tools developed for use in the construction and real estate sectors are simplifications compared with more complex LCA tools such as OpenLCA, as was the goal of their development. Several studies have shown that one limitation of implementing LCA in the construction and real estate sectors has been the complexity of performing an LCA [2]. It is evident in this study that the user can make more adaptations and complex assessments in OpenLCA than in the applied tools. This makes OpenLCA more complex to use, especially due to the greater need for project-specific information and gathering of material properties and their environmental impacts. The applied tools access generic data, which simplifies their use and enables an LCA without any in-depth knowledge about LCA. More in-depth knowledge is needed to interpret the results.

The usability of the four tools has been evaluated through the same case study. For someone with experience of Excel, Beceren and RenoBuild are initially easier to use, as is the BM tool, to some extent. OpenLCA is a more complex tool, and some of the user aids (guide, video, courses) can be of great help. Some understanding of the concept of LCA is needed for all the tools but more so for OpenLCA, which requires more LCA information to be able to use it.

The two Excel-based tools, Beceren and RenoBuild, have a similar purpose but are very different. In Beceren, a simplified energy calculation can be performed and all the background data accessed by making hidden tabs visible. Using the background data requires more knowledge for the LCA, energy assessments and Excel. Compared with Beceren, RenoBuild does not include an energy calculation, and the background information is hidden from the user. The energy calculation needs to be performed separately and the result fed into RenoBuild. In RenoBuild, more of the material relevant for the case study could be included with generic data in the tool, which gives a higher result for the potential environmental impact of the production of the material than the others, as seen in Fig. 1. Compared with the BM tool, the input data in this tool are visible and changeable. The generic data for transportation and additional material, and for the construction stage give a more comprehensive LCA without the need to make any own assumptions. The limitation of this tool is that it does not include the user stage (with the energy demand for the building).

Comparisons of the results from the different tools are limited due to the differences in the presentation of the results as well as the limitations and differences in the way they are calculated. The differences that have affected the results are mainly:

- Only the production stage (A1-A4) is included in BM.

- RenoBuild calculates the increased/decreased potential environmental impact in relation to not performing any renovation measure.
- The use of the different tools' generic data.
- The limitation of available information in the tools/included databases.

For the production stage, RenoBuild results in a higher potential environmental impact than the other tools. In RenoBuild, the production of the AHU, duct system and supply air device and dampers is included, compared with only the duct system in BM1.0 and only the production of the metal in OpenLCA (due to the database used). In Beceren, even with the possibility of showing the tabs with input data and calculations, it is not clear which material production is included in the results. This is also the case for the way the energy for the user stage is calculated. For the tools RenoBuild and OpenLCA, the results are similar for the potential environmental impact during the user stage.

The main advantage of the simplified tools is the generic information of the potential environmental impacts for different materials and services. Depending on the aim of an LCA study, the tools' limitations could prevent their use. For the case study of installing a heat recovery in the ventilation system, none of the tools include all the parameters in this study. The complex tool OpenLCA and the simplified BM1.0 have the potential to meet the aim if more information were gathered and other databases/EPDs used. In this study, the main limitation of RenoBuild is the presentation of the results as a difference in potential environmental impact in relation to a reference case. For the tool Beceren, the potential environmental impact for relevant material production when installing a supply ventilation system and heat recovery is limited.

Acknowledgement

This study has been carried out within the Strong Research environment SIRen [27]*, financed by the Swedish research council Formas. The study was co-funded by the Swedish National Board of Housing, Building and Planning.*

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Barriers, Challenges, and Driving Forces in Adopting Green Building Simulation in Design Practices: Cases from Taiwanese Architectural Firms

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Abstract

Although the value of simulation in architectural design has been widely emphasized in the literature, the adoption of green building simulation (GBS) in the design process remains limited in practices. The main objective of this research is to understand the variables that influence the adoption of GBS tools. In this manuscript, we discuss the preliminary findings of qualitative investigation through semi-structured interviews with managing architects from 16 Taiwanese architectural firms. The results indicated that the threshold of technology, lack of technical operator, inability to afford the cost, lack of urgent requirement, and no positive external environment are considered barriers and challenges, while having a project in competition and skilled employees are considered the driving forces for organizations to adopt simulation tools. The results also demonstrated that larger firms that focus on public or tendering building projects are more likely to adopt GBS tools.

Keywords: *architecture design, adoption, Green building simulation, semi-structured interview*

1 Introduction

Green building simulation (GBS) tools, also referred to in some articles as building performance simulation (BPS) tools, are defined in this study as tools that calculate and visualize the general physical environments of buildings by computer (e.g., light environment, acoustical environment, thermal environment, wind environment, energy consumption). With growing concerns about making decisions in the architectural design process and their effect on building performance and quality of life, architects and designers are actively encouraged to integrate green building simulation tools into their design process in order to create energy efficient and sustainable buildings [1].

Integrating these simulation tools into the design process has been widely touted as having various positive advantages, such as helping designers choose the optimal solution regarding the considered criteria, validating building performance, preventing potentially poor decisions, and visualizing the design results. However, the method for integrating these simulation tools into the architectural design process and practice has always posed a challenge. Past literature has reported many barriers and considerations regarding these simulation tools, such as being too complex, cumbersome, expensive, or systemic, taking too much time, or not being integrated into CAAD software [2][3][4]. In general, the interface and operation of these GBS tools are not considered ‘architect friendly’ or compatible with architects' work methods and needs, as most of them were developed by technologically oriented people like scholars, scientists, and technical engineers [1][5][6][7].

To help architects and designers bridge these gaps, many researchers have contributed to reducing the complexity of such tools by simplifying the process to meet architects' needs; for example, they have tried to reduce parameter setting complexity, shorten simulation time, and provide an image interface [8][9][10][11][12]. However, the adoption of GBS tools remains limited in some architectural practices despite these constant efforts in recent decades. A survey in Belgium showed that less than 30% of architect respondents use design aids like simulation, assessment, and analysis tools [13]. This phenomenon suggests that other variables or characteristics may significantly influence the decision to adopt GBS tools in the architectural design process. This opinion is also supported by research that has indicated that an interface's ease of use does not make simulation available to everyone; other crucial factors like limitations of knowledge and understanding of the programs or process also affect adoption [14]. Furthermore, with regard to the probability of adopting GBS tools in architectural practices, the greatest challenge is not only in the interaction between tools and operators, but also extends to larger aspects, such as an architectural firm's project management. Since the adoption of GBS tools involves the firm's orientation, project requirements, budget, staffing, technical skills, and time allocation into the design process, it is considered a firm-level decision issue. Therefore, in such a cumbersome process, the variables that influence firm managers' perspectives and intent to adopt GBS tools are key for improving the implementation of GBS. However, information about these variables are still not clear and have rarely been discussed from the perspective of management in past research.

To better understand the potential variables and their interactive effect for developing evidence-based strategies to promote GBS tools in practice, the main objective of this manuscript is trying to figure out the influencing factors from perspectives of management in architectural firms. In this paper, we discuss the major findings of qualitative investigation and describe the survey results regarding the practices of green building and green building simulation in Taiwanese architectural firms. The paper is organized as follows: first, a description of the development of green building and green building simulation practices in Taiwan, then illustration of the GBS in Taiwanese design workflow, and lastly the thoughts of respondents, including their usage situation of GBS tools, and the challenges and driving forces of adopting GBS tools from different aspects.

2 Method

The purpose of this research was to explore the potential variables/characteristics that influence the decision to adopt GBS tools in Taiwanese architectural firms. Due to the limited information on this topic, this research was considered both exploratory. Therefore, we carry out a qualitative investigation with an inductive approach for data collection and analysis. We conducted semi-structured interviews with the managers of architectural firms to gain an in-depth understanding of thoughts on GPS tool practices in Taiwanese architectural firms.

2.1 The participants

Since introducing GBS tools in architectural practices involves many major issues (e.g., requirements, budget, staffing, time), firm managers have to think carefully when making related decisions. Therefore, participants were selected based on their managerial positions in their organizations to ensure that they had the power to make decisions to adopt GBS tools in their firms or projects. This study consists of 16 interviewees from 16 architectural firms, all of whom are architectural firms' managers (founders or project managers). In the interviews, all participants were asked to respond from the company's position to make sure that the considerations are from the perspective of management. The individual backgrounds of the participants vary significantly, as shown in Figure 1–4 and Table 1.

Of the interview samples, 15 participants were founders and one was a project manager in their firms. The participants' years of industry experience ranged from less than 10 years to more than 30 years, representing various generations of architectural practitioners. We divided firm size into small firms (1–14 employees), medium-sized firms (15–49 employees), and large firms (50 or more employees), and this study included three large firms, seven medium-sized firms, and six small firms. The project types of the firms ranged from private buildings like residential, commercial, and factories to public buildings like schools, art galleries, and other public construction. As for green building, eight participants (50%) indicated that they were active in it, while the other eight participants said that they participated in it only occasionally.

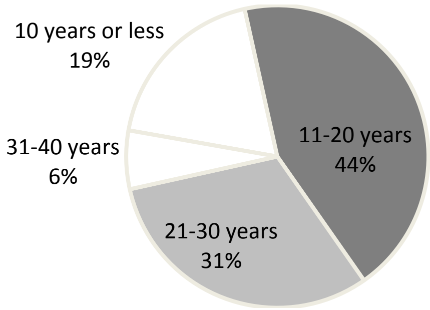

Fig. 1 *Years of industry experience*

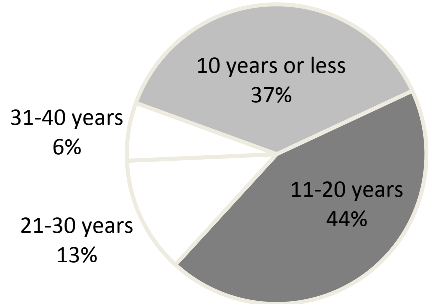

Fig. 2 *Age of firm*

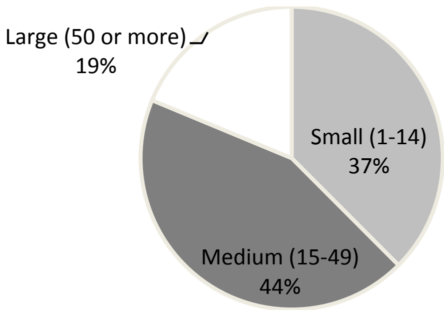

Fig. 3 *Size of firm*

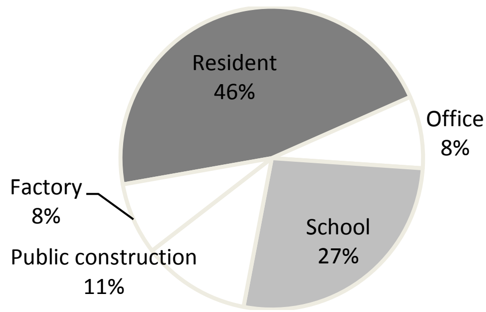

Fig. 4 *Project types*

Tab. 1 *Participants' profile*

Identifiers	Position	Industry Experience (Years)	Size of firm	Type of project	GB-related experience	Adopts BPS tools (Y/N)
A	Founder	18	Medium	Residence	Occasional	N
B	Manager	6	Large	Residence, School	Active	Y
C	Founder	12	Small	Residence	Occasional	N
D	Founder	12	Small	School, Public	Occasional	N
E	Founder	34	Medium	School	Active	N
F	Founder	26	Large	Residence, Public	Active	Y
G	Founder	18	Medium	School, Factory	Occasional	N
H	Founder	9	Small	Residence, Office	Occasional	N
I	Founder	30	Medium	Residence, School	Active	N
J	Founder	16	Small	Residence, School	Occasional	Y
K	Founder	21	Small	Residence	Occasional	N
L	Founder	15	Medium	School, Museum	Active	N
M	Founder	30	Medium	Residence	Occasional	N
N	Founder	28	Large	Residence, Office	Active	N
O	Founder	18	Medium	Residence	Active	Y
P	Founder	3.5	Small	Residence, Factory	Active	N

2.2 The interviews

The first part of the semi-structured interview assessed participants on their organizations' development in green building. Then, the interview focused on the current status, obstacles, and future directions of GBS practices in Taiwan's architectural industry. The outline of the interview questions included: the development situation of green building in firms; operating situation and challenges of GBS tools; willingness and considerations when adopting GBS tools; and recommendations and expectations about introducing GBS tools into the architecture industry as a whole.

3 Results and Discussion

3.1 Development of GB/GBS practices

As the awareness of environmental sustainability increases, many governments and organizations have developed green building evaluation criteria in order to implement sustainable building practices (e.g., LEED in the US, BREEAM in the UK, and CASBEE in Japan). In Taiwan, an official green building rating system has also been established to facilitate green (or sustainable) building practices for the past twenty years. Therefore, when dealing with green building development, green building practices have been observed. For example, respondent B described that, "Almost every project in their firm needs to assess the green building criteria for certification." This view was further supported by 10 other respondents (D, E, F, G, I, K, L, M, N and O) who mentioned that they referred to the required regulations for green building certification. These respondents belonged to firms whose projects usually contained public buildings. Other respondents (A, P) indicated that "projects in their firms are generally private residences, which do not require evaluation based on the green building criteria." The results implied the potential difference in positive levels of green building practices between private and public projects.

As for green building design approaches, many participants (C, D, E, F, G, H, I, J, K, L, M) said that they relied on intuition, common sense, rules of thumb, or experience (keywords from respondents) and admitted that they lacked scientific verification and were uncertain about design effectiveness. For example, respondent C claimed that "The firm cares about the space with good daylight and appropriate ventilation, but at present, designs are developed with common sense, but without scientific verification of analysis or simulation." Some respondents (E, F, G, K, L, M, N) stated that when a project is in a competition/according to project requirement, they sometimes seek external help (e.g., consultant company) for assisting with green building simulation. Only four of the 16 architectural firms indicated that they currently adopted GBS tools in their architectural design process. The results showed that most Taiwanese architectural firms currently adopt a more flexible approach for adopting these GBS tools, instead of actually introducing GBS tools into the workflow. The situation confirmed that GBS implementation is insufficient, as well as that Taiwan has a lot of room for improvement.

3.2 GBS in design workflow of Taiwan

According to the interviews, the authors illustrated the most general scene of adopting GBS in the design workflow of Taiwanese architectural firms (Figure 5). The scene is for projects in competition, as respondent M described that "They usually need these GBS tools when their projects are in a competition." This view was also supported by respondents B, E, F, G, and O. Respondent O even commented that "Firms that take private projects may not need to do these (GBS) because the owners (of private projects) generally do not have such requirements." Therefore, despite the advantage of GBS for scientifically evaluating building performance, GBS tools are rarely adopted in private projects, apart from competitive ones. Jernigan F.E. (2007) indicated that the most important decisions take place in the early conceptual design phase of architectural design, which have the greatest influence on building life-cycle costs (LCC) [15]. Therefore, most of the powerful modifications of architectural design that influence building performance happen during the design process. However, as shown in Figure 5, architects in Taiwan make significant building decisions in this critical process using their common sense, basic knowledge, and experiences. Then, after the conceptual design has been completed, projects are finally delivered to the person operating the GBS tools or external experts (e.g. consultant companies) for GBS. This workflow suggests that GBS is considered a step to verify design results rather than a tool for assisting decision-making. GBS tools actually have very little feedback on a design.

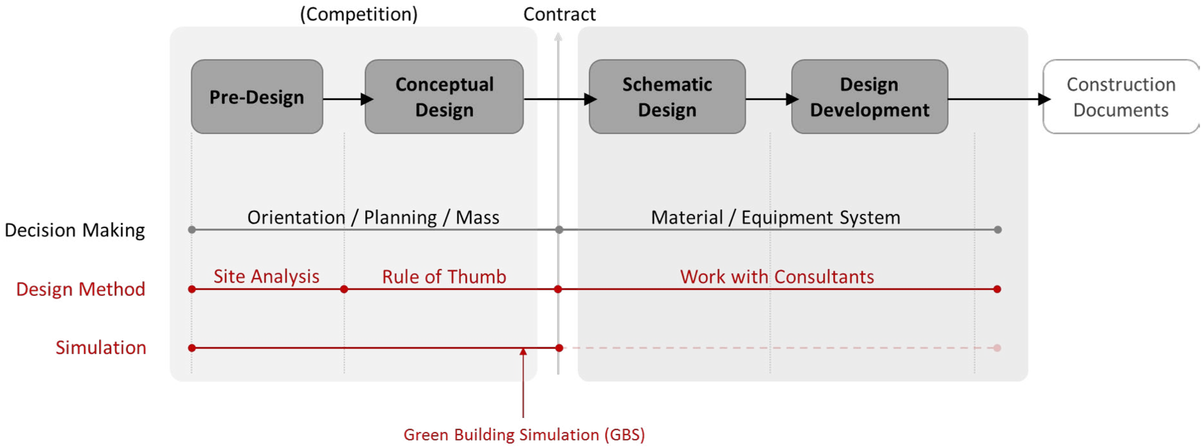

Fig. 5 *General scene of adopting GBS in Taiwan design workflow*

3.3 Thoughts about adopting GBS tools

3.3.1 Usage situation of GBS tools

Only four in 16 firms (Respondents B, F, J, and O) indicated that they use GBS in their design process. The GBS tools used by each firm are different. However, even if they have adopted GBS tools, these respondents, except B, did not understand the details of their operations. For example, respondent O was unable to discuss the feeling of using the simulation tool that they adopted, while respondents F and J did not even know the name of the tool they used. Therefore, the situation of using GBS tools was not clear in this study as the respondents (F, J, and O) explained that the operators of these tools were their employees. Even so, respondent F, who adopted a wind simulation tool, mentioned the concept of the model and described that "The wind simulation model does not need to be as detailed as the 3D model in the design process." Respondent B is the only one (of the four respondents) who had experience operating a simulation tool and commented that the function of the free tool they use is very limited, and the results are rough; better tools are quite detailed and meticulous but much too expensive, so the selection is very limited.

Other respondents (C, G, J, M) who have not adopted GBS tools also explained their experience with using GBS in past projects. In their experience, they indicated that the GBS only helped to compare schemes with huge differences. For example, according to respondent C, "It just helped us simply decide whether to use vertical or horizontal shading in the project". Furthermore, some respondents (G, J, M) indicated that they were uncertain of the simulation results. Respondent M described that "They simulated the wind environment and got some results, but they could not interpret the message in the results." Furthermore, parameter input was considered a barrier when operating GBS tools. For example, respondent B stated that "The built-in material properties are usually not suitable for the subtropical climate in Taiwan." Respondent K stated that "It was difficult to input the correct parameters (e.g. wind direction and wind speed) in the wind simulation for them." The results showed that respondents seemed to be unable to flexibly operate the GBS tools as expected.

3.3.2 Barriers, challenges and driving forces of adopting GBS tools

According to the responses, the data were categorized into three groups (technological, organizational, and environmental) using an inductive approach. In the technological aspect, the data contained responses on the threshold of GBS and tools (e.g., information, knowledge, operating). In the organizational aspect, the data contained responses on organizational and managing characteristics (e.g., staffing, cost, firm size, and business type). In the environmental aspect, the data contained responses on external support and environment (e.g., force and competitive). The barriers, challenges, and driving forces were then discussed respectively.

1. Technological

In fact, correctly adopting GBS tools in the design process was viewed as “having a much higher threshold”, according to respondent C, who does not adopt any GBS tools. This view was supported by many other respondents from the technological aspect. For example, respondent K explained that “It needs the operator to have a certain degree of physical environment expertise, scientific data, and complex process to obtain accurate simulation results; however, such knowledge and data are usually not easy to learn. Respondent G supplemented that “Running GBS for visual presentations is not difficult, but getting reliable results through simulation is the key problem.” Therefore, some respondents clearly had no confidence in their simulation results (respondent G, J, M).

Furthermore, we found that many respondents were lacking information about GBS tools. For example, respondent I expressed that "They actually did not know the selection of GBS tools and cost,” which was also supported by respondents C, E, L, and P. The problem was neglected but significant, as it implied that the respondents were quite unfamiliar with GBS technology, resulting in their not knowing how to start.

2. Organizational

The reason for not using GBS tools was found to be related to the presence or absence of a relevant technical employee in the organization, according to statements like "They did not adopt because they have no technical employee" provided by respondents C, G, H, I, M, and N. Furthermore, respondent G stated "If there are relevant technical employees, maybe we will consider it (GBS) in the process," which implies that an employee with technical skills in the firm may increase their intention to use GBS tools. This possibility was also supported by the fact that respondents B and F, who adopted GBS tools, stated that they hire employees with related skills specializing in these tasks. Notably, both respondent B and respondent F come from large firms. In contrast, many respondents representing small and medium-sized firms expressed that "They cannot afford an employee specializing in green building simulation or the cost of software or consultants (respondents A, C, G, H, and L)." As shown in Table 2, the results implied that small & medium-sized organizations differ from large organizations with regard to staffing and cost.

The types of projects in an organization also seemed to influence the demand perception of respondents for GBS. In Taiwan's small residential cases, the design is usually very restricted by the condition of the site, scale, budget, and owner's requirement. Based on the scale and extent of the design, the opportunity to talk about green building or apply GBS tools was considerably lower (respondent A). Furthermore, the usefulness of GBS tools is also believed to be less since the owner generally does not request it (respondent G). This view was supported by respondents A and P, who stated that "Unless requested by the owner, these (GBS) are all additional costs." However, respondent L described that "They usually try to add some innovative ideas to public buildings that require the help of GBS." As shown in Table 3, the perception of demands on GBS differs between private projects and public projects. The results implied that larger firms that focus on public or tendering building projects are more likely to adopt GBS tools.

3. Environmental

Respondent P stated that “Unless there is a substantial and necessary usefulness for the firm (e.g., requirement of the owner or a regulation), the firm tends to not spend more on the work." Furthermore, respondent B described that "No verification and reward mechanisms are actually available for architects to actively adopt these GBS tools." These views indicated the importance of the external environment and that Taiwan has no positive external environment (e.g., requirement of owner or regulation, positive support of a software supplier) to encourage architect firms to adopt these green building practices.

Even if the environment is passive, many respondents believed that adopting GBS when a project is in a competition shows a positive trend. By using simulation tools in the competition project, the firms have an opportunity to show their distinguishing feature and specialty (respondent F). Respondent O also stated that they thought the project would be more convincing with these GBS tools. Once a firm does this, other firms follow suit. As time passes, these GBS will practically become essential elements of the competition project, according to respondent I. Therefore, many respondents that do not use these tools in their organizations (respondents E, I, L, M, and N) expressed that they usually asked consultants (from companies or academia) for GBS assistance, especially when the project was in a competition. In this case, the results showed that the demand and perception of usefulness on GBS increased along with competitiveness and promoted respondents to utilize GBS.

Tab. 2 *Different firm sizes on staffing*

Large firms	Medium-sized and small firms
▪ Hire employees with related skills ▪ Specialized employees and even departments	▪ Very streamlined manpower ▪ Without skilled employees ▪ Cannot afford specialized employees

Tab. 3 *Features of different types of projects*

Project types		Differences
Public buildings	▪ Schools ▪ Art galleries ▪ Public construction	▪ Tendering project ▪ Competitive ▪ Green design enhances performance
Private buildings	▪ Residential ▪ Commercial ▪ Factory	▪ Few requirements by owner ▪ Less discussion of green building

4 Conclusions and future work

In this study, we conducted semi-structured interviews with 16 managers from different Taiwanese architectural firms. The manuscript has described the results of our survey on green building practices and thoughts about adopting GBS tools. The results showed that although only 25% of the firms used simulation tools, almost every respondent expressed positive attitude and willingness toward their use. However, implementing these tools in design practice still faces many practical challenges and obstacles. In fact, Taiwan has no regulations or encouragement with regard to conducting green building simulation. Therefore, respondents indicated that they have to prioritize essential tasks when a project includes a lot of information that needs to be finished in a short time (respondent E). Usually, such tasks as GBS are ranked toward the end of that list (respondent H).

In this manuscript, the threshold of technology, inability to afford cost in organizations, lack of urgent requirement, and no positive external support are considered the barriers and challenges to adopting GBS tools in design practice. On the other hand, having the project in a competition is considered the main driving force for organizations to adopt simulation tools. Furthermore, according to the results, employees with related skills in organizations seem to be a shortcut. In contrast, the lack of such employees is the biggest obstacle to adopting GBS tools. We also observed a difference between small & medium-sized organizations and large organizations with regard to staffing and cost. Firms that focus on different project types (Public building/Private building) also have different requirements regarding GBS. When the project is a public building, a firm is more likely to adopt GBS.

Currently, the research results have presented some potential variables that influence managers' view and intent on adopting GBS tools, but these results are considered to be preliminary and need to be confirmed further. In future work, the research attempt is to comprehensively verified in a wider database (i.e. investigate theoretically, quantitatively, or even qualitative again) to enhance the confirmatory about variables for the purpose of developing evidence-based strategies to promote GBS tools in practice.

Acknowledgement

The authors would like to express their thanks to all the respondents who participated in the interviews and appreciate their valuable comments and feedback.

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Life Cycle Costing And Embodied Energy Analysis Of Self-Compacting In-Situ Cast Mud-Concrete Load Bearing Walling System (MCW) – An Innovative Earth Based Walling Material Application For Energy Efficient Buildings

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Abstract

The Life Cycle Costing (LCC) and the Embodied Energy (EE) of a construction material provide a useful insight on decision making regarding the choice of the most environmentally friendly product.

This study explains how the technology of in-situ cast Mud-Concrete load-bearing walling system (MCW) is optimized to save the LCC and EE in energy efficient building construction. The methods were adopted to evaluate the basic optimum production pathway and evaluate the unit cost value of Mud-Concrete wall. The results, in terms of EE of Mud-Concrete walling produced, confirm that the minimization of transportation needs and the utilization of locally available resources, formwork optimization and local labour can significantly affect the environmental footprint of Mud-Concrete production system. Finally, the results were compared to equivalent data referring to other common masonry materials (ex; brick, cement block) highlighting the eco-friendliness of the material.

Keywords: *Mud-Concrete, Life Cycle Costing, Embodied Energy, Earth-based materials, Masonry*

1 Introduction

Materials are used throughout a building's life, initially and primarily during the construction phase and consequently for maintenance or for alterations. Materials have an extensive impact on buildings ranging from the aesthetics and appeal of a building to its buildability and cost [1]. The building industry, directly or indirectly causing a significant part of the annual environmental damage, can take up the responsibility to contribute to sustainable development by finding more environmentally compassionate ways of construction and building [2], [3], [4]. One of the directions for solutions is to be found in new material applications: recycling and reuse, sustainable production of products, or use of renewable resources [4].

Soil has been recognized as a sustainable walling material thousands of years ago. Earthen architecture has been used worldwide due to its multiple advantages such as simple construction technologies, economic affordability, thermal comfortability and low embodied energy consumption [5], [6], [7], [8], [9], [10], [11], [12]. Though earthen architecture is popular due to its sustainable norms its popularity is limited due to the lack of scientific base in earthen construction comparing to the other contemporary construction technologies which exist [13].

Mud-Concrete (MC) is such a novel and sustainable construction technology which introduced through series of research process recently [14], [15], [16], [17], [18], [19]. The concept of MC is to develop a composite material similar to concrete out of soil and it is not a typical soil block that already exists. In this MC technology, sand and coarse aggregate of concrete are replaced by fine and coarse aggregates of soil. The precise gravel and sand combination governs the strength of the MC. Cement in this MC is also used as a stabilizer in very low quantities. There are two types of masonry units that could be developed through MC technology. First one is Mud-Concrete Block (MCB) [14] and the second one is in-situ cast Mud-Concrete load bearing wall (MCW) [20], [21], [22]. In this research, the focus is to discuss the self-compacting in-situ cast Mud-Concrete load-bearing walls (MCW). The best mix design of MCW was found as 45% gravel (4.75mm <gravel < 31.5mm), 50% sand (0.425mm <sand <4.75mm) and 5% fine (fine < 0.425mm) with minimum 4% cement [20]. 10% optimum water of total dry mix is used to keep the self-compacting quality of the MC material. 2400mm (width) x 1200mm (height) x 150mm (thickness) MC wall segments were developed to optimise the construction methodology in in-situ construction. Modular formwork was designed and optimised to reduce the cost and to enhance the quality of construction. After analysing the best mix design and optimum construction technology, calculating embedded energy and life-cycle cost of this novel earth based walling material is in a way stepping towards the environmental conservation as wall is the most expensive building component in a building. Also, the cost of the wall may govern the 35% of a typically affordable building in Sri Lanka. [23]. Thus the objective of this study is to understand the real value of embedded energy and total life-cycle cost of MCW and to compare with the conventional walling materials (ex: bricks and cement blocks) in the market.

2 Life Cycle Costing (LCC) of MCW

LCC can be defined as the total cost of an item through its life, including planning, design, acquisition, operations, maintenance and disposal, less any residual value [24]. The total cost of both acquiring and maintaining a building over its life is the sum of the capital cost and the accumulated sum of maintenance costs, energy costs and other recurrent costs, less any disposal value at the end:

$$LCC = Ic + (Mc + Ec + Cc + Oc) + Uc - Rv \quad (1)$$

Where, Ic – Initial cost, Mc – Maintenance costs, Ec – Energy costs, Cc- Cleaning costs, Oc – Overhead and management costs, Uc – utilization costs, Rv – Resale value.

The sixty-year life span of the affordable house was defined by using British standards. The sixty-year definition helps the research to omit unnecessary calculation. However, all the selected walling materials have the life span more than sixty years, therefore, the replacement cost of walling materials was neglected from the LCC calculation process. But necessary maintenance cost was included while calculating the total life-cycle cost of the building. The initial cost (Ic) of the basic house was calculated by using Bills of quantities considering 2017 market prices. Quantities were calculated by using technical data sheets (TDS) sheet. The quantity changes due to the change in walling material were added to BOQ. Maintenance cost (Mc) of the building calculated only for the walling material. Other maintenance works such as roof flooring etc. were omitted from the analysis in order to understand the cost changes due to walling materials. By all mean basic houses in Sri Lanka doesn't use air conditioners to cool their houses. Therefore, the energy cost (Ec) is more or less zero. But in order to understand the thermal comfort factors and the cooling load acquired by differentiating walling material, we assumed that all four types of different walling material used houses are using an air conditioner to cool their house. The energy cost of cooling loads was calculated by using Design Builder software for a period of sixty years. U-values, measure the efficiency of a walling material as an insulator for buildings. The lower the U-value, the better the walling material as a heat insulator for a tropical country [19]. For example, brick is a comparatively better heat insulator than cement block walls. Then brick U-value is lower than cement block U-value. Perhaps, the efficiency of walling materials can be easily compared by using U-value. But at the same time, the thickness of the walling materials affect on U-value. Tab. 1 shows the U-values of brick, cement blocks, MCB and MCW. Resale value (Rv) is the trade value of a building after using for a specific period. But in this case, it is sixty years. But the problem is after sixty years the basic house cannot resale. Therefore, the reusability of materials has taken into consideration. Since this is about walling materials only, resale value of walling materials were taken into final comparison.

Tab. 1 *U-values of different walling materials*

Walling Materials	U value	Thickness	Reference
Brick	2.110 W/m^2K	150mm	[25], [26],[27]
Cement Block (CB)	2.617 W/m^2K	150mm	[27], [26]
MCB	2.315 W/m^2K	150mm	[19]
MCW	2.170 W/m^2K	150mm	(Measured and tested via simulation)

2.1 LCC techniques

Several methods of calculating the LCC exists in the industrial/business sectors. The three most common LCC methods are as follows [3];

a) Simple Payback
b) Net present value (NPV)
c) Internal rate of return (IRR)

Between all three methods, the most preferred LCC technique in the construction industry is the NPV method; because simple payback is not widely used and IRR is a more comprehensive procedure [3]. NPV is defined as the sum of money that needs to be invested today to meet all future financial requirements as they arise throughout the life of an investment.

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \quad (2)$$

Where C_t is the estimated cost in year t, r is the discount rate and T is the period of analysis in years.

The above equation makes allowance for interest receivable on the sum invested. In reality, the value of our investment will be eroded by the pernicious effects of inflation. Therefore, the above formula needs to be modified by a factor which will take account of inflation. Inflation will increase the costs at year n and therefore increase the present day investment level. The modified factor is known as "net of inflation discount rate" (NDR):

$$NDR = \frac{1+int\%}{1+inf\%} - 1 \quad (3)$$

Where, int. % is the interest rate and inf. % is the inflation rate.

2.2 Real scale work study of calculating the unit cost MCW material

In this study, 16'-0" (4876.8mm) x 16'-0" (4876.8mm) room with a one single sash 7' (2133.6m) x 3' (914.4mm) door and a one 4'(1219.2mm)) x 4'(1219.2mm) window(double sash) has been built up to see the needed optimum number of labour within a practical time frame. Fig. 1 explain the manufacturing framework of MCW and how the number of labourers was optimized using the process of the manufacturing framework of MCW. Four labourers were used to cast the MC walls of this 16'-0"x16'-0' room using two sets of formworks. Optimum lifting height of a MC wall segment is 4'-0" (1200mm) and 0'-6" (150mm) thickness. In two steps 8'-0" height (2400mm) wall can be cast using the lifting formwork within two days. After 24 hours of casting, formwork can be dismantled and curing should be started soon after removing the formwork. This real scale work study has been used to calculate the rate per sq.ft value of MCW. Tab. 2 demonstrates how the material and labour cost values were added to calculate the unit cost of MCW. Thus the unit cost value of MCW is approximately LKR. 60 (USD 0.3) per square feet.

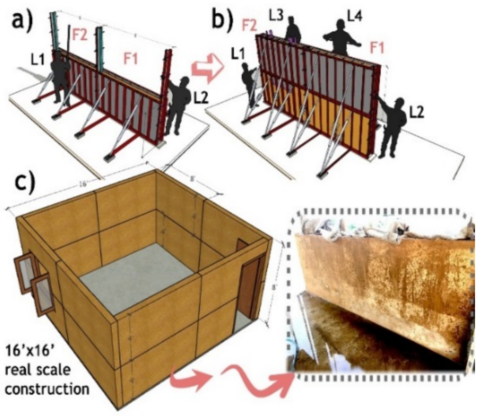


Fig. 1 *a) Step one; Formwork (F) assembling for 16'-0" length and 4'-0" height. b) Step two; bottom formwork dissembling and assembling the top formwork. 02 nos. of labour (L) required for formwork assembling and 02 labour (L) was required for mixing and pouring the MC mix.*

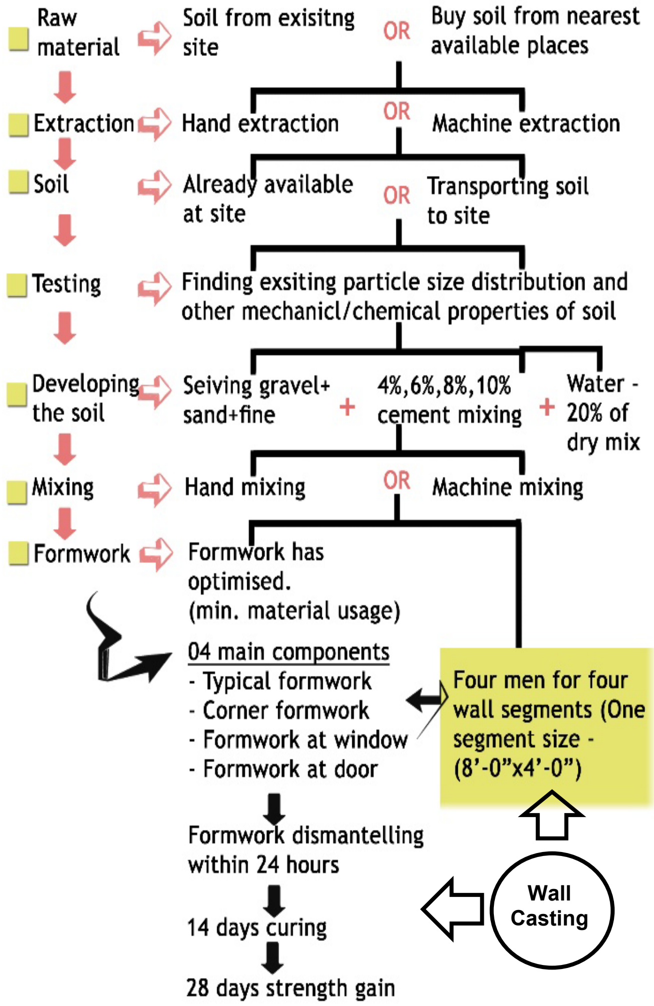


Fig. 2 *Manufacturing framework of in-situ cast MC wall (Seven stages)*

Tab. 2 *Work study to calculate the Mud-Concrete walling cost per sq.ft*

Item	**Description**	**Amount (LKR)**	**Amount (USD)**
Material Cost	Formwork	7.18	0.04
	Mud-Concrete Mix	29.60	0.16
	Mould oil	0.50	0.0028
	Wall Curing	0.05	0.00028
Labour Cost	Formwork erecting	13.92	0.077
	Wall Casting	9.60	0.053
	Wall Curing	0.59	0.0033
Total Cost per sq.ft		**61.43**	**0.33638**

2.3 Selecting a basic house model for LCC calculation and energy accounting

The Ministry of Housing & Samurdhi in Sri Lanka has launched a hundred-day programme to develop hundred and fifty thousand houses in the country. Most of these house designs are built all over the country [2]. These basic house models were given to poor locals by the Sri Lankan government as a manual of building their own house. The house manual was given to the general public with a costing sheet and a material sheet. The house design was published by the national housing development authority and Samurdhi division [2]. The basic home is built on levelled land and it consists of 500 Sq.

ft (46.4 m^2) of floor area, two bedrooms with open plan living and dine together, separate bathroom and shower. In addition, it consists 10 lights, seven power units, and three fans. Fig. 3 shows the plan view of selected basic house model. Bill of quantities was prepared to understand the total initial construction cost of the selected houses with selected walling materials.

Fig. 5 shows the total construction cost vs. walling cost of selected basic house model. It was clear that MCW material gives the least construction cost among the selected walling materials. Then the selected basic house model was modeled on Design Builder V5 software (Fig. 4) to calculate the cooling loads (Fig.6) and through that energy cost was calculated. Every item of the BOQ was calculated up to the recommended years of LCC and final maintenance cost was calculated. Then the sum of the initial cost, the maintenance cost, resale value, energy cost and overheads of the each item were calculated to find the 60 years period of LCC of walling materials (Fig. 7, Tab. 3 and Tab. 4.) The reusability was considered basically after calculating the total life span of the building material. Not only for the walling materials but also for the other building elements, the life span was measured accordingly to calculate the total reusability of the building. It was assumed that the total lifespan of the building is sixty years and more than sixty-year life span building materials were multiplied by the reusability factor. However, the reusability was measured only for the similar usage in the future. The other alternative reuses or recycle were omitted because of their complexity in alternative reuses.

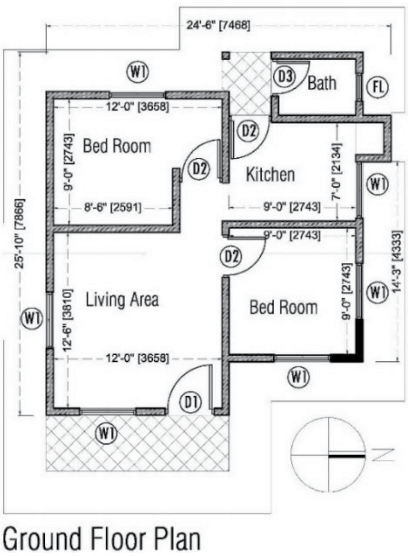


Fig. 3 *Selected basic house model*

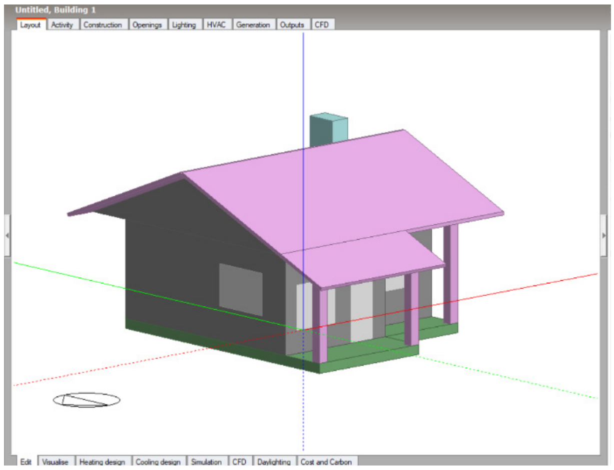


Fig. 4 *Modelled the basic house design on Design Builder software to calculate the cooling loads with different walling materials*

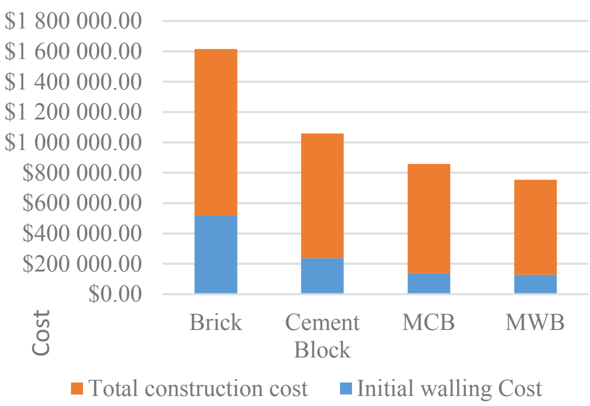


Fig. 5 *Total initial construction cost vs. walling cost*

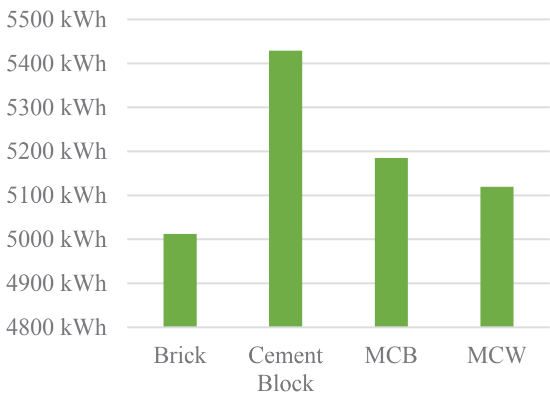


Fig. 6 *Cooling load calculation for 60 year*

Tab. 3 *Calculating initial cost and resale value of different walling materials*

NPV as of January 2017 – Interest rate 8.0%					
Item & life span	Description	Brick	Cement block	MCB	MCW
Wall (Square feet 1460) >60 years	Initial walling Cost ($)	2810.3	1292.5	745.3	693.6
	Reusability factor	60%	70%	92%	96%
	Resale value ($)	1423.6	904.7	685.6	665.9

Tab. 4 *Life cycle costing of 60 years in different walling materials*

	Brick	Cement Block	MCB	MCW
Basic House model with different walling materials				
Total initial cost ($)	6001.9	4484.0	3936.8	3885.2
Total energy cost ($)	480.1	16659.0	15910.3	15710.9
Over heads ($)	480.1	358.7	314.9	310.8
Life cycle cost ($)	23266.6	22903.8	21564.1	20560.2

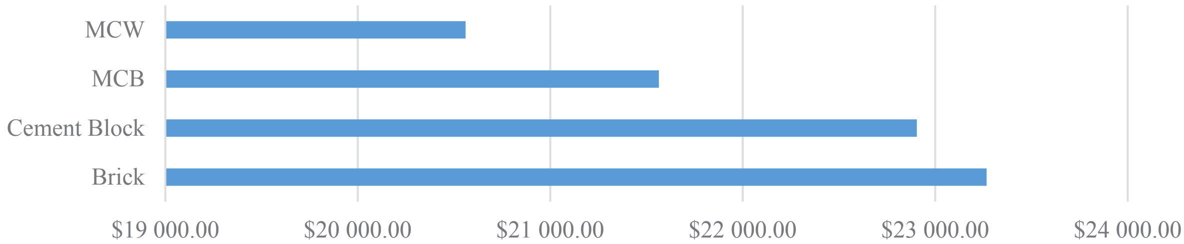


Fig. 7 *Life cycle cost of different walling materials (for 60 years) NPV as of 1st Jan 2017*

3 Embodied Energy (EE) of MCW

The total energy for material at a given level becomes the embodied energy of the raw material, at next higher level. Apart from the items specialized in the BSR the data required to estimate the embodied energies are collected from building material manufacturers, contractors and merchants. Only three forms of energy are considered [3]:

a) Level one: Energy embodied in raw materials;
b) Level two: Transport energy for raw materials and finished products;
c) Level three: Energy in construction.

Same basic house model and the calculated data used in LCC were used to calculate the Embodied Energy (EE) of MCW. In addition, a comparison study was done for brick, cement block, Mud-Concrete block (MCB) with self-compacting in-situ cast Mud-Concrete load-bearing (MCW) walls. Thus the EE calculation was done at different levels.150mm (0'-6") thick, 3m (10'-0") x 3m (10'-0") walls were considered in EE calculations. Embodied energy in selected walling materials were calculated without the internal and external plasterwork. Plastering work was calculated separately to understand the materials contribution to the total embodied energy of the house. And it was assumed that all the walling material were constructed with a similar smooth finish. In addition, stretcher bond was used to build all three types of walls excluding MCW. It was assumed that all the labour was available within the site. The mortar was mixed at the same place where the brick wall was being built. Tab. 5 shows the energy consumed to build a hundred square feet wall of MCW. In addition, energy consumption of the machines was given in Tab. 6.

***Tab. 5** Energy consumed to build a hundred square feet MCW – an example of EE measuring method*

	The material requirement for 100 square feet wall							
Requirement	Area (sq.ft)	Soil (m^3)	Mortar (m^3)	Cement (kg)	Cement 50kg Bags	Sand (Kg)	Sand 40kg Bags	Water (L)
	100	10.5	0.00	114	3	0	0	6
Distance	Transport distance							
	Manufacturing (Level 01)		Transporting to the site (Level 2)			Construction of one square wall (level 3)		
	Soil	Water	MCW	Cement	Sand	MCW	Labour	Mortar
	20.0km	0.15km	0.00km	152.0km	0.0km	0.0km	0.0km	0.0km
Method	Soil	Water	MCW	Cement	Sand	MCW	Labour	Mortar
	01 tractor	100Pm	0 Lorry	01 Lorry	01 Lorry	0 Wheel Barrow	On site	0 Wheel Barrow

Level one (01)	Level one (Manufacturing MCW)				
	Raw material	Biomass	Fossil fuel	Electricity	Total Energy
	Soil	0.00 kg	2.07 Litr	0.00 MWh	74.3122 MJ
	Cement	0.00 kg	19.00 Litr	0.00 MWh	682.1000 MJ
	Water	0.00 kg	0.00 Litr	0.20 MWh	720.1296 MJ
	Molding	0.00 kg	2.00 Litr	0.000 MWh	72 MJ
	Total energy for MCW production				1548.34179 MJ
Level two (02)	Level two (Transporting material to the site)				
	Method	Biomass	Fossil fuel	Electricity	Total Energy
	Uploading	0.00 kg	0.00 Litr	0.00 MWh	0 MJ
	Transporting	0.00 kg	0.00 Litr	0.00 MWh	0 MJ
	Unloading	0.00 kg	0.00 Litr	0.00 MWh	0 MJ
	Cement (for mortar)	0.00 kg	0.00 Litr	0.00 MWh	0 MJ
	Sand (for mortar)	0.00 kg	0.00 Litr	0.00 MWh	0 MJ
	Total energy after producing and transporting materials to the site				1548.34179 MJ
Level three (03)	Level three (Construction of one square MCW wall)				
	Method	Biomass	Fossil fuel	Electricity	Total Energy
	Masonry	0.00kg	0.00Litr	0.00 MWh	0 MJ
	Mortar mixing	0.00kg	0.00Litr	0.00 MWh	0 MJ
	Constructing	0.00kg	0.00Litr	0.00 MWh	0 MJ
	Total energy for construct hundred square feet MCW				1548.34179 MJ

Several assumptions were considered for brick, cement blocks, MCB and MCW production. Such as soil extraction was done using human labour. It was considered the block making factory is 500m away from the construction site for brick, cement blocks and MCB. In MCW technology soil is directly transported to the site because it is in-situ cast system and there is no transport cost form the factory to site. But it was considered the bricks, cement blocks and MCB were transported to the site by a lorry. Water was collected from a well 150m away using an electric pump (125 litres per minutes). Mould oil was used as a separator for formwork of MCB and MCW. It was considered as mortar was mixed at the same place where the brick and block wall are being built. Also, mortar mixing were done using human labour; no machinery was used whatsoever while building the brick and block walls. But there is no necessity of using mortar in MCW construction as wall segments can be joint using a tongue and groove joint or dowel bars.

Tab. 6 *Energy consumption of machines*

Description	Bricks	Cement blocks	MCB	MCW
Blocks per 100 sq.ft of single skin wall 225mm	1150	80	302	Not applicable
Wheel barrow volume (l)	65	65	65	Not applicable
Weight of cement bag	50	50	50	50
Volume of bag of cement (l)	33	33	33	33
Volume of mortar per brick laid	0.00034	0.00034	0.00034	Not applicable
Cement bags per cubic meter of class I mortar	9.5	9.5	9.5	Not applicable
Volume of sand per cubic meter of class I mortar	1.23	1.23	1.23	Not applicable
Weight of 40 kg sand bag	30	30	30	Not applicable
Liters in a cubic meter	1000	1000	1000	Not applicable
Joint width on block work	10mm	10mm	10mm	Not applicable

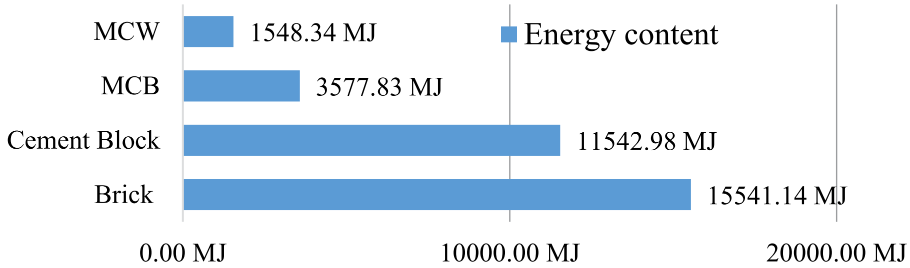
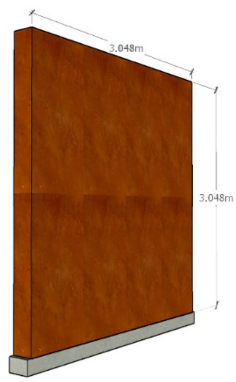


Fig. 8 *Energy content of building hundred square feet wall from different walling materials*



10’-0” x 10’-0” MCW

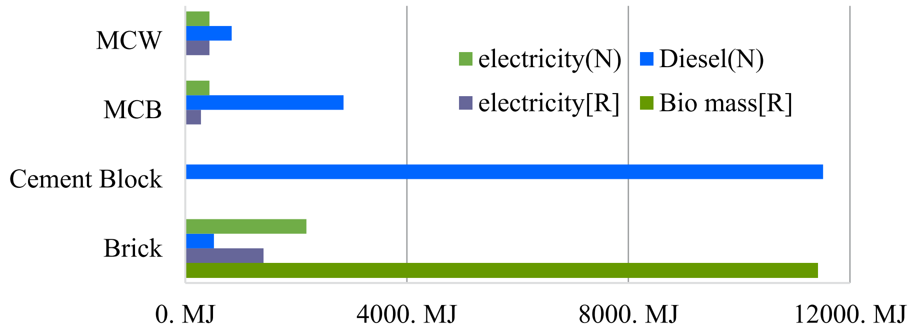


Fig. 9 *Comparison of the energy content of different materials (calculating energy source and energy type)*

MCW has lesser embedded energy comparing to brick, cement blocks and MCB (Fig. 8 and Fig. 9). Because MCW is a self-compacting, in-situ cast, quick construction walling method. MCW can be made by soil extracted from a location near the site and no burning energy cost is added. All its highest energy content purely comes due to the embedded energy cost of cement production. But in MCW only for 4% cement is used as the total raw material cost. Though MCB is also produced using similar material the LCC and EE differ due to the followed construction technology. In MCB production transportation cost and the labour cost is high than the in-situ method of MCW. Hence, the production of MCW and construction of MCW wall has lesser energy consumption comparing to brick, cement block and MCB.

4 Conclusion

This paper examines the LCC and EE of MCW and other conventional material available in the market such as bricks and cement blocks. In addition, MCW (in-situ cast walls) system was compared with MCB (blocks) system to see the difference and advantages of the developed system of MCW. Considering all the scales given to measure the suitability of different walling materials such as embedded energy, initial cost, operation cost and Life cycle cost; MCW is the best walling materials to build affordable houses. When comparing the cooling load calculation cement block is the worst material for tropical condition. The brick wall has the highest energy content. Brick contain highest embodied energy due to its burning process. Cement block wall and MCB show intermediate energy consumption. But MCB has less energy consumption than cement blocks as cement block made of quarry dust which need a lot more non-renewable energy to produce. The MCW has comparatively lowest embedded energy content due to its self-compacting methods, in-situ construction and less-labour usage in the construction process (due to optimised formwork system). Not only that MCW is 96% reusable, its ingredient can be crushed and reused to produce same walling material with an addition of cement ratio of 4%. Therefore, overall the MCW is one of the best alternative building materials to suit tropical climate condition like Sri Lanka. However, this will depend on the raw material availability of the context.

Acknowledgement

The authors would like to acknowledge the support provided by D.M.H.C.Bandara, T.D. Bebilegedara, and K.A.K.Pathirana during the experimental campaign. This research has been carried out with the financial support of the grant RG/2015/EA & ICT /02 from National Science Foundation (NSF), Sri Lanka.

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Assessment of the Critical Parameters on Hygro-Thermal Performance of Timber Structures' Envelope

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Abstract

Hygro-thermal performance of timber structures due to the sensitivity of wood to ambient conditions is a critical issue. Reducing the condensation risk and mold growth potential are important parameters which should be considered in the design of building envelopes. This study investigates how different parameters can affect the hygro-thermal performance of recent standard timber structures in Germany. Different types of assemblies of lightweight wooden frames or panels, as well as cross-laminated timber structures under long-term European outdoor climate changes regarding global warming, have been taken into account. Effect of several kinds of façade, wood and insulation materials, with different arrangement in assemblies, have been analyzed. Numerical simulations with coupled heat, air and moisture (HAM) transfer method are conducted to evaluate the hygro-thermal performance of walls with several parameter-combinations. Finally, the study makes comparisons between the effective parameters on the moisture content of different layers in order to specify the critical conditions.

Keywords: *Coupled heat and moisture transfer, Humidity control, Timber building envelope*

1 Introduction

Many researches has been done, but no standardized methodology for dynamic moisture design and hygro-thermal loads exist yet. Determining all effective parameters to reach an optimum hygro-thermal design of a building is still an ongoing process [1]. There are hundreds of assemblies that can fulfill regulations requirement, but do they work properly during their service life? The problem is building envelopes are designed based on recent climatic condition but climate transitions due to phenomenon like global warming will change the boundary condition, therefore an assembly which has no hygro-thermal problem under the recent outdoor conditions, may encounter moisture problem and mold or decay growth under climate changes after 50 or 100 years.

There are many parameters influence the hygro-thermal behavior of structures. J. Vinha [2] categorized performance of timber structure's envelopes, which have been reported from 1980 to the first years of the 21st century in the literature, to find main reasons lead to moisture problems. Künzel [3] pointed out that the influence of the exterior and interior climate conditions on the results of hygro-thermal simulations is comparable to the influence of the material property variation. The aim of this study is to do a sensitivity analysis on different timber structures' envelope under same boundary condition; in this case, wall configuration, type of material used for them and the initial condition of the materials, play the most important roles. Each of these parameters has been partially investigated under specific conditions by many authors, but not under same long-term boundary condition to find the optimum or critical configurations of envelopes.

Building envelopes, regarding new versions of regulations, are becoming more and more energy efficient, especially in Europe; therefore, assemblies of the new buildings are tighter and are designed with thicker insulation layers and materials with low thermal conductivities. European external walls, generally are open to moisture entrance and their critical situations regarding moisture problems, are dependent on various factors. Main effective parameters related to material properties depend on, thermal resistance of wind barriers [4], water vapor permeability of vapor barriers [5, 6] and moisture capacity of the insulation layers [7]. Furthermore, low heat flow in new assemblies because of thick their insulation layer, prolongs drying-out process in cases that internal materials have high initial moisture content [8].

Assemblies' configuration also has an important effect on hygro-thermal performance of the envelope. Well-functioning air layers under cladding can control moisture by preventing the moisture entrance from driving rain to the wall assembly and to allow extra moisture to escape from the assembly [9]. Location of insulation as an internal external layers effect on overall air tightness and vapor permeability of the assemblies [10]. Critical points in assemblies with and without vapor barriers depends on the type of insulation material as well as outdoor and indoor boundary conditions [7].

In this study the main goal is assessing the efficiency of different parameters on hygro-thermal performance of building envelope by means of numerical simulation. Type and quantity of these impressions will be analysed to improve durability and sustainability of building envelopes throughout their service life (100 years) with considering effect of climate changes by the end of 21st century.

2 Methodology

2.1 Boundary conditions

In numerical simulation based on coupled heat and moisture transfer, outdoor and indoor climate, as well as the initial condition of the materials, are considered as boundary conditions. In this study, future predicted climate conditions of Germany for 100 years from 2001 to 2100 has been taken into account. The reason for considering this condition is to investigate the hygro-thermal performance of each layer of the envelopes with changes of climate condition until the end of the century.

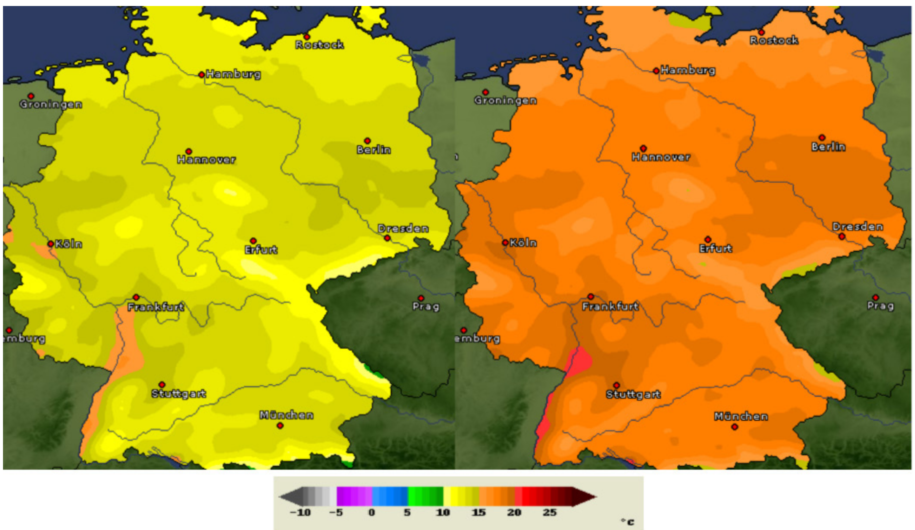

Fig. 1 *A comparison between temperature in Germany during the first (left) and last (right) decade of 21st century [12]*

Significant increase in the temperature is one of the main consequences of global warming which has been verified by multiple climate prediction programs [11]. Climate data is extracted from the database provided by the German climate computing center (DKRZ). In this study, daily average climate data from Remo, as a regional climate model for Germany has been taken into account.

Figure (**Fig. 1**) represented in the regional-climatic atlas of Germany [12], indicates the amount of temperature increase in different part of Germany between first and last decade of the 21st century. Interpretation of predicted climate data doesn't show significant changes in the amount of relative humidity in different parts of Germany. Therefore, risk of mould growth will increase with raise in temperature. Frankfurt climate data which is located in the region with maximum temperature increase by the end of century has been considered as outdoor climate condition. One hundred years of daily average temperature and relative humidity of Frankfurt have been applied as outdoor condition in numerical simulations.

Indoor climate is defined as a sinusoidal function with low amplitude around 20°C temperature and 55% relative humidity. The initial condition of the materials is considered as 20°C temperature and 70% relative humidity.

2.2 Wall configuration

Different types of buildings in Germany have been categorization in the Tabula project [13]. The first series of regulations regarding energy efficiency of building goes to 1979-1983; maximum allowable thermal transmittance (known as U or R-value) in this period is equal to 0.8 [W/m^2.K]. Recent regulations are getting more and more restricted; maximum allowable thermal transmittance after 2010 is equal to 0.3 [W/m^2.K] which should be decreased to minimum 0.12 [W/m^2.K] for passive structures.

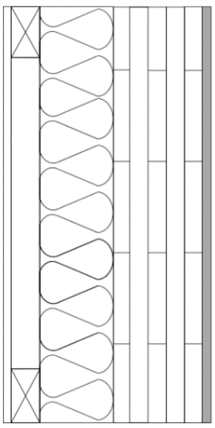

Fig. 2 *Wall type 1*

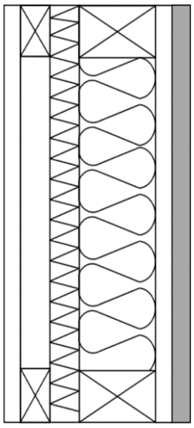

Fig. 3 *Wall type 2*

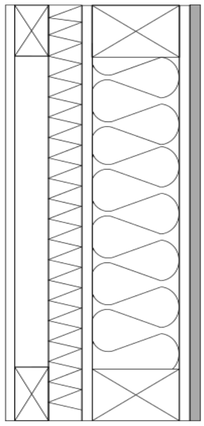

Fig. 4 *Wall type 3*

Tab. 1 *Material and thickness of layers in wall types 1, 2 & 3*

Assembly layers	Wall type 1	Wall type 2	Wall type 3
Facade	Larch-20mm	Larch-20 mm	Larch-20 mm
Furring strips	Pine-30mm	Pine-30 mm	Pine-30 mm
External insulation	Wood fibre-180mm	Wood fibre-60 mm	Wood fibre-60 mm
Structural framing	CLT-Spruce-100mm	Spruce-60x200 mm Wood fibre insu.-200 mm Sheathing-chipboard-15 mm	Sheathing-chipboard-15 mm Spruce-60x200 mm Wood fiber insu.-200 mm Sheathing-chipboard-15 mm
Interior finishing	Plaster board-12.5 mm	Plaster board-12.5 mm	Plaster board-12.5 mm

There are three common types of assemblies for timber structures, which are being constructed in Germany: solid timber, wooden frame and wooden panel structures (**Fig. 2, Fig. 3** & **Fig. 4**). Three reference wall assemblies are defined with U-value between 0.3 and 0.12 [W/m^2.K]; the material considered for each layer and their thickness is displayed in (**Tab. 1**). Material properties used in the calculation models were chosen from the WUFI material database.

2.3 Sensitive analysis

There are many uncertainties in this research; some of them can be determined by parametric analysis to find optimum combinations and some others should be covered by safety factors. For sure there is no certainty for the predicted climate data, especially over a hundred year period. There is no accuracy in the definition of material properties and their degradation rate due to aging. Human errors during construction is another inevitable problem. Numerical simulations have also limitations which makes uncertainty in the results. These are problems that, there is no way to estimate them accurately, therefore a safety factor should be considered during the design of building envelopes. On the other hand, there are some parameters such as wall configuration, material type and thickness of each layer in the assembly, which has direct effect on hygro-thermal performance of envelope. Each of these parameters and combination of them can be studied for determination of optimum configurations.

Despite all restrictions, numerical simulation is the most reasonable and reliable tool, especially in the cases that there is no opportunity for experimental tests. The heat, air, and moisture transfer method (HAM) is the basis of all numerical simulation software which analyzes the hygro-thermal performance of multi-layer building envelopes. In this study, finite volume based program called WUFI® Pro have been used to make a comprehensive dynamic transient hygro-thermal analysis of structural assemblies. The predictions of the models in this software were in good agreement with the experimental tests data, which has been confirmed in various articles [14, 15], therefore this software has been used to assess moisture risk and hygro-thermal analyzes of building envelopes.

Different effective parameters that have been mentioned in the literatures, have been studied in the sensitivity analyses. Boundary conditions have remained constant and effect of parameter changes regarding material type, assembly configuration and the initial condition of layers have been investigated. Worst case, as well as optimum case, will be defined based on the results.

3 Parameter analysis and discussion

In order to achieve the main objective of the research, it is necessary to investigate the general trend in long-term hygrothermal performance of each layer in the reference envelopes and determination of their critical interfaces. Then effect of different parameters will be analyzed in the critical points.

Frankfurt climate data for 100 years is applied to all three reference wall assemblies. Since moisture accumulation occurs in the interface of materials with different densifications, the interfaces between insulation layers and wooden or sheathing elements are in the highest moisture level. Furthermore, with temperature increase by the end of the century, amount of moisture content will increase in structural elements and amount of relative humidity in the interface between external insulation and wooden elements or sheathings show an increasing trend. In general, the most critical moisture problems may happen in the second half of the 21^{st} century.

The possibility of mold growth in reference envelopes has been investigated by an additional program for WUFI called Mould-Index. The software developed according to the researches have been done by Viitanen [16] with Fraunhofer- IBP (Institute of Building Physics) cooperation. Results show that onset of mold growth will be after 2050 and its rate will increase over time, but in general it will stay in microscopic level. Consequently, any parameter which increases the amount of relative humidity in critical interfaces can increase rate of mold growth to macroscopic and even degradation levels. In the next parts range of relative humidity changes will be calculated in critical locations with considering different parameters and results will be compared with reference envelopes' performance; when a parameter increases maximum relative humidity in critical points, it means that rate of mold growth will increase, too. For illustration of results, box graphs used to show variation of results including: minimum and maximum values and statistical distribution of data between 25% and 75% with considering outliners (plotted as individual points).

3.1 Effect of insulation material

Effect of four common insulation material including wood fiber, mineral wool, polystyrene, and cellulose have been considered in the simulations. Considering the fact that density of insulation materials affect their thermal resistance performance and vapor permeability, material properties of standard insulation plates which commonly applied in practice, considered in simulations. Figure (**Fig. 5**) indicates the range of relative humidity changes of the interface between wooden elements and external insulation layers during the whole 100 years.

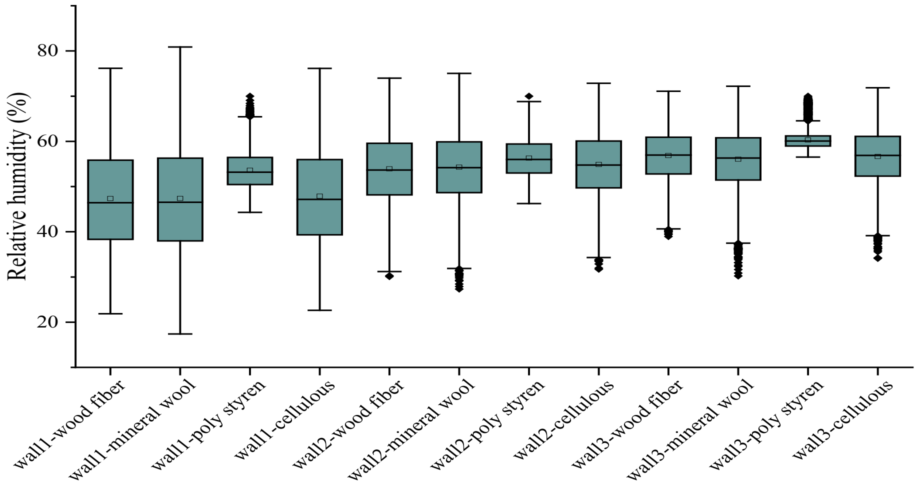

Fig. 5 *Relative humidity of the interface between external insulation and structural element – effect of different insulation materials*

Results indicate that using mineral wool as insulation material cause significant increase in the range of relative humidity on the interface between insulation and wooden elements in comparison with reference material which is wood fiber insulation; cellulose material perform more or less as wood fiber insulation without remarkable differences. Polystyrene has the best performance with significant reduction of maximum relative humidity in summers but on the other hand, it will increase minimum relative humidity in winter, which means it won't let internal layers to dry out as fast as the other insulation types. It should be mentioned that relative humidity of all assemblies in this location reach their maximum values after 2050. In general, these results follows that higher air permeability levels of insulation material, correspond to higher relative humidity in their internal interface, which leads to increase the rate of mold growth. Temperature raise by the time, increases amount of natural convection inside the component, resulting in a higher moisture ingress.

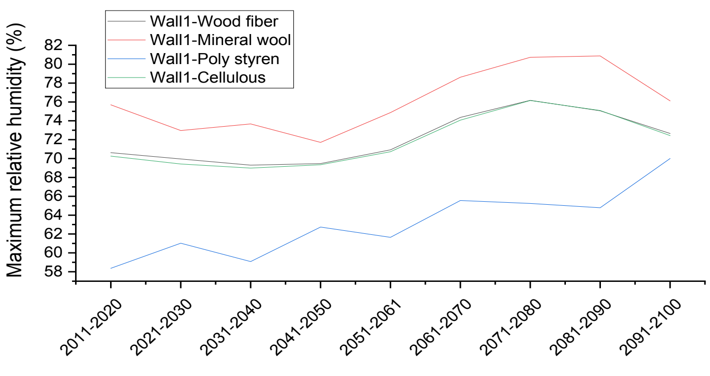

Fig. 6 *Maximum Relative humidity in each decade in the interface between external insulation and structural element – effect of different insulation material*

Figure (**Fig. 6**) make a closer look on the effect of insulation materials on maximum relative humidity of structural elements during the decades (results are shown just for wall type 1).

There is an important issue that should be considered in this case; due to the gaps between insulation plates, initial high moisture content of building materials and human errors during construction or operation of the building, moisture may accumulate in internal layers of envelope; therefore, rate of drying out process become an important parameter for avoiding moisture problems. Figure (**Fig. 7**) indicates result of simulation in the case wooden structural element has initial moisture content of 30%. Drying out process will take more than 8 years when external insulation is made out of polystyrene but using other types of insulations decrease this period to around 4 to 5 years.

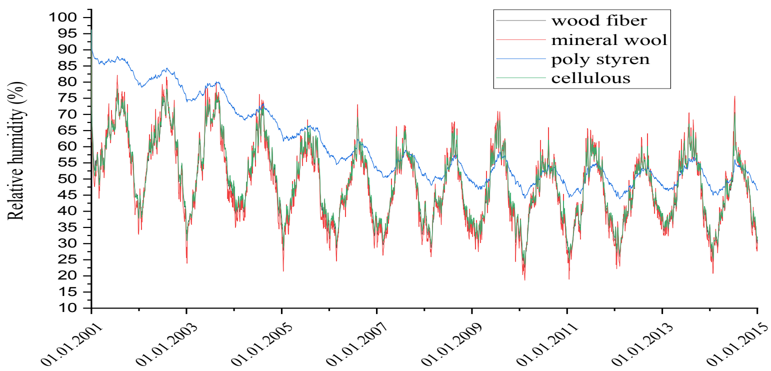

Fig. 7 *Drying out process of structural element with different external insulations - wall type1*

Using Polystyrene can increase the drying out period double in comparison with application of wood fiber or cellulose as external insulation.

3.2 Effect of wooden material

Nowadays, wooden products made out of different species. In Germany, spruce and pine woods are the most common ones in the construction industry. Beside spruce and pine, effect of beech wood as a hardwood which is increasingly used in timber engineering, is also taken into account. According to the result of simulation shown in figure (**Fig. 8**), structural elements made out of spruce has the highest relative humidity on their external surface. But, in wood panel assemblies, type of wood doesn't have remarkable effect on hygro-thermal performance of the envelope, in these type of structures type of material used for panel sheathing has the most critical role.

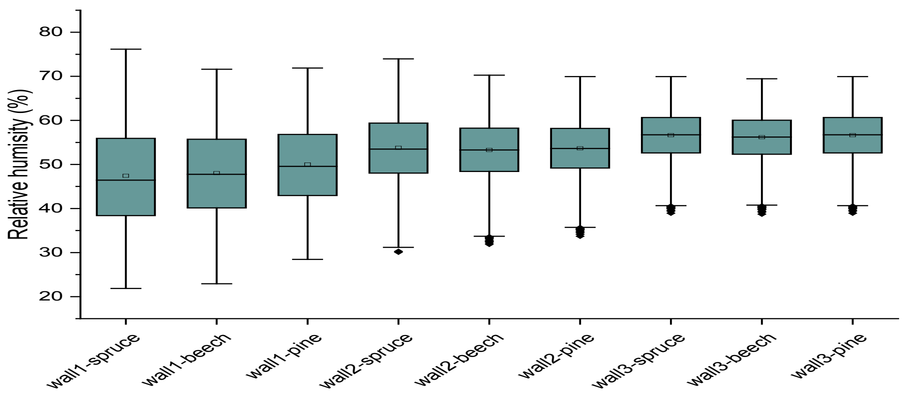

Fig. 8 *Effect of different wood species on relative humidity of structural elements*

Different types of materials such as chipboard, MDF and OSB used for sheathing prefabricated panels. Each of these boards produced in different densities and with different vapor permeability. In the result of simulations, the interface between insulation layer inside the panel with external sheathing layer is the location of maximum moisture accumulation. Considering Figure (**Fig. 9**), maximum amount of relative humidity in this location is higher in the first half of the century and it will decrease by the time. This value is related to vapor diffusion resistance factor of the sheathing material (**Fig. 10**), when the board has lower vapor permeability, amount of moisture accumulation will increase. However, since maximum amount of relative humidity happen in wintertime, which temperature is low, there won't be any mold problem. In general, it is recommended to use vapor barrier next to the internal sheathing, preferably inside the panel; it can avoid moisture entrance to internal layers. It is also suggested to use two different materials for internal and external sheathing of the panels in a way that the material with higher vapor permeability applied to external layer to help faster drying out during summer, and use the material with lower vapor permeability for internal layer, for making it tighter and avoid water and vapor entrance to internal layers.

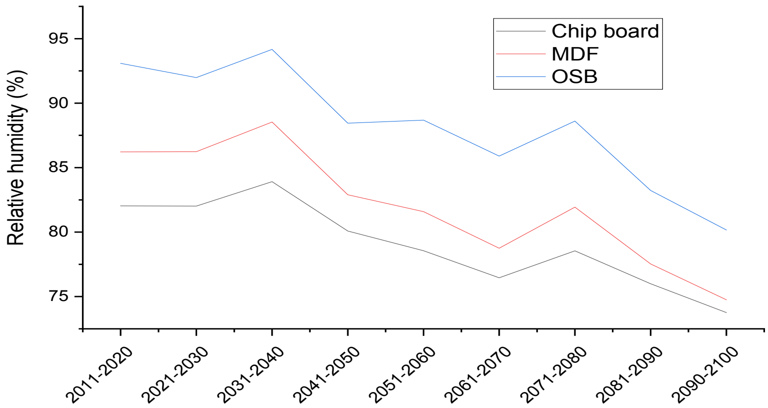

Fig. 9 *Maximum Relative humidity of each decade in the interface between external sheathing of panel and internal insulation layer - with different sheathing material – wall type 3*

The type of insulation used inside panels has significant effect of relative humidity not only on the internal interface between insulation and sheathing but also on the relative humidity of external insulation layer. Polystyrene indicates the best performance in comparison with other materials (**Fig. 11**).

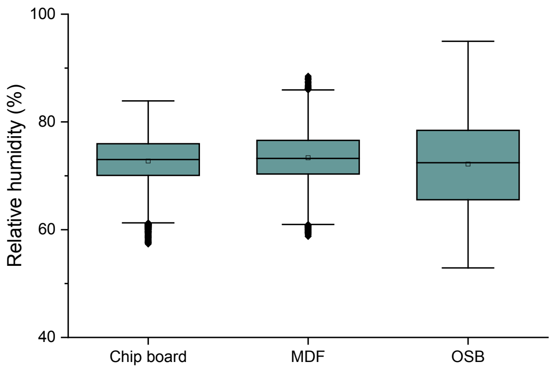

Fig. 10 *Effect of sheathing material on relative humidity in the interface between external sheathing and insulation*

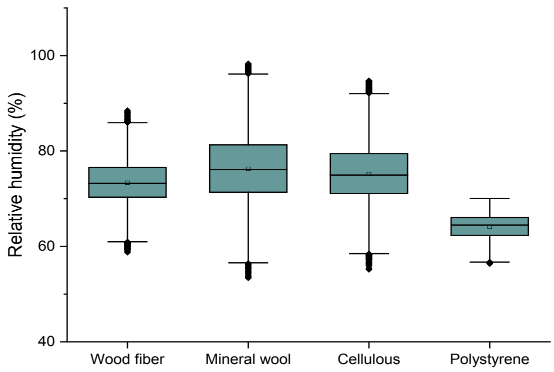

Fig. 11 *Effect of insulation material on relative humidity in the interface between external sheathing and insulation*

Air barriers control air flow into and out of the building envelope. Air barrier systems can be located anywhere in the building enclosure. In cold climates, interior air barrier systems control the exfiltration of interior. Whereas exterior air barrier systems control the infiltration of exterior air and prevent wind going through cavity insulation systems. Since, simulation done with this assumption that assemblies are tight and there is no way for air flow between them, effect of air barriers haven't been considered in this study.

3.3 Effect of ventilation rate of façade and façade material

Back ventilating the exterior finishing layers of external wall assemblies is to prevent entrance of fluid water because of driving rain into the wall and to dry out the excess moisture inside the envelope. Two important factors should be considered for the air layers used behind façade; their ventilation rate and water and/or vapor permeability of the material used for façade.

Researches based on fluid mechanic [17] show that vent size and cavity depth highly influence ventilation rate under the façades. On the other hand some barriers like trees in front of structures can decrease ventilation rate of air layers. Künzel [18] studies show that ventilation rate can change between 10 to 200 1/h in the air layers. Results of Figure (**Fig. 12**) is related to the range of relative humidity in the outer layer of structural elements with considering low (10 1/h) and high (200 1/h) ventilation rate in the air layers behind the façade. Simulation results show that high ventilation rate in air layer leads to moisture content increase in the external surface of structural elements. It should be one more time mentioned here that just temperature and relative humidity applied as outdoor climate condition; air layer behind façade and their ventilation rate is more affected by other weather characteristics like precipitation and solar radiation which haven't considered in this study.

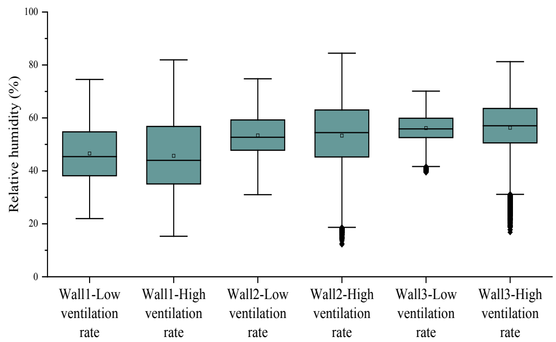

***Fig. 12** Effect of ventilation rate in the air layer behind Façade on outer layer of structural elements*

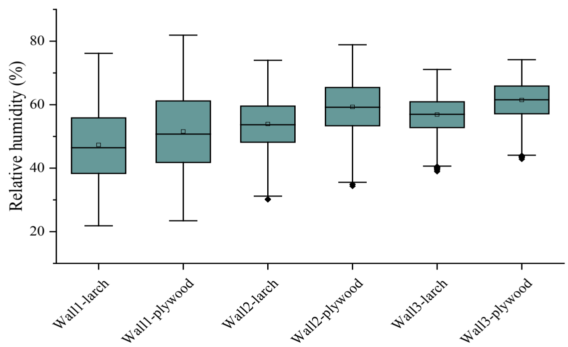

***Fig. 13** Effect of façade material on outer layer of structural elements*

For facades which have been made out of wooden materials, because of their high vapor permeability, ventilated air layers are always under the cladding. Effect of Larch and plywood as two common façade material has been evaluated by simulation. Results indicate (**Fig. 13**) that using plywood for façade leads to higher moisture content on the external surface of structural element in comparison with using larch wood for cladding.

4 Conclusions

This study is part of a project for investigating effect of future climate condition changes on timber structures being constructed based on recent building physics regulations in Germany. Hundred years of outdoor climate data (21st century) applied on different external wall assemblies; effect of different wall configurations and the material used for them analyzed with aid of numerical simulations. Since moisture-induced damage is one of the major causes of degradations and reduces thermal performance in wood frame buildings, the focus of the study is on moisture problems and probability of mold growth in the envelopes. Frankfurt climate data is decided to be used as outdoor climate data because Frankfurt is one of the main cities in Germany which located in a region with highest temperature increase by the end of the century. The major effect of outdoor temperature increase is on structural elements; because most of building envelopes in Germany is open for vapor entrance, with temperature increase, vapor drives into the assembly and increases the moisture content of structural elements. Result of analyses show that, in the second half of the century there will be mold growth risk with low rate in mentioned reference walls. Other effective parameters which can increase amount of moisture content in structural elements have been studied and briefly summarized below:

- Using Polystyrene as insulation layer because of its low vapor permeability decreases amount of moisture content remarkably in structural elements. In contrast mineral wool increases mold growth rate significantly. Wood fiber and Cellulous materials have similar effect on hygro-thermal performance of the envelopes.
- Drying-out process in cases that moisture goes into the assembly, because of any leakage, is an important issue. This process will take too long if polystyrene is used as insulation. In this regard, using wood fiber or cellulose can be more conservative.
- In structural elements made out of spruce, amount of maximum relative humidity is higher than structural elements made out of beech or pine wood. In wood-panel assemblies, type of wood used for frame doesn't have significant effect on hygro-thermal performance of the envelope.
- In wood-panel assemblies, it is recommended to use a material with low vapor resistance as external sheathing (helps faster drying out process) and a material with high vapor resistance as internal sheathing (increase internal tightness).
- Vapor barriers are highly recommended in wood frame and wood panels, especially when mineral wool is used as insulation between frames prevents moisture entrance inside home.
- Ventilation rate of air layers behind facade should be taken into account more precisely, especially when a material with high vapor permeability used as façade.

Acknowledgement

Presented results in this paper obtained within the 'Holzstrategie' project funded by the Federal ministry of food and agriculture in Germany. The financial support is gratefully acknowledged.

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Design of uncertainty. The Role of the intangible factors into the built environment transformation

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Abstract

The Architectural disciplines are involved in an epistemological evolution due to the increasing conscious of the uncertainty and intangible factors that compose the phenomenological dynamics within the built environment.

Big Data and the techniques of Building Information Modeling exert a substantial theorical and instrumental pressure on the Design culture and on the methodologies of transformation processes.

The essay, that we intend to present, means to dwell upon the interactions between occupant's behavior and building systems, through a non-deterministic approach. Furthermore, affords a possible formalization of an operational term, able to specify the Cost-Optimal evaluation formula.

The reliability of the adopted approach will be demonstrated through a study conducted on the school building stock, in which cognitive capabilities, users' behavior and learning environment occur strictly connected. A qualitative model framework, able to drive and evaluate the transformative processes of a strategic public building sector, will be provide.

Keywords: *Building Information Modeling, Behavioral Modeling, School Buildings, Cost-Optimal Evaluation, Uncertainty*

1 Introduction

The real capability of the project disciplines is to address the complex processes of meanings and aim that characterize the action in the built environment. In this paper, we intend to consolidate the scientific depth of the intangible resources linked to the physical consistency of the city, information of a system considered in its behavior [1], within its domain, understood as a relative field of interactions. On the other hand, the informations encode a system's ability to behave, and the correlation of data provides an interpretation that is anything but neutral. In the domain of the built environment, human behaviour is easily recognized as the exceptional complexity of the variables to be modelled and predicted.

The measurable characteristics of the type of construction, the type of distribution and the comfort performance generated by the morphology of the spaces acquire complexity in the real, relative dimension, in which architecture is a relational space, a perceived artifact, a practiced path.

The research intends to provide the basis for answering three orders of questions:

- What are the elements that reinforce the predictive reliability of the project;
- Which theoretical and operational models can be used to improve the simulation of design scenarios close to reality;
- How to translate into a scientific measure the qualities expressed by these models and the relationships they generate because the quality of the interior spaces becomes a virtuous component in the energy balance of the building-system.

2 Building Information Modeling: material and immaterial cognition

The International Organization for Standardization (ISO) defines the Building Construction Information Model methodology as the "shared digital representation of physical and functional charateristics of any built object […] which forms a reliable basis for decision" [2]; therefore "the BIM may be defined as a modeling methodology and a series of processes that are associated for the purpose of producing, communicating, and analyzing the *models of buildings*" [3].

In the BIM environment, the product is defined as a datum of complete, material, and productive reality, and not as its synthetic representation.

A building's technical and functional information is organized in a given moment of the life cycle. In the case of the modeling of existing buildings, the distance between the architectural body and the model originates from the simplifications taken on to bridge the system's fragmentations and gaps in knowledge; a systematic quantitative increase of diagnostic activity would be decisive for the model's effectiveness.

The international research framework and the development of ICT applications are moving in the direction of allowing designers the same level of reliability and completeness of the new project, especially in the energy prefiguration and economic evaluation of the intervention scenarios [4].

The most sophisticated aspect, in terms of scientific complexity, that engages scholars for obvious economic repercussions on the process, is placed in the optimization of the exchange of information between processing systems.

Consider the information that is able to generate the building automation systems (Building Automation System – BAS) and the energy management and control systems (Building Energy Management and Control System – EMCS). The research horizon aims to provide the methodology with a "critical sense", through the development of optimal intervention scenarios.

3 Methodology and models: the operational framework

The application phase, therefore, develops within two operational and conceptual domains. The first, in the direction traced by Directive 2010/31/ EU, concerns the implementation of analytical criteria, which strictly refer to architectural culture in order to construct a different framework of reference scenarios. In other words, the study combines cost-benefit quantification due to the efficiency of the building envelope and of the system systems, already extensively investigated by other studies, a more systemic assessment that deals with the dimensional and functional optimization of the building heritage.

The second domain, on which the greatest experimental effort is concentrated, concerns the dimension of neuro-physiology applied to learning contexts. Scientific research in the psycho-pedagogical field has amply demonstrated that the current conformation of educational spaces is a model at a loss, from the cultural point of view, of the competitiveness of subjects in training and social inclusion. Among the parameters that the technological discipline frequents most often, there are levels of discomfort and concentration of unavoidable pollutants due to the impact on health, therefore as a social cost [6].

In the first phase of the work, the survey sample was identified. It was chosen, according to the variety of typological and technological solutions used, to refer to the high schools of Rome. The choice of the level of training is to be attributed to the possibility of developing resources and information provided by a single administration, the Metropolitan City of Rome, and therefore to the substantial qualitative and quantitative homogeneity of the data provided.

The data provided were verified through direct survey campaigns (inspections and measurements) and desk surveys on historical documents and sources.

In a second phase, the data relating to the sample, made up of 185 buildings, were organized according to morphometric criteria in order to formulate a sufficiently rigorous series of reference buildings.

Reference Buildings (RBs) must be representative in functional terms and with respect to climatic conditions, both external and internal.

The literature on the methodology for the definition of RBs [4] compares three different approaches, linked to the qualitative and quantitative framework of the information available.

In the third phase were the elaborations to which the innovative character of the research is recognized: the construction of an experimental subject able to implement the complexity of physical phenomena, to identify alterations that condition the life and usefulness of buildings, in the transition between different ways of use and behavior of its occupants. Taking explicit cue from the EPBD recast directive, it was intended to elaborate a virtual formulation of Reference Built Units that constitute the theoretical-scientific basis for the preparation of physical models of study.

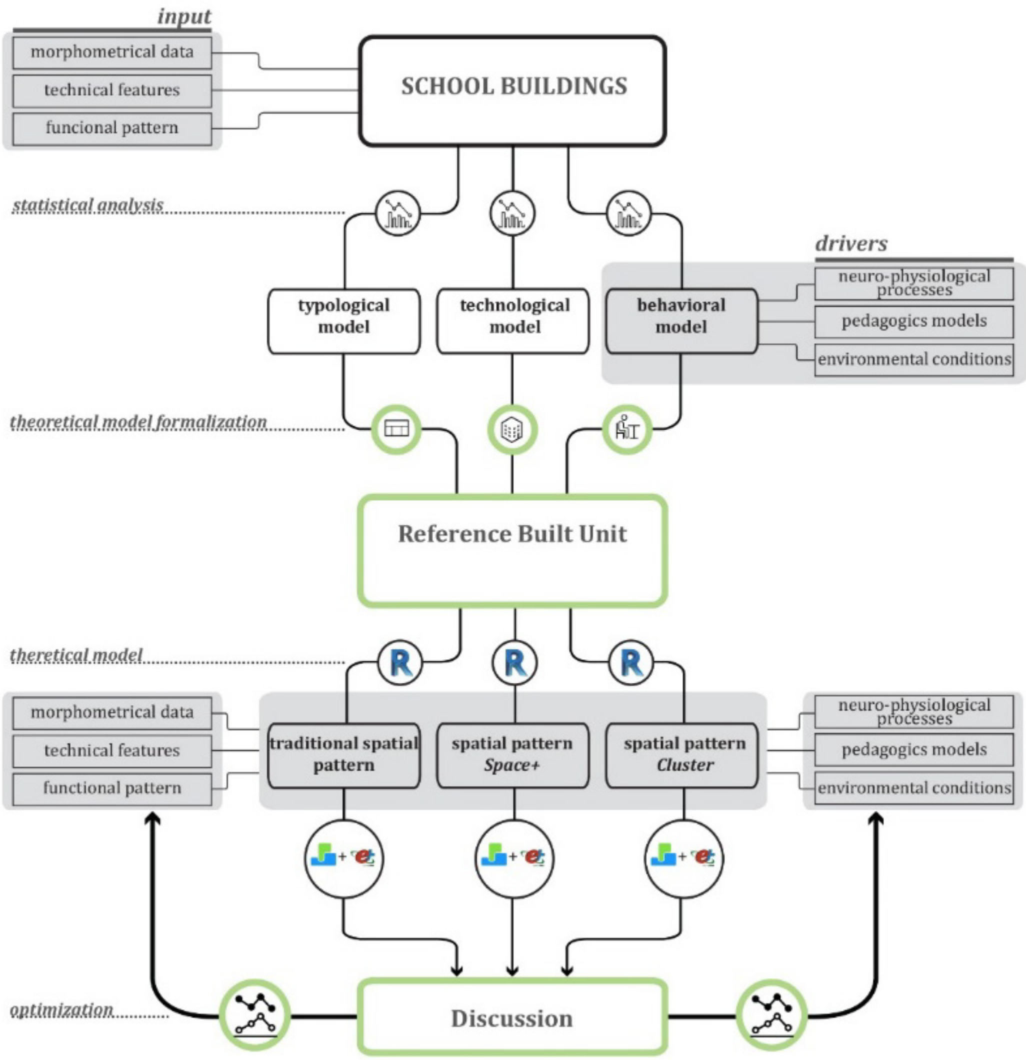

Fig. 1 Flowchart of the methology

3.1 Case studies: architectures to learn, learn from architectures

The learning architectures represent a particularly interesting case to evaluate the spectrum of reasoning and technical applications just introduced.

The exceptionality lies in the coexistence of low technological complexity of the buildings and of intense relational activity between the educating, the educator and the educating body of architecture and in the humanistic effort that the designer is called upon to perform in order to qualify or redevelop the learning.

Reshaping and qualifying the complex of school buildings implies a design exercise not so much and not only aimed at restoring the conditions of security and collective decency, which is also a present need where the institutions have acted almost exclusively in an emergency, but also in the relate the innovation of the educational model with the prefiguration and requalification of the technological and spatial performance of the building system.

The question today is to understand if the existing buildings are able to sustain the transformation of the didactic liturgy, the technological metabolism, the general reorganization of the city that definitively leaves behind a season of static and compartmentalized building-function correspondences. To the urban economy the same elastic effort is required that invests the anthropic community: minimization of consumption, maximization of adaptive ability, time and modality of discrete use, linked to specific skills.

3.2 Reference typologies.

In addition to the numerous studies on the topic [5-6-7], the re-reading of the traditional manuals [8–9] contributed to the construction of the framework of the school typologies of reference, surpassed by a more agile project culture, but which must be recovered as the reason for the construction itself, in the process of overall regeneration of the building. Building types have been correlated to the study of spatial models, that emerge from international research on education [10], which addressed the design of transformation scenarios.

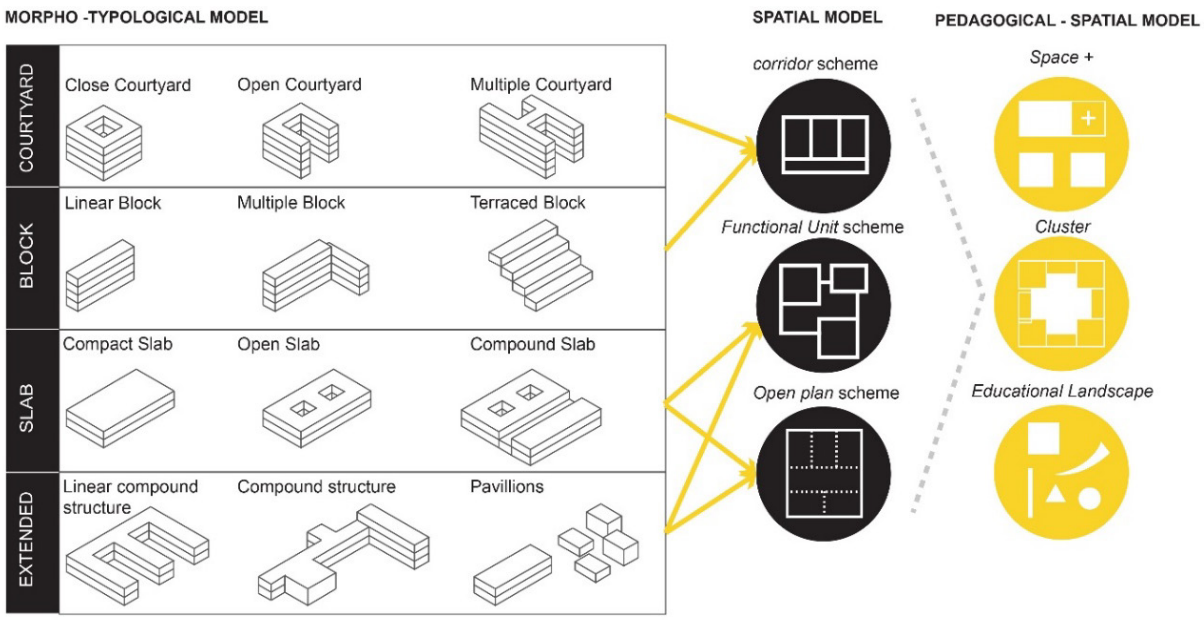

Fig. 2 *School Building Typologies and spatial models*

The model informed summarizes results from the adoption of the three approaches, distinct by systems, with reference to the availability and accuracy of the information. Therefore, the morphometric data, treated statistically, allow the definition of a *Real Reference Building*.

The school building chosen as reference for the elaboration of the Reference Built Units, to which to apply the proposed methodology, meet the characteristics described in Tab. 1.

Tab. 1 Reference Building – Slab

	Reference Building 1
1. Parameters	
Classification of the construction period	1941–1974
Typology	Morpho – typological model: **Slab** Spatial model: **Functional Unit Scheme**
Occupancy	Type: **high school** Ratio: **1200 students/50 classrooms** Individual ratio: **12.5 m^2/student**
2. Calculation method	Calculation of energy performance **UNI / TS 11300: 2014** Annual global requirement
3. Climatic Data	Outdoor temperature (implemented profiles – Standard) Solar radiation (implemented profiles – Standard) Variables: **Set point indoor temperature** **Air change rate**
4. Building Envelope Characteristics	V= **52.500 m^3** **S/V: 0.45** **Tranparent S/Env. S = 35%**
5. Thermal Trasmittance [W/m^{2}K]	External wall: **0.85** Internal wall: **1.1** Floor: **0.96** Roof: **1.54** Windows: **3.3**

4 Modeling and Simulation

Modeling and simulations were carried out on configurations related to a Reference Built Unit, which refers to the plate type, characterized by a distribution model with functional units. The Autodesk Revit software was used to build the informed model. The model and its variations have been imported into Design Builder, Energy Plus graphical interface software, that allows a discrete possibility to specify user profiles.

4.1 Behavioral modeling

On the modeling of user behaviors, starting from a traditional scheduling, we worked on subsequent improvements.

The maximum figure is provided by the programs of the individual schools that almost entirely participate in the organization of lessons developed over five days per week for a total of 30 hours of teaching.

From the analysis of the daily timetable, it is noted that each class occupies an average time of 20% of the day in environments that are not their own class. Based on this first simple consideration, the standard time schedule proposed by both the modeling and the simulation software has been refined by this first evaluation.

Employment profiles were further refined following a campaign to detect the presence and frequency of opening of doors and windows, carried out by means of commercial home automation sensors (Xiaomi Mi Smart Home Gateway Kit2 – Door Window Sensor Human Body Sensor Wireless Smart Devices Switch Sets For Mi Smart Home), linked to its application, a class of an Institute of Rome for a week.

The measurements show a window opening time equal to 5% of the duration of the lessons and an hourly exit of the occupants from the room ranging from 0% to 10%.

In consideration of the type of studies proposed to be conducted, it was considered acceptable to use a profiled scheduling as a weekly compact employment program. Finally, with the data collected and deriving realistic modeling for the two non-monitored configurations, employment profiles were set, as shown in Fig. 3.

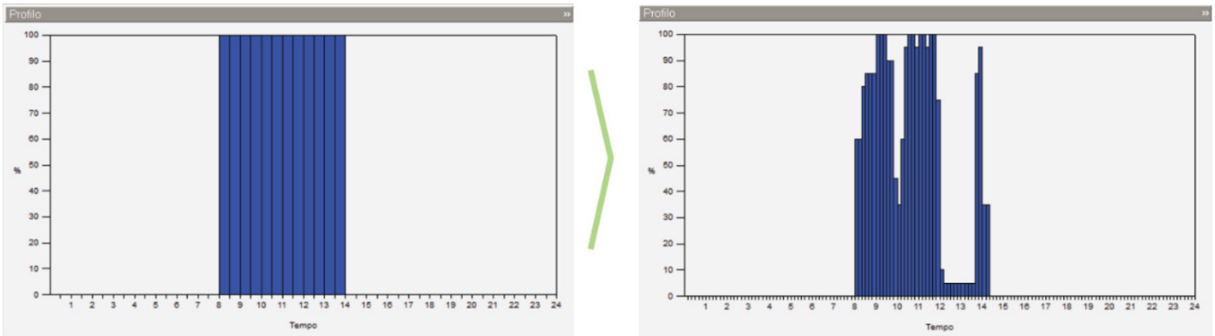

Fig. 3 *Behavioral profiles. On the left, traditional scheduling implemented into the simulation software. On the right, the behavioral profile due to the statistical analysis*

4.2 Input data

The Reference Unit placed in the middle block of a building, composed by three levels, in order to minimize the peculiarity of the positioning of the rooms and the impact of the dispersions and therefore concentrate the study on the effects of internal phenomena (Fig. 4)

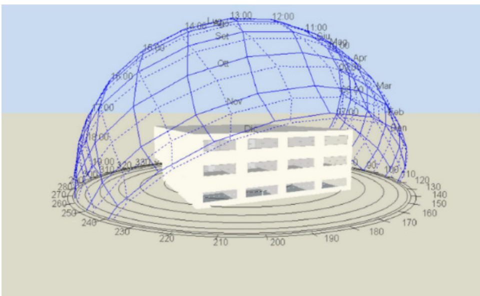

Fig. 4 *Complete Model. Slab type – Building that implement RBU solution*

The variables have been established:

- Traditional high efficiency boiler and production of domestic hot water and heating;
- Distribution system with manifolds, distributed to the various floors;
- Regulation system with centralized control;
- Emission system realized with radiators placed in the rooms;
- Average seasonal performance coefficient (CoP) of 0.85;
- Emission terminals for summer cooling: fan convectors;
- Set point temperature in winter: 20 ° (UNI EN ISO 7730 and ASHRAE Standard 55);
- Attenuation temperature in winter: 15 °;
- Set point temperature in summer: 26 ° (UNI EN ISO 7730 and ASHRAE Standard 55);
- Attenuation temperature in summer: 28 °;
- Period of use of the environments: from 8:00 to 14:00 every day of the week, excluding weekends, but including the summer period (July-August);
- Value of illuminance in the room on a work surface placed at 0.85 m from the floor: 300 lux;
- Type of lighting: applied to the surface;
- Type of artificial lighting control system: on-off;
- Hourly air replacement volumes for ventilation: 0.625 vol / hour
- Presence of electronic and computer equipment in dedicated environments and in operation from 8.00 to 14.00 every day of the week, excluding holidays but including the summer period (July–August)

Therefore, it has been hypothesized that the RBUs are equipped with cooling systems and that they are frequented also during the two summer months, circumstances that are not reflected in the Italian context. However, the events that are the object of the study significantly influence the internal heat contributions, so a complete assessment of the scenarios can only start from overall measurements.

The virtual model linked to the plate type is articulated around a large distribution space, punctuated by vertical connections, and organized by functional units. In the model, even if not directly studied, the laboratories are considered because they are considered a conditioning part of the phenomena occurring within RBU.

It is expected that in these there is a thermal and electrical load due to the operation of specific computers and equipment; based on the ASHRAE 55 standard, it is estimated that laboratory activities imply a metabolic rate of 123 W / sq m, compared to 108 W / sq m of traditional study activity.

The configurations 2 and 3, in which the transition from a traditional didactic model to the didactics for environments is foreseen, implies the total occupation of the spaces. The implementation of collaborative models that support the traditional study translates into an increase in the metabolic rate: from 108 W / m 2 to 133 W / m^2.

Thus, the physical model was stressed with a load of additional use, carried by a group of students for configuration 2 and two groups for configuration 3 outside the system, composed of 25 elements each.

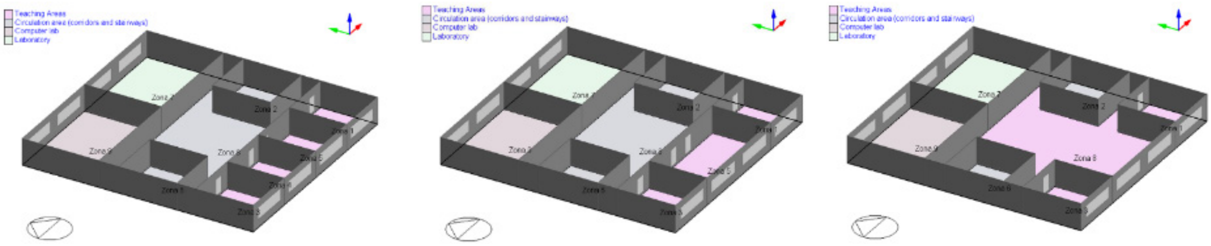

Fig. 5 *Reference Built Unit (RBU). Configurations, from the left: traditional, space+, cluster*

The simulations were conducted in two weeks relevant both from the point of view of thermal conditions and of school activities scheduling, to achieve a punctual assessment of comfort perception in built enviroment:

- winter week: 3 February – 9 February
- summer week: 16–22 June.

The in-depth analyzes carried out on a confined space of RBU, dedicated to didactics and on the spatial units that are expected to be transformed, are reported.

The heat is not completely dissipated because the absence of natural ventilation, provided in this set of simulations, entrusts to the opening of the windows only the air exchange, which is evidently insufficient. This is attributable to the rapid growth of the comfort diagram that does not stabilize, for an appreciable duration, on high or medium levels. Comfort improves slightly in the project summer week. More limited oscillations are recognized and the comfort values slightly exceed the value of 0.7 of the Fanger Index.

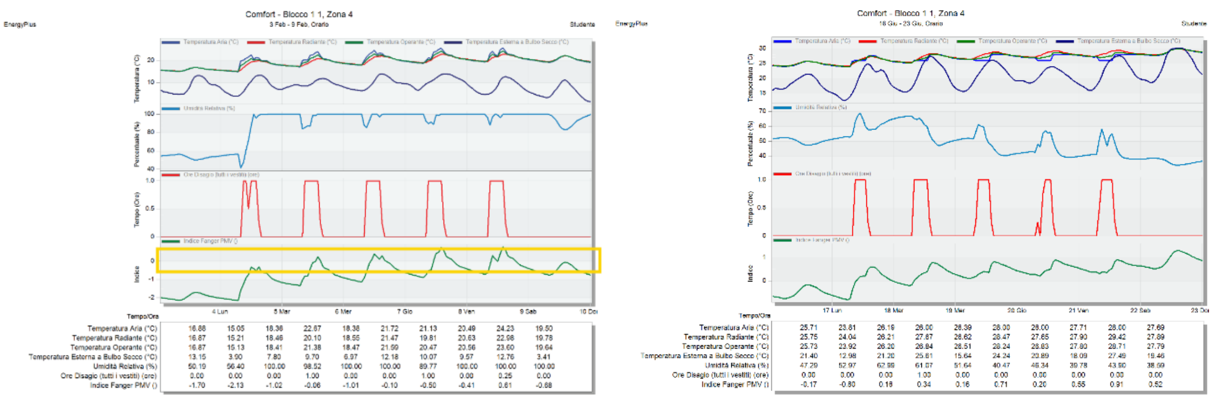

Fig. 6 *Perception of comfort into the zone 4. Traditional configuration. Winter week (left) and Summer Week (right)*

The perception of comfort in zone 5, configured as an increased space for teaching that hosts inter-class collaborative moments, varies significantly from the tradition classroom. As shown in the graph in Fig. 7, the average rating of users is expected to oscillate rapidly until a too high indoor temperature is recorded, even in typically winter outdoor conditions

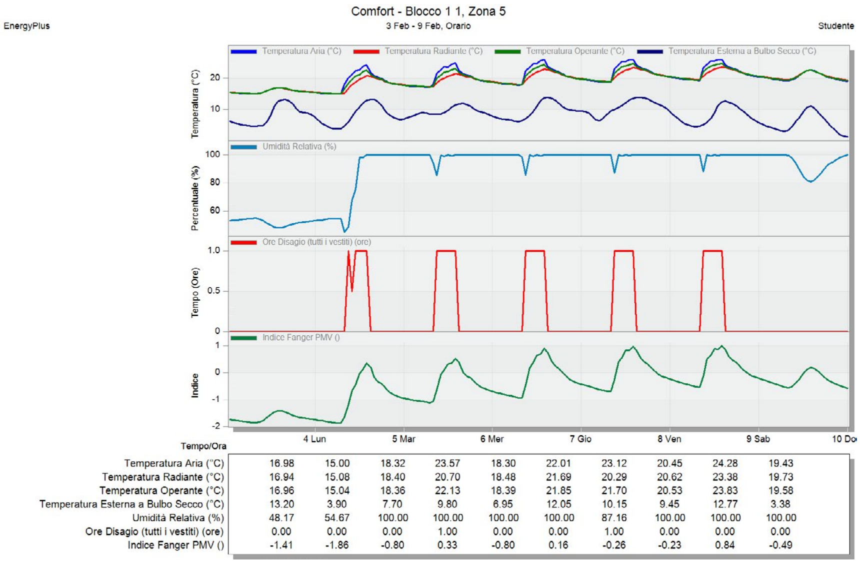

Fig. 7 *Perception of comfort into the zone 5. Configuration: Space+. Winter week*

The last scenario concerns the total opening of two intermediate classrooms towards the connective space that articulates different didactic moments: collaborative, individual study, research and socialization.

The considerable amplitude and the contiguity with external or unheated spaces determines the amplitude of the discomfort hours intervals that result both from the simulation of the winter project week and the summer one (Fig. 8).

It is interesting to note, on the other hand, that the same reasons are attributable to the lower variability of the comfort indices, compared to the confined spaces.

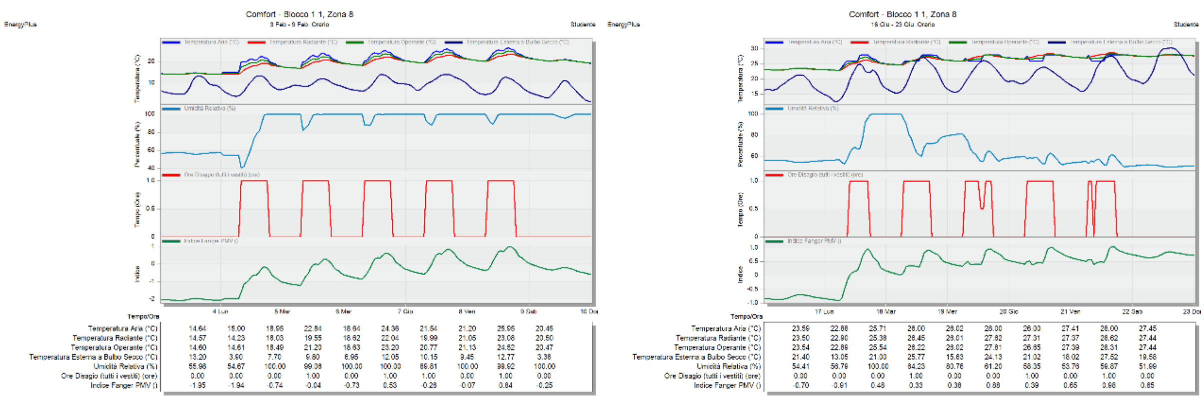

Fig. 8 *Perception of comfort into the zone 8 of RBU, Configuration Cluster. Winter week (left) and Summer Week (right)*

5 Conclusions

The research attempt to trace a path towards a possible implementation of the redevelopment methodologies applied exclusively to the building envelope and the need to shift part of the investment to the qualification of the internal environments.

In this regard, on the Cost-Optimal evaluation methodology, in addition to the previously raised interpretative issues, considerations on the character of the ability to guide the choice of administrations towards the optimal insist. The second recast of the EPBD Directive, in 2018 [13], implemented the obligation of monitoring through integrated energy management systems, as strongly advocated by a large part of the scientific community. Furthermore, policies and actions to promote smart technologies and communities and evidence based

The need to evaluate the alternatives of the redevelopment projects is still urgent, not only because of the burdens but above all the benefits that over time can repay the investment, more significantly than traditional payback time, as the resilience of the built environment.

By introducing the terms of benefit and profit, a very different evaluation of the optimal scenario would be obtained [14]. Assessments of an aesthetic nature, of market appeal [15] of long-term investment sustainability certainly have uncertainty margins both in quantification and in monetization. In the Tab 2, the contribution of the technologies and methodologies applied during the research is linked to the terms of the Cost-Optimal formula and evaluate the possibility to implement three additional terms suggested in [14–15].

Tab. 2 *Contribution in Optimal level definition. Costs and Values of intangible factors.*

Cost-Optimal Terms	Design and simulation methodologies	Spatial /Functional Optimization	Smart Technologies (ICT /IoT)	Awareness and Energy Management	IEQ monitoring
Ci – Investment Cost	●	●	●		●
Ca – Annual Cost				●	●
Cp – Emission Cost		●	●	●	●
Vm – Market Value	●	●	●	●	●
Cc – Health and safety cost	●	●	●	●	●
Vdis – District value	●	●	●	●	●

The last term, District Value (*Vdis*) refers to the ability of the transformation process to generate direct or no direct advantages at a district level, in terms of public life quality, energy production, climate mitigation and urban robustness. The research is ongoing to detail this interactional term.

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Daylight Modelling of a Portuguese Baroque Library

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Abstract

The XVIII century baroque King John's Library is one of the most important buildings of the University of Coimbra, which was declared World Heritage patrimony by UNESCO in 2013. As one of the main touristic attractions, it has been object of study on the assessment of the books and furniture conservation. One of the aspects that affect their preservation is the exposure to daylight, which degrades the shelves finishing and the books covers and paper. To prevent the continuous degradation of the patrimony, this work presents a study of the indoor daylight conditions. The software Radiance is used in order to generate accurate annual illuminance maps and detailed daylight indoors images. The results show that natural lighting is a threat to most of the patrimony and must be reduced. This analysis is a contribution to determine an appropriate and comprehensive preservation strategy leaving space to further investigation within this field.

Keywords: *Daylighting simulation, Indoor light, Illuminance maps, Heritage buildings*

1 Introduction

Nowadays, according to International Council of Museums (ICOM) [1], the definition of museum can be applied to a historical library, which mostly "conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity". The conservation of such patrimony can be endangered by excessive exposure to light. For this reason, sunlight must be controlled by avoiding high illuminance levels and direct exposure on books and furniture [2]. However, lighting conditions must be suitable to allow visitors to clearly view exhibited material and satisfy visual comfort [3].

As a radiant source of energy, light causes non-reversible damages in more delicate type of materials such as, colour fading or surface cracking [2], [4].The degradation process is cumulative and mainly caused by the heating expansion (physical damage) and the changing of materials molecule structure (chemical damage) of more sensible materials due to incident radiation [4]. From guidelines and standards [4]–[6] it is known that damage on materials depends on its properties, light intensity and the annual exposure time. Therefore, a proper lighting quantification and damage assessment are crucial in sparing the lifetime of heritage patrimony. Therefore, several research work have been made contributing with methodologies for proper lighting in museums and evaluate damage risks on artefacts via measurement analysis [7], numerical simulation of annual light [8] and both [9]–[11].

A correct lighting strategy should lay on several procedures to evaluate its effectiveness. As the first step, it should be done an assessment of natural daylight conditions via both measurement and numerical analysis. As said by the Illuminating Engineering Society of North America (IESNA) [5], "Calculations are useful, but mockups are most informative". This idea reinforces the importance of measurement analysis, but does not take credit to daylight modelling. The latter represents the foundation to following studies within the whole process of designing or refurbishment. In this perspective, the present study has three main objectives: i) to correctly model the historical library, taking into account most of the geometry complexity, materials and details of the building; ii) to run an annual daylight simulation using Radiance; and iii) to compare the results obtained with the recommended thresholds of guidelines and standards to evaluate which are the most endangered books and shelves.

With the given objectives stated and achieved, this research work becomes an auxiliary tool for the initial phase of refurbishment of a historical library. Some changes must be implemented in order to protect heritage patrimony, such as books and shelves. Therefore, the work is described in a cohesive structure starting with a brief introduction on the importance of conserving sensible artefacts and controlling natural light in a historical library. In Section 2, the lighting requirements for the conservation are described as well as the case study. The strategy of research was stated along with the lighting simulation tools used. The results were presented and discussed in the next Section 3. Finally, Section 4 concludes the article with the main topics highlighting the importance of preliminary studies and further research opportunities on the refurbishment or even design process.

2 Methodology

This research work has followed a work plan divided in two phases: identification of the most recent and used guidelines and standards to evaluate the most endangered artefacts; and simulation of daylight inside a case study of a historical library using Radiance software.

2.1 Lighting requirements

To ensure artefacts conservation, relevant guidelines and standards have to be satisfied in terms of light requirements. Among all the guidelines available, CEN/TS 16163:2013 [6] and IESNA 2011 [5] were used because are the most recent, complete and used nowadays. Both follow and ensure the research alignment from the previous ones within this field.

CEN/TS 16163:2013 [6] follows CIE:157 [12] directive and defines four material classes of sensitivity: highly sensitive (silk, highly fugitive colourants, most graphic art and photographic documents), moderately sensitive (most textiles, manuscripts, draws, prints, paintings and most natural history objects) , slightly sensitive (undyed leather and wood, horn, bone, ivory and some plastics) and insensitive (most metals, stone, glass, ceramic and most minerals). IESNA [4] guideline of 2009 contemplates only three materials classes: highly susceptible (textiles, cotton, natural fibers, furs, silk, writing inks, paper documents and wool), moderately susceptible (oil paintings, wood finishes, leather, textiles with stable dyes and some plastics) and least susceptible (metal, stone, glass, ceramic, most minerals). In 2011, IESNA updated the guideline by changing the light sensitivity categories' names (high, low, no) but maintaining the materials in the same category as before. In the case of historical libraries, books and bookshelves are included in the moderately sensitive category (CEN/TS 16163) and highly susceptible category (IESNA 2011). For a simpler representation of the conservation categories, another nomenclature was used: A, B, C, D and E.

In terms of light intensity, CEN/TS 16163:2013 [6] establishes that limit illuminance level of both classes (highly and moderately) is the same, 50 lux, once it is the threshold for visibility. However, IESNA 2009 [4] states that "for particularly susceptible materials, illuminance can be reduced to 35 lux and still provide for satisfactory viewing" if the brightness levels are low. Later on, IESNA 2011 [5] introduced a new specification by discretizing the recommended illuminances levels depending on the visual ages of observers. The values presented are recommended to people with visual ages between 25 and 65 years. It is also important to note that the recommended values address to maximum limits and, preferably, those should be lower.

As the damage effect of light on materials is cumulative, guidelines also recommend annual exposure limits that are calculated as the "product of illuminance levels by the total annual exposure time" [2]. In other words, the principle of reciprocity is applicable in this case meaning that the damage caused by 50 lux for 1000 h is similar to one with 500 lux for 100 h. Both recommended illuminance levels and annual exposure limits according to materials' susceptibility are presented in *Tab. 1*.

Tab. 1 *Recommended limits according to light sensitivity categories*

Guidelines		CEN/TS 16163		IESNA			
Light sensitivity		**Illuminance** (lux)	**Light exposure** ($lux \cdot h \cdot year^{-1}$)	**Illuminance** (lux)		**Light exposure** ($lux \cdot h \cdot year^{-1}$)	
Highly sensitive	A	50	15 000	50[a]	50[b]	50 000[a]	150 000[b]
Moderately sensitive	B	50	150 000	200[a]	-	480 000[a]	-
Slightly sensitive	C	200	600 000	-	200[b]	-	600 000[b]
No sensitive	D	-	-	-	1000[b]	-	-
No conservation	E						

[a] IESNA 2009; [b] IESNA 2011

2.2 Case study

The baroque library started to be built in the 18th century and is located at the University yard. The city where the building is located has the following coordinates: latitude 40°12′20″ N and longitude 8°25′10″ O. The main room has a useful area rounding 550 m^2 divided in three spaces (Space 1, Space 2, Space 3) with a height of 11.50 m. Each space has a balcony surrounding the space that creates two floors with shelves (bottom floor BF and upper floor UF). The entrance door faces East with an angle of 78° E relatively to the North. Despite existing other library spaces in lower floors, the main room was the object of study since it is "richly decorated where the wood shelves are painted with gold leaves storing historical and valuable books" [13], being the most delicate room from conservation perspective. The bottom and upper floor plans (BF and UF) and bookshelf numbering inside the historical library are presented in the *Tab. 2* and *Fig. 1*.

Tab. 2 *Numbering of bookshelves*

Space	Floor	Bookshelf
1	BF	1 to 10
	UF	11 to 16
2	BF	17 to 26
	UF	27 to 32
3	BF	33 to 42
	UF	43 to 48

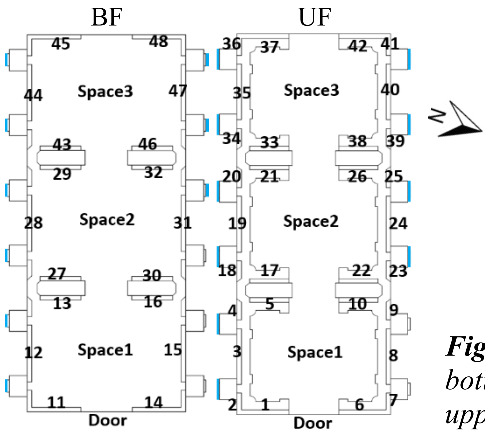

Fig. 1 *Top view of bottom floor (left) and upper floor (right)*

The historical library has 19 windows represented on *Fig. 1* by blue markers, 12 facing South (*Fig. 2)* and 7 facing North. BF and UF windows have the following dimensions: 1.00 x 1.13 m^2 and 2.40 x 5.20 m^2, respectively. All are single glazing with 0.03 m of thickness. The windows reveals were considered by a shading object with e the same shape of the windows and 0.30 m of depth.

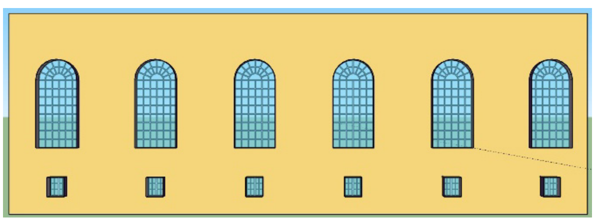

Fig. 2 *South façade – window representation*

2.3 Daylighting simulation

The simulation process was based on a sequential set of tasks. Firstly, the study required several technical visits in order to take up geometry measurements, materials information and lighting distribution inside of the historical library. All the information was needed to model and simplify the 3D geometry in SketchUp software [14]. 3D model was converted to a Radiance [15], [16] scene file using a SketchUp script, OpenStudio Plugin [17], that also runs the daylighting simulation using Radiance engine. However, OpenStudio Plugin does not support material change for Radiance simulations and due to the complexity of the geometry, the model was very heavy what required that the historical library was divided in three spaces, as represented in *Fig. 1* and *Fig. 3.*

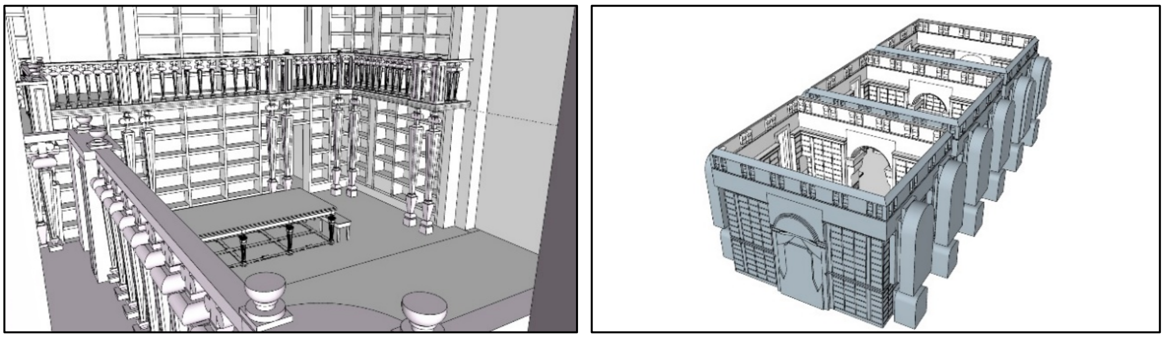

Fig. 3 *3D model of the historical library*

The three spaces were designed in SketchUp and then converted, attached and simulated using Radiance. In addition to the scene files was required to detail more information: surface properties, weather and maps of points where lux was measured (illuminance maps). The illuminance maps were produced by an auxiliary script that created a grid of points distanced approximately 0.10 m from the bookshelves' surfaces. From the annual simulation, hourly illuminance maps were produced as the output of each bookshelf. This data was processed and presented in the following Section.

3 Results and Discussion

The results of the annual daylighting simulation were processed seeking a comprehension of the most endangered shelves and books. Firstly, a global analysis was made pointing average values of illuminance levels and light exposure over one year. Furthermore, worst case scenarios were presented: season (divided by solstices and equinoxes), space, floor and section. Secondly, every bookshelf was analysed individually where the average and maximum values were calculated as well as the average of the annual light exposure of every point in a bookshelf. In addition, the worst season in terms of light exposure for each bookshelf was analysed. All values were presented in *Tab. 3* and coloured according to CEN/TS 16163 limits. Finally, the percentage of simulated points distributed according to standard conservation thresholds in terms of illuminance values and annual light exposure are presented in *Fig. 5*. Only Space 1 and Space 2 results were presented since represent the least and most endangered ones, respectively.

Statistically, the mean average value of illuminance is 156.93 lux over one year for every bookshelf during sunlight period. This value assigns a conservation class of C for the whole historical library. However, when evaluating the mean average light exposure, 725 939.69 lux·h·year^{-1} is the corresponding value over one year for every bookshelf, which exceeds the higher threshold of both standards of 600 000 lux·h·year^{-1} (class E = no conservation). Therefore, these indicators highlight the need to control and reduce natural light inside of the library in order to achieve a conservation class appropriated for books, paper and painted wood. Desirable conservation classes are different for standards: B for CEN/TS 16163 and A for IESNA 2011 but both with a 50 lux threshold. These values are only indicative and should be analysed individually for every bookshelf to really understand the class distribution in the historical library.

Generally, Winter (between 21st of December and 20th of March) is the most damaging season followed by Spring. It is understandable that during this period, the sun is in a lower position, which allows more sunrays to penetrate inside of the historical library. However, considering the weather patterns, Winter will be the season with several overcast skies what in the reality reflects in lower illuminance values inside. Moreover, sectioning the library relatively to the cardinal directions, the North section of bookshelves is the one that is the most vulnerable receiving more light during a year what is explicable by the fact that the building has windows facing South. Light rays enter directly in the library and land on the bookshelves of the North section. Contrarily, South section is the least damaged by light exposure since it is backwards from where the direct light enters what means that there is no direct light exposure of the bookshelves. East and West have similar distributions. However, when looking for the different spaces, Space 2 is the most endangered because it has more windows than the Space 1 and receive reflected rays from both Spaces 1 and 3. It has a similar light behaviour of Space 3 but the latter does not have reflected rays coming from two spaces as Space 2 has. Also, the bigger windows in UF endanger more bookshelves on this floor, which means that UF has higher risks of book degradation than BF.

Due to document restrictions the results presented on *Tab. 3* are only referring to Space 1 and 2 (least and worst situation) for one of the conservation standards, CEN/TS 16163. The colouration of used for the two indicators, annual average of illuminance level and annual average of light exposure, is according to the scale defined in Section 2.

As expected from the global analysis, the annual mean illuminance distribution where the mean illuminance punctually over a year, it represents better the trends when compared with annual light exposure values, which is confirmed by looking to the individual values of every bookshelf. Indeed, category C is predominant for both spaces for annual average of illuminances values. However, the most important concept to conservation, annual light exposure, decreases to class E (undefined by guidelines), which reveals an extremely high risk of degradation by light exposure regarding the type of material. The same argument results from the analysis of both graphs in *Fig. 5*, where class A and B have acceptable percentages for punctually illuminance vales but unacceptable (almost null) for annual light exposure. Thereby, the idea of increasing the control of the available natural light gets stronger.

Space 1 has lower incident light on bookshelves because there are no windows in the northern façade what also contributes to no direct radiation on southern bookshelves. In Space 2 and 3 the same does not happen what puts in danger the southern bookshelves. Both Spaces, 2 and 3, have higher illuminances values and identical light distribution.

Bookshelf 12 is the least endangered and 21 the most. Furthermore, as the three spaces are similar, the light distribution inside the library is similar to the corresponding bookshelf of every space. In other words, the example of bookshelves 5, 21 and 37 show that all have the same position relatively to each space, same western direction and same dimensions, which reflects in a very identical behaviour in terms of light exposure during the year. Identically, the same occurs with the rest of the bookshelves.

The peak hour period is between 9:00 and 13:00 depending on the bookshelf. This period corresponds to lower sun positions where rays are focusing on the bookshelves with a considerable lux intensity. Especially in days close to the Winter solstice justifying the existence of a tendency for the peak hours to occur near Winter solstice. On the other hand, occasional occurrences of peak hours distributed during Spring or Autumn are explained by the fact of those bookshelves not being exposed to direct sunlight which peak hours occur for the biggest reflection scenario (mostly in the BF that is more protected).

The results prove the need to control the light levels inside the library. This must be seen as a priority by applying several techniques and tools for the effect. Measures should cover changes in the windows' glass, a simple glass with 0.30 of thickness does has a high transmission of radiation (Visible and UV) and must be changed for a glass type that eliminates all wavelengths lower than 400 nm or at least apply UV filter stickers to the such windows. Thus, an internal diffusion element should be mounted in order to diffuse light avoiding the direct exposure to the reminiscent light that enters. Nevertheless, these measures can affect the visual conditions of the interior for visitors, even though vision perception depends mostly on contrast and not illuminance intensity. For this reason, a proper artificial lighting system should be designed to complement natural lighting. This system must have both efficiency and efficacy in terms of energy and viewing conditions. Artificial lights should not produce heat and must emit as less UV radiation as possible. Regarding the visiting period, historical libraries “should incorporate a method for completely restricting daylighting when the galleries are closed to the public” [5].

Tab. 3 *Daylighting analysis for CEN/TS 16163 standard limits conservation. For each bookshelf of Space 1 and 2, there are presented: the respective direction, season corresponding to the largest light exposure, hour in which the maximum illuminance is achieved, annual average of the illuminance map and the annual average of light exposure.*

	Overall	**Worst Section**	**Worst Season**	**Most Endangered Space**		**Most Endangered Floor**
		North	Winter	Space 2		UF
	Bookshelf	**Direction**	**Worst Season**	**Peak Hour**	**Annual Average [lux]**	**Annual Average light exposure [lux·h·year^{-1}]**
Space 1	1	E	Winter	13:00 19/12	352.96	1 632 774.99
	2	S	Winter	13:00 18/01	41.33	191 177.68
	3	S	Winter	12:00 19/12	51.77	239 494.62
	4	S	Winter	10:00 19/12	43.53	201 366.86
	5	W	Winter	10:00 19/12	390.00	1 804 157.49
	6	E	Winter	12:00 19/12	69.41	321 081.48
	7	N	Winter	12: 00 23/12	142.40	658 752.43
	8	N	Winter	10:00 31/12	204.49	945 985.54
	9	N	Winter	09:00 19/12	145.18	671 604.06
	10	W	Winter	09:00 18/01	75.08	347 304.18
	11	E	Winter	13:00 03/03	49.52	229 066.68
	12	S	Winter	11:00 19/12	20.70	95 749.97
	13	W	Winter	10:00 01/10	52.10	241 028.63
	14	E	Winter	12:00 30/12	85.71	396 502.63
	15	N	Winter	11:00 19/12	252.36	1 167 411.08
	16	W	Winter	11:00 30/01	92.19	426 492.17
Space 2	17	E	Winter	13:00 30/12	385.01	1 781 061.59
	18	S	Winter	13:00 31/01	121.10	560 211.85
	19	S	Spring	10:00 31/10	159.27	736 796.37
	20	S	Winter	10:00 24/02	121.24	560 836.96
	21	W	Winter	10:00 10/02	406.34	1 879 715.70
	22	E	Spring	12:00 23/12	181.94	841 677.07
	23	N	Winter	12:00 16/12	146.69	678 602.19
	24	N	Winter	10:00 30/12	209.33	968 358.97
	25	N	Winter	09:00 19/12	150.63	696 811.10
	26	W	Spring	09:00 18/01	192.54	890 684.73
	27	E	Winter	13:00 03/03	73.85	341 645.79
	28	S	Spring	11:00 18/11	112.31	519 543.88
	29	W	Winter	10:00 01/10	72.01	333 115.21
	30	E	Winter	12:00 30/12	99.19	458 843.23
	31	N	Winter	11:00 19/12	259.38	1 199 881.85
	32	W	Winter	11:00 31/01	103.12	477 011.74

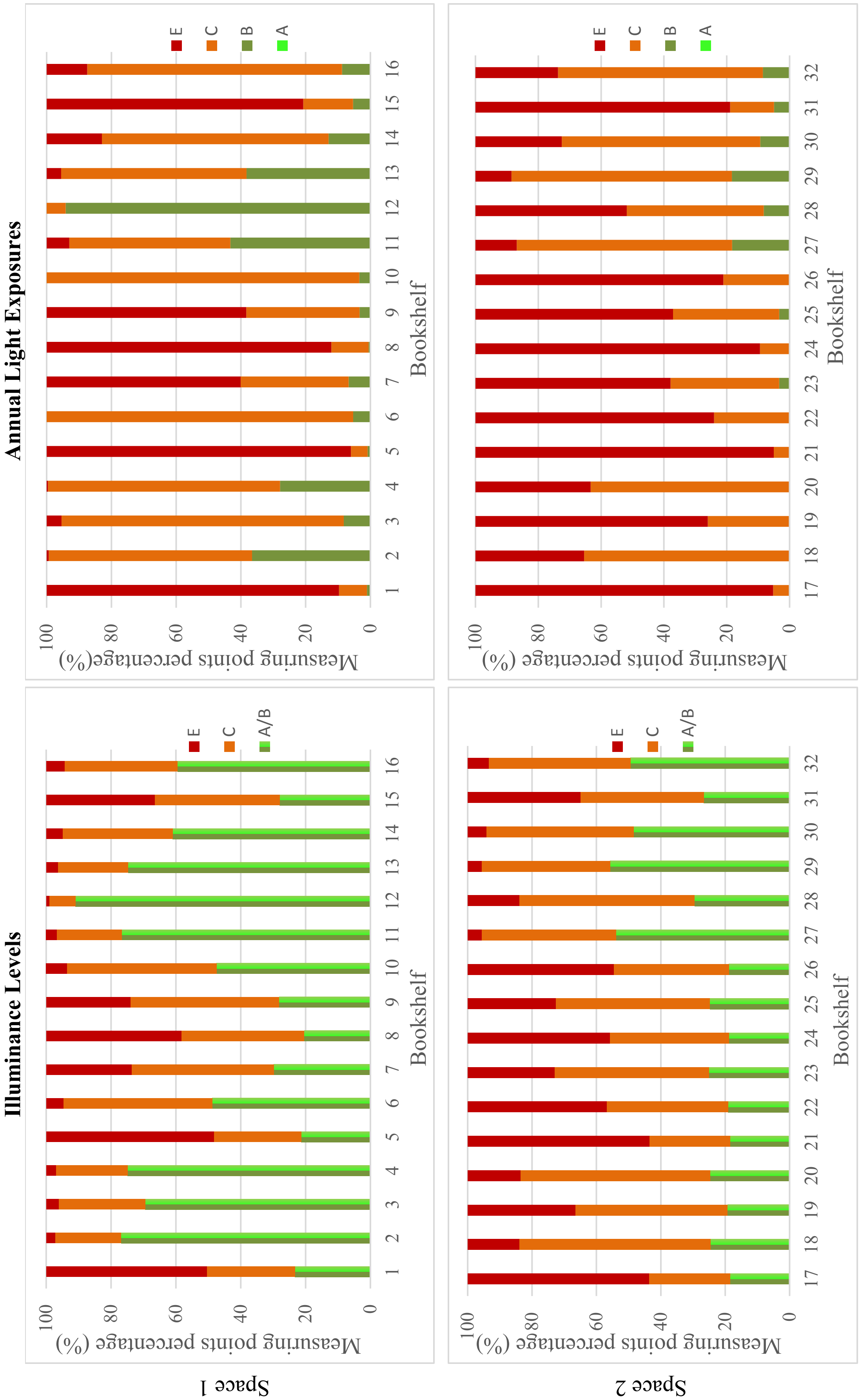

***Fig. 4** Conservation classes distribution for CEN/TS 16163 standard limits*

4 Conclusion

The present research work is a first approach in the design and model process of the 3D of a baroque library that is used for the simulation of annual daylighting conditions with Radiance software. The study represents the preliminary assessment of natural daylighting conditions and was carried out to evaluate the most endangered bookshelves seeking the proposal of preventive actions in the lighting strategy of the case study.

From the results, it was concluded that natural lighting is a threat to most of the patrimony and must be controlled by reducing the amount of ray penetration inside of the baroque library. Several measures can be applied to reduce light incidence. The aim of the study allowed to develop a model that can be used to test and evaluate the impact of these measures allowing further investigation on the topic. Moreover, Radiance is a complex software that requires a detailed modelling to achieve quantitative results bringing simulation come closer to reality. A continuously improvement of small details as well as a validation of the model leave space for future research work to be done.

Acknowledgement

The research presented has been developed under the project Ren4EEnIEQ at INESC Coimbra and supported by the Portuguese Foundation for Science and Technology (FCT) and European Regional Development Fund (FEDER) through COMPETE with references PTDC/EMS-ENE/3238/2014, POCI-01-0145-FEDER-016760, and LISBOA-01-0145-FEDER-016760.

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Investigating Overheating of Nursing Homes to Support Heatwave Risk Analysis Methodology

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Abstract

The duration and frequency of summer heatwaves in Europe have substantially increased recently due to climate change. A clear correlation can be shown between the rise in outside temperature and the risk of mortality. The aim of our research is to examine the nursing homes in Budapest from this point of view. Therefore, a survey was conducted in which we analysed the building structures and examined the preventive methods used in these homes. After evaluating the results, one of the most vulnerable building was analysed using dynamic whole-building simulation. During the simulations, the summer internal conditions in the buildings with different user habits were analysed. We also examined the models according to future IPCC scenarios. In the study, we determined the most important parameters for internal air temperature and later on with additional parameters and city-level data. This can lead to the creation of a more complex hazard risk model.

***Keywords**:* *summer overheating, heatwave, dynamic simulation, survey*

1 Introduction

The European Union has set itself a long-term goal of reducing greenhouse gas emissions [1] to mitigate the effects of climate change, and tightening requirements in the building industry [2] has effects on refurbishment of non-residential buildings [3]. Climate change has significant effect on the ecosystem, but its influence on health is also decisive. High temperatures may cause various diseases, including: skin rash, fatigue, sudden fainting or heat stroke, symptoms which indicate that the body's heat regulation system is not working properly. There are several general pieces of advice for prevention: sufficient amount of liquid consumption avoiding high-caffeine and alcoholic drinks, night-time ventilation and daytime shading, changing people's daily routine.

In the case of Hungary, in the decade through 2016, the number of heatwave days reached 14 per year, which represents a 6-day increase compared to the beginning of the last century. If we look at the future climate, we can expect a clear increase in the number of summer days where the temperature exceeds 25 °C at maximum – expected to be 16–20 days between 2021–2050 [4].

As the frequency of extreme weather phenomena is expected to increase in the next century, it is a very important task to examine the effects of heatwaves in detail, develop local warning strategies and develop an effective prevention plan. Several research papers analyse the excess-death due to climate change [5][6]. In Italy, it has been shown that there is a change in the number of excess deaths after applying a heat prevention plan [7]. It can be seen that the action plan introduced helped cut the number of deaths. In order to reduce the negative impacts of climate change, cities need to create a vulnerability index that involves not only the spatial relationship between different socio-economic, demographic, health and environmental variables but also the results of dynamic analysis. Several dynamic simulations have been made [8], [9] to analyse the overheating of buildings, the purpose of which was to examine the building structures, adaptation strategies or different climates. When examining the shading of buildings (especially in case of office buildings), it is important not to forget about the additional costs of artificial lighting. Different shading and ventilation strategies can greatly alter the interior comfort of buildings.

The aim of the paper is to analyse the internal temperature of an existing nursing home using dynamic simulations. During the examination of the building we analysed not only the user habits, but also examined the changes in the internal temperature using future climate.

2 The survey

During the research, we made a database containing all the elderly homes in Budapest. After that, we created a questionnaire that was sent to the executive manager of the homes.

Our primary purpose was to evaluate the state of the buildings in Budapest and the methods and experiences of the institutions on summer overheating. During the compilation of the questionnaire, it was a primary consideration to prepare a quick fill-in form that summarizes useful information relevant to the topic. We have used open and closed questions with alternative, selective and scale response options, we have also given the opportunity to describe individual opinions.

The response rate was greater than expected, with 30 respondents from the 73 elderly homes. These results contribute to the accurate assessment of the buildings in Budapest and the preventive methods applied in summer.

2.1 Results

Based on the results of the survey, it can be seen that the type, condition and age of Budapest's nursing homes are very diverse (Fig. 1). The classification of the construction periods was based on the National Building Energy Strategy. Most of the buildings were built in the period 1946–1979, and close to a quarter in the early part of the century. The proportion of newer homes (after 1990) is 33%. Comparing the results with the completed database, it is also apparent that most of the homes participating in the survey are newly built, so the result cannot be fully applied to the entire Budapest stock.

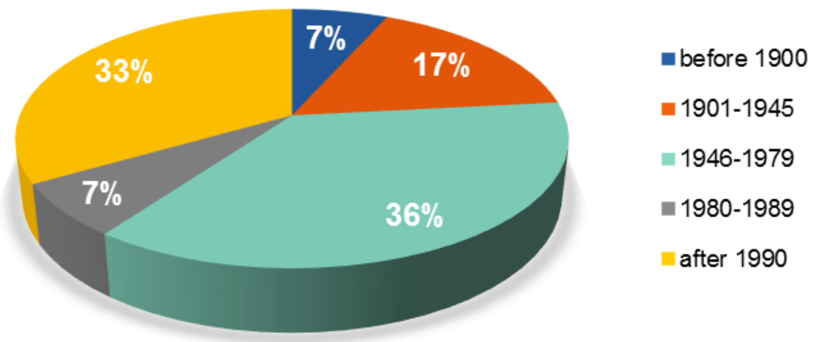

Fig. 1 *Construction period of the buildings*

2.1.1 Size of the homes

The size of the homes is also quite diverse, the questionnaire mainly includes institutions with higher capacity, but smaller homes (less than 50 people) are also relatively common in Budapest. 30% of the homes are suitable for 75–100 people, and a little more than 30% can accommodate more than 100. In total, the elderly homes surveyed can accommodate 3085 people, which is about half of Budapest's capacity based on the data of National Employment Service [10]. Based on these data, the total capacity available in the country is 51,345 people, of which Budapest accounts for 12%.

2.1.2 Retrofitting options

In the majority of the buildings in the survey, 20 energy-related retrofits have taken place in the last 10 years, while 4 of the remaining 10 are planning to renovate the building in the next 4 years.

The frequently used retrofit measures (Fig. 2) were the replacement of doors and windows and the modernization of the heating system. 25% of the buildings renewed the electrical system too. These solutions were generally combined: in case of one building, all 5 measures have been applied.

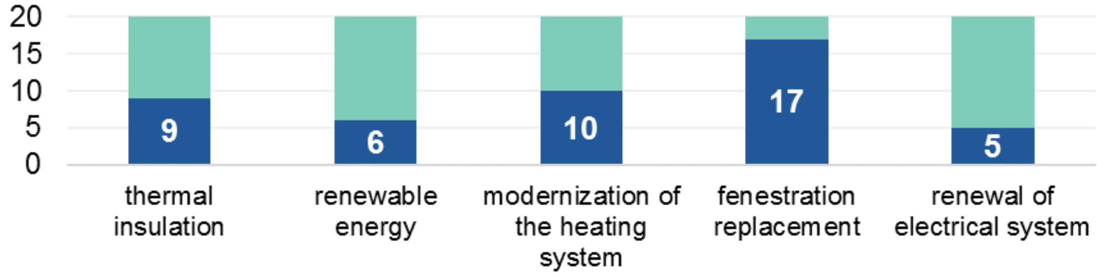

Fig. 2 *Retrofitting options applied in the homes*

2.1.3 Air conditioning

There are only two examples of air conditioning in the buildings, which is mainly due to high investment and operating costs. In some cases, separate rooms have air conditioning, because of the health conditions of the inhabitants.

The use of air conditioning systems in the elderly homes is a really important question; due to the clear link between daily temperatures and mortality, it is worth considering a more detailed examination of its application [11].

2.1.4 Internal temperature, health conditions

The situation is critical in the case of the temperature measured in the upper floors. More than 66% of the respondents say it is really hot or warm in the rooms, even though the building has been renovated. It is also talkative that none of the 30 homes have chosen a "pleasant temperature" option and only 10% of them are relatively comfortable with temperature on the upper levels of the building.

It is the most difficult task to judge emerging health problems. 43% think that problems are more likely to occur when heatwaves occur, 26% cannot judge, while 30% do not notice the difference. In this respect, the survey shows consistency with the data in the literature. In general, it can be said that higher temperatures increase the health risk.

Fig. 3 *Internal temperature on the upper floors*

2.1.5 Equipment of the homes

In the remaining part of the survey, the energy saving and the most useful equipment during heatwaves (Fig. 4) were also evaluated. More than half of the nursing homes use LED light sources, and shading solutions can be found in 80% of the buildings. However, 26% of the homes have electric fans and 13% have some kind of automatic ventilation (e.g. air inlet in windows), which rate is quite low.

Residents and practitioners often underestimate the role of fans during heatwaves. Public health guidelines often say the fan is not so effective as the air temperature exceeds the skin's surface temperature, but according to O. Jay et al. [12], it is worth considering their use as they help to reduce heat-related morbidity and mortality.

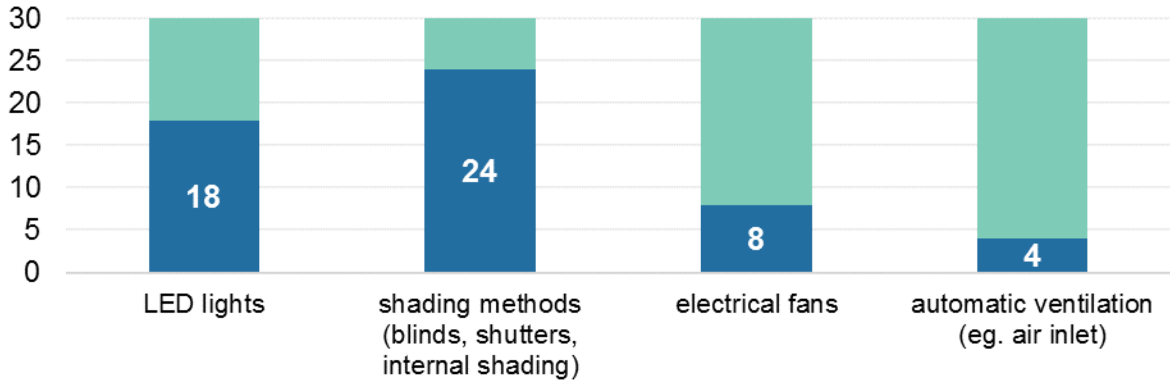

Fig. 4 *Equipment of the homes*

2.1.6 Used methods during summer

In the last section, we evaluated the methods used during the summer and heatwaves (Fig. 5). The most commonly used solution is the use of daytime shading, night-time ventilation and cold refreshments. 56% of the homes change the daily routine regularly during summer, that is, the time of daily activities, exercise classes and walks are modified due to the summer weather. More than half of the respondents regularly ventilate during the daytime in the summer heat, even though night-time ventilation is preferred. 30% of the buildings have an air-conditioned room where residents can spend a few hours.

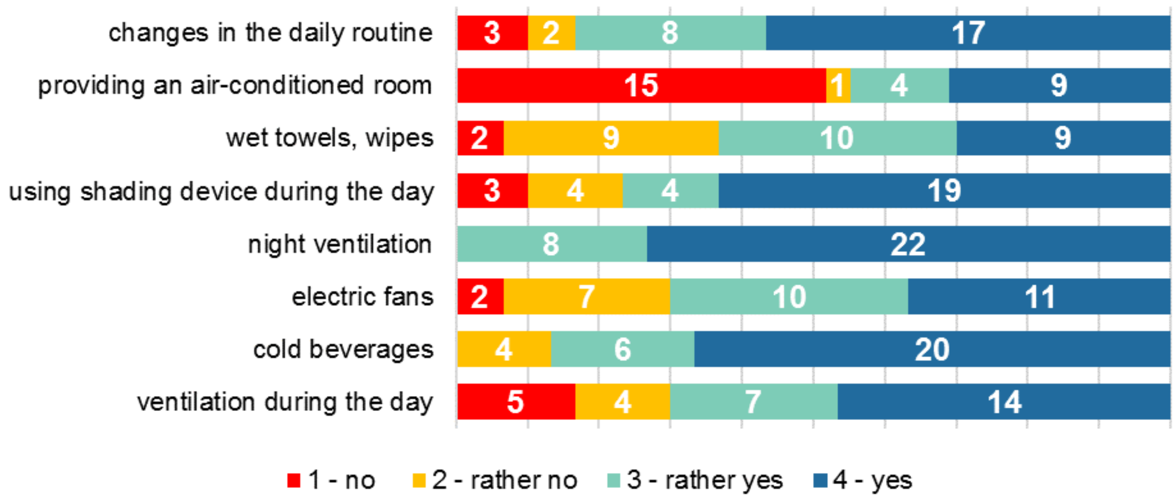

Fig. 5 *Methods used during summer and heatwaves*

2.1.7 Major conclusions

Using this survey, we learned a lot of useful information about the nursing homes in Budapest.

- We can say that most respondents work in a building built between 1946–1979, and most of the buildings in Budapest do not have air conditioning.
- 67% of the building stock have undergone some kind of energy-related renovation, but only 10% of respondents say that temperatures are relatively pleasant on higher floors.
- In general, 80% of homes have shading solutions and 60% of them use LED light sources.
- Over 80% of the nursing homes change their daily routine in hot weather and where shading is available, 76% of them use it during the day.
- The most popular methods include cold refreshments (86%), with wet wipes and towels used in 63% of the cases.

3 Overheating of buildings

There are a several factors which are influencing the overheating of a building, including internal gains, user habits, building structure, location and shading strategies. With dynamic whole-building simulation, we can assess the indoor temperatures, so we can determine how comfortable the conditions are for a given building.

In this case, overheating of the examined building was investigated by the ODH_{26} indicator, which was used in some previous research [13]. ODH_{26} is the number of hours with temperature above 26 °C, which determines the duration and the extent of the indicated overheating (unit of measure Kh/a). The analysis was performed using the validated WUFI Plus whole-building simulation software [14] in accordance with EBC Annex 41 guidance [15].

3.1 Analysed building

Building stock of the elderly homes in Hungary is very diverse, not possible to create a typology. Here we analyse one building with a large capacity, it was built in the period 1946-1979, accommodating 131 people. Several energy-related renovations have taken place, such as the installation of thermal insulation, the doors and windows have been replaced and solar panels installed. The building was mainly built of prefabricated concrete panels, the current plastic windows are made of double-layered glass with low-E coating. Only floor plans were available for the building, so the composition of the layers was partly based on on-site measurements and the typical constructions of the era. The thermal transmittance values of the structures can be found in Table 1.

Tab. 1 *Thermal transmittance of the main structures*

Structure	Thermal transmittance (W/m^{2}K)
basement walls	2.156
ground contact floors	2.874
façade wall	0.366
internal slab	0.859
roof slab	1.313
division wall (conc. block)	2.065

After defining the building geometry, we had to create the investigated zones. In this part we wanted to focus on the rooms where the elderly live, so the building was divided into a total of 5 zones per floor (in total 3 floors): south left, south right, north left, north right, and an “other” zone (corridor, mechanical room, staircase) as seen on Fig. 6.

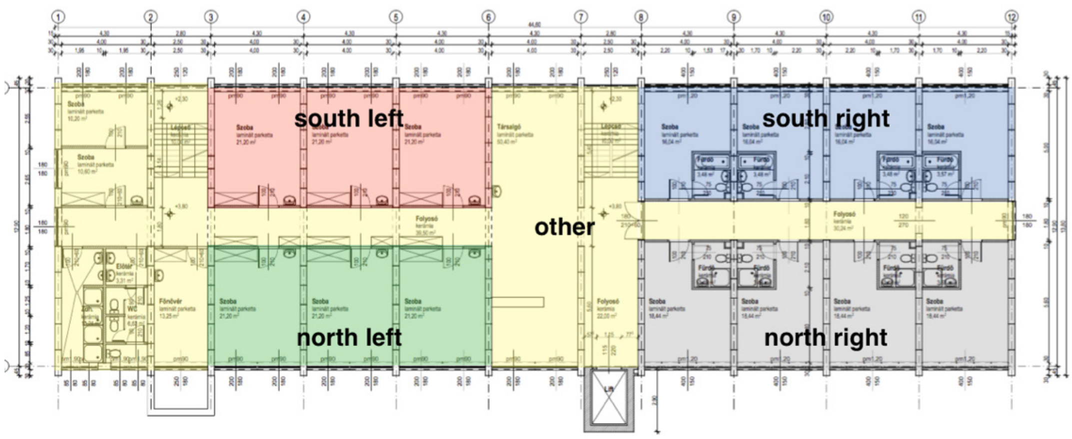

Fig. 6 *Zone distribution of a floor*

3.2 Boundary conditions

In the case of the ventilation 0.1 1/h infiltration was assumed with 0.5 air change rate during a day, while in the summer time increased air exchange (2 1/h) was used in the night hours (between 8 pm. and 6 am.). Regarding the internal gains, the values were individually set, taking into account the number of people in the zones and the activities taken. This means generally sitting or a light sitting activity and some slow walking according to the capacity of the rooms.

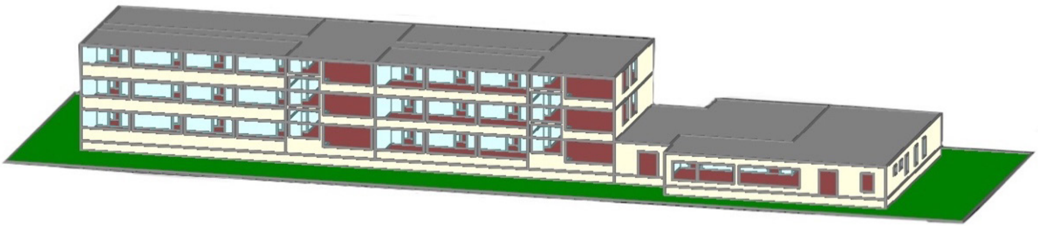

Fig. 7 *3-dimensional model of the building*

The most important boundary condition was the weather. The generated climate file used for the simulation is based on measured data. In the research we also examine the effect of the future climate, for this we used the generated weather data by IPCC A2 scenarios for 2050 and 2100.

Based on Fig. 8 the air temperature rises significantly in all future climates, the average annual temperature is 12.38 °C in 2018, 14.38 °C in 2050 and 16.44 °C in 2100. This warming is also visible at minimum temperatures (-11.7 °C, -8.6 °C, -6.5 °C) and maximum values (34.8 °C, 38.5 °C, 41.9 °C, respectively). The value of the relative humidity is approximately the same for all scenarios (Fig. 9). With respect to precipitation, the annual amount is 546 mm in 2018, 537 mm in 2050 and 491 mm in 2100.

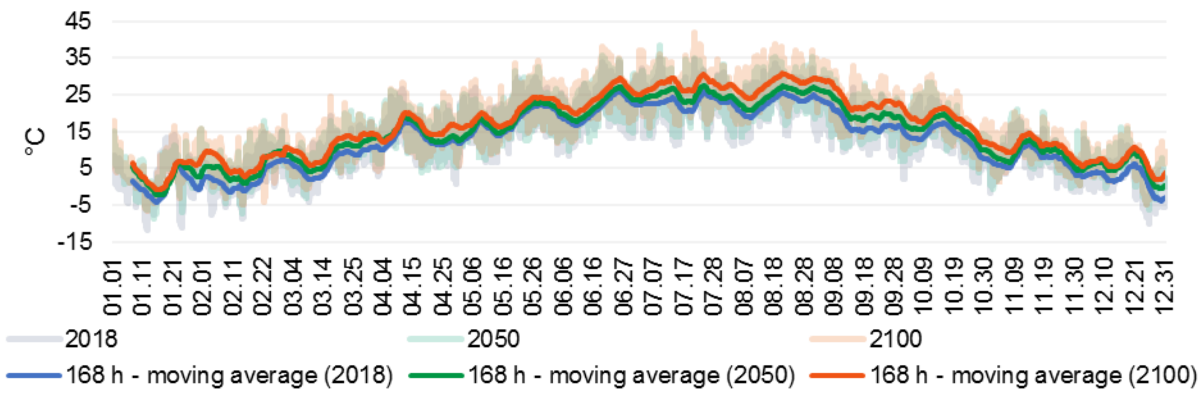

Fig. 8 *Temperature values according to the 3 scenarios*

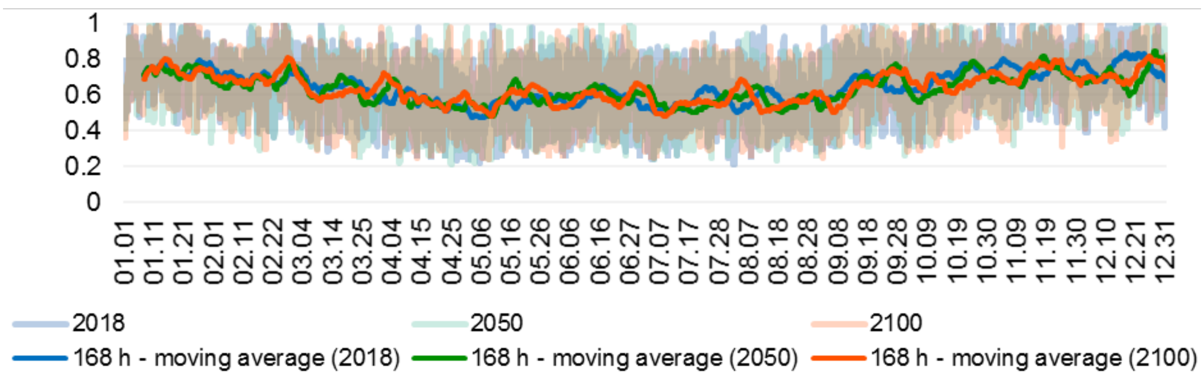

Fig. 9 *Relative humidity values according to the 3 scenarios*

Compared to the basic model (REF), we have also looked at several types of user habits that effect the value of summer overheating. We analysed the effect of air change rate and different shading options according to the software. The summer night-time ventilation rates were raised to 4 1/h and 6 1/h, and in case of shading, three different methods were used: limit radiation value (LRV), reduce overheating (REF) and schedule (SCHED) options. In case of the reference model (REF), and the optimised user behaviour model (OPT) all three climates have been investigated. From the 2-year simulation, we used the last year's data in the comparison process.

3.3 Results

The results were evaluated according to the ODH_{26} indicator. The value of the indicator was very high in the reference model – this can be seen in Fig. 10 grouped by zones and climates. Looking at the same structure for the weather in the 2050s, the value increases up to 1.5-fold. It can be seen that this value in the expected climate of 2100 – without artificial cooling – will be 2.5 times higher.

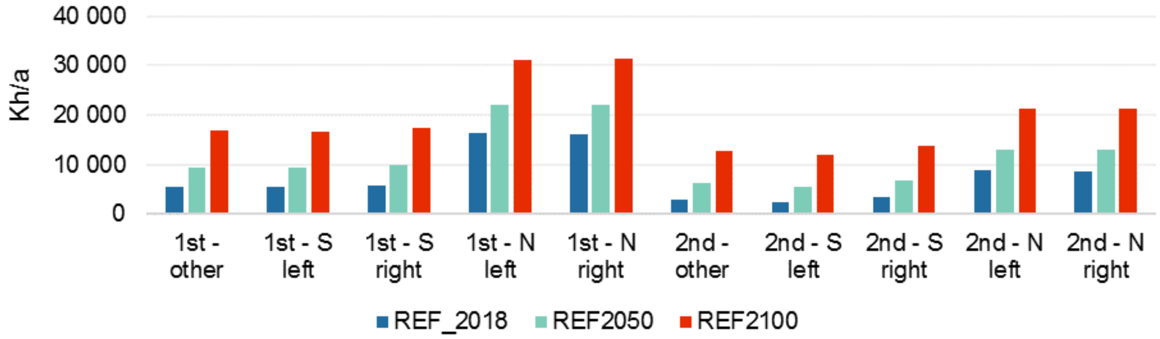

Fig. 10 *ODH_{26} values in the zones of reference building according to 3 climate scenarios*

Figure 11 shows the internal air temperatures measured in the south right zones at different levels. Generally speaking, the temperature on the 1st floor was the hottest in the same type of zone. One of the possible explanations is that the second floor without a thermally insulated roof could cool down faster during the night.

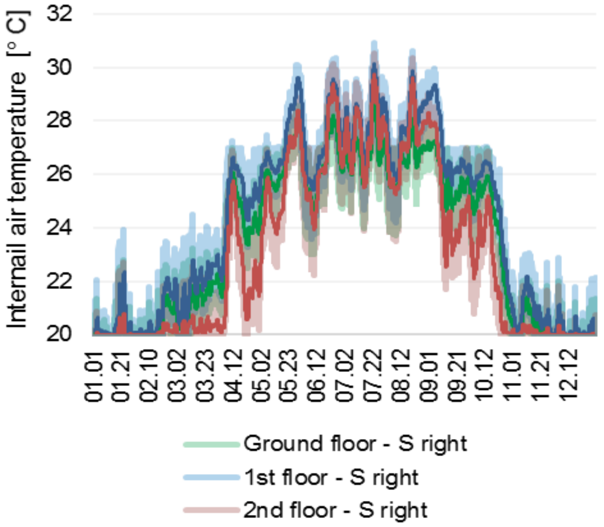

Fig. 11 *Internal air temperature fluctuation in the reference model*

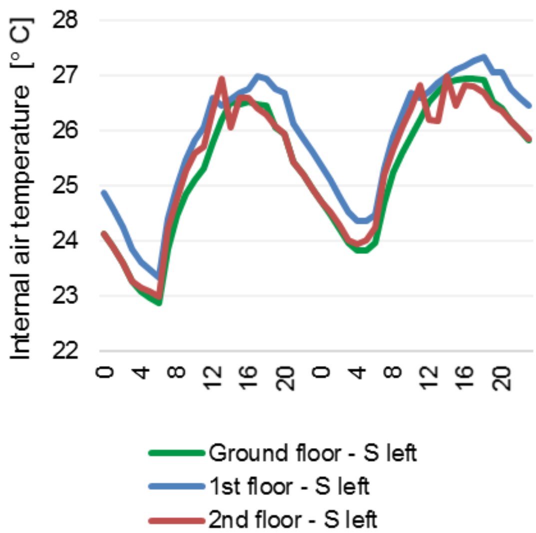

Fig. 12 *Internal air temperature fluctuation (4 1/h model)*

Increasing the rate of night ventilation significantly reduced the number of overheated hours, by using a value of 4 1/h by 36% and using a value of 6 1/h by 52%. Figure 12 shows the internal air temperature for 2 days. It can be noticed that night-time (between 8 pm. and 6 am.) elevated ventilation greatly helps to cool down the zone's internal temperature.

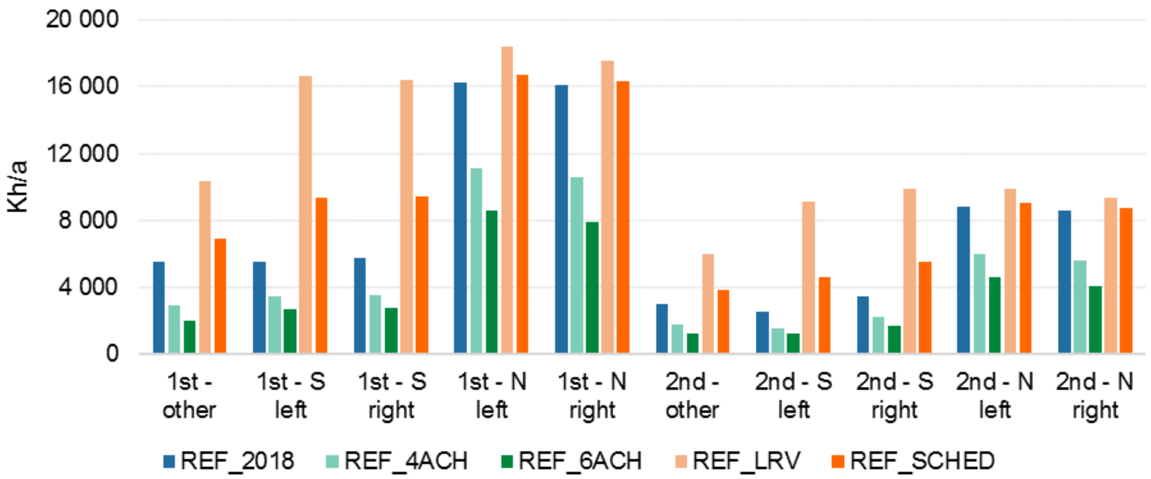

Fig. 13 *ODH_{26} values in the reference building and with different ventilation/shading*

In case of shading options, the "reduce overheating" method was the most effective, where the sunscreen device was closed as long as the maximum temperature defined in the design conditions was exceeded. With the "Limit radiation value" a maximum radiation can be entered. As long as the solar radiation exceeds this value, the device will stay closed. In this case this maximum radiation value was set to 500 W/m^2. In the last setting, during the summer period a schedule was given where the shutters were gradually lowered. They were rolled down in the morning and most of the time in the afternoon. ODH_{26} indicator values achieved by different user habits are shown in Figure 13.

With these results we created an optimized model, where the highest air change rate and the optimal shading method were used simultaneously, furthermore we used the future climate scenarios too. Based on Figure 14, it can be said that the optimized model managed to reduce the number of overheated hours by 50–75%.

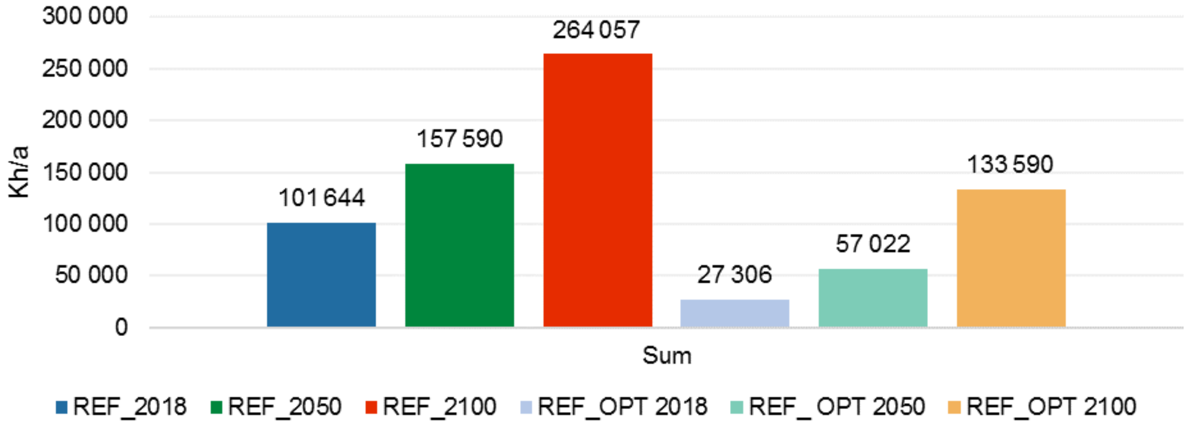

Fig. 14 *ODH_{26} values in the reference building and in the optimized model according to 3 climate scenarios*

4 Conclusions

This research contributed greatly to the assessment of the condition of Budapest's nursing homes. About half of Budapest's capacity submitted the forms and shared their opinions on the subject. Based on the results of the survey, it can be said that this group of buildings is quite vulnerable. In many cases an energy-related renovation had been carried out, but the majority of the homes are not satisfied with the indoor temperature in the buildings.

Based on the survey, the summer overheating of buildings is a very serious problem today in Hungary and it is of utmost importance to address not only the reduction of winter heating energy demand but also the overheating of buildings in summer.

The database created during the research can form the basis of subsequent analyses and can help create a vulnerability index.

Based on the results of the dynamic simulation, we determined the main parameters that play a major role in reducing the internal temperature in the summer. They can provide useful guidance for improving the overheating of a "free-running" type building during summer. Since the results clearly reveal the importance of user habits, it may be worthwhile to draw the attention of residents to the proper building management habits and their importance.

There is no analysis of artificial cooling in this paper, but it may be interesting to analyse it, as it may be an important factor in setting the internal optimum temperature in the future. It is necessary to examine the effect of the building structure on the building's warming, which would allow conclusions to be drawn on the whole of Budapest with the examination of several other buildings.

Acknowledgement

The publication of the work reported herein has been supported by ETDB at BME. Project FK 128663 has been implemented with the support provided from the National Research, Development and Innovation Fund of Hungary, financed under the FK_18 funding scheme. The research reported in this paper was also supported by the FIKP grant of EMMI in the frame of BME-Water sciences & Disaster Prevention (BME FIKP-VÍZ).

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A Study on Multi Objective Optimization Applications Used to Optimize Building Shape for Energy Efficiency

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Abstract

Energy efficiency improvement has been proposed as a shared policy goal for many governments around the world in order to find solutions to the problems such as energy dependency, global warming and climate change. The building sector has an important role in total energy consumption, carbon dioxide emissions and greenhouse gases on the planet. Building energy efficient design optimization technique can be seen as a productive approach in the conceptual design stage in comparison to the conventional "trial-and-error" design methodology since the latter is largely dependent on designers' knowledge and experience. This study analyses the multi-objective optimization studies that deal with building shape to improve energy performance of buildings. The results are presented based on several features such as optimization algorithms, optimization objectives, energy simulation programs and building typologies in order to present the current research trends in literature.

Keywords: *Multi objective optimization, energy performance, energy efficiency, building shape*

1 Introduction

The building shape is one of the most important considerations in the conceptual stage of building design (Wang et al., 2006). The shape of the building affects many performances, such as energy consumption, daylight usage, layout configuration, functional accessibility, shading performance, solar gain, acoustics, and others (Ekici et al. (2019), Kheiri (2018)).

The research on building energy efficient design optimization which was not an active field throughout 1980s and 1990s, showed a clear upward trend in the number of core literature published over time especially in the past five years (Shi *et al*., 2016). The multi-objective optimization methods have become the norm from 2009 onward (Lin, 2014).

Burry&Burry (2010) states that optimization has been used in an architecture as a form-finding tool. The art of architecture always engages, at some level, the search for an optimal formal, spatial, constructional answer to diverse aesthetic and performance measures. Structural economy, flows of air, heat, the best use of natural light and acoustic performance are all valid goals for optimization routines.

According to Si *et al.* (2016), the conventional "trial-and-error" design methodology is largely dependent on designers' knowledge and experience and building energy efficient design optimization technique is a more efficient, more powerful design solution. Since early design decisions have a more profound impact on the final quality of buildings compared with decisions made later in general, optimization techniques are especially productive if they are applied in the architectural conceptual design stage (Tian *et al*., 2015).

Multi-objective optimization which has to combine two aspects: optimization and decision support, engages optimization in the presence of more than one objective functions. The major difference between single and multi-objective optimization is that in the case of latter, there is usually no single optimal solution, but a set of equally good alternatives with different trade-offs, also known as Pareto-optimal solutions (Karmellos *et al*., 2015).

According to Tian *et al*. (2015) the existing building energy optimization techniques can be classified into three categories:

- Stand-alone optimization tools such as GenOpt,MATLAB,Dakota,modeFRONTIER and ModelCenter,
- Optimization engine oriented tools such as GENE_ARCH,MOBO,jEPlus+EA and MultiOpt,
- Building Energy simulation tool- based optimization tools such as Design Builder optimization module, BEopt, and Opt-E-Plus.

Mora et al. (2018) state that MATLAB toolbox and GenOpt are the most used optimizations tools. Building optimization procedures typically consist of six distinct steps that can be repeated in an iterative manner (Touloupaki& Theodosiou (2017):

- Identification of design variables and constraints.
- Selection of simulation tool and creation of a baseline model.
- Selection of objective function(s).
- Selection of optimization algorithm.
- Running simulations until optimization convergence is achieved.
- Interpretation and presentation of data.

Shi *et al*. (2016) made a comprehensive analyze in the core literature in building energy efficient design optimization. In this study, it was seen that minimizing the annual energy consumption, CO_2 emissions and reducing life cycle costs are the main design objectives found in the core literature. The study also showed that 66.4% of cases were on simplified and fictious buildings, whereas 27.6% were on real-world buildings. In addition, residential (28), office (27) and educational buildings (7) were the three most common building types studied in the literature.

Ekici et al. (2019) made a systematic review and summary of performative computational architecture using swarm and evolutionary optimization by focussing on different aspects of buildings. The authors stated that NSGA-II was mostly used for multi-objective optimisation problems.While the major building topic was the building's skin, studies on the building layout and building shape were almost equally distributed.In the analyzed literature, combinations of objectives in regard to sustainability such as energy,daylight,solar radiation, environmental impact, thermal comfort and holistic sustainability were dominant.

2 Method

Three stages applied during the article search process in this study are listed as follow;

- Stage 1: Science Direct Database is used for article selection.
- Stage 2: “multi objective optimization”, “shape”, “form”, “buildings” and “architecture” were searched to decide the academic journals used for the article search.
- Stage 3: A two-round article selection strategy was applied. In the first round, “Title and abstract” of the articles were checked. After that, unrelated articles were excluded. In the second round, “The whole article” was analysed. 15 articles were selected and used in the study.

3 Analysis on selected articles

3.1 Optimization Algorithms

Si *et al.* (2016) group the commonly used algorithms in the energy efficient design optimization for buildings into three categories, namely evolutionary algorithms (EAs), derivative-free search algorithms, and hybrid algorithms. Since the mid-eighties, substantial literature has been developed and several types of EAs (Genetic Algorithms, Evolutionary Programming and Genetic Programming, Covariance Matrix Adaptation Evolutionary Strategy, Differential Evolution, Harmony Search, Particle Swarm Optimization, Ant Colony Optimization and Simulated Annealing) have been identified (Touloupaki&Theodosiou, 2017).

Non-dominated Sorting Genetic Algorithm II was mostly used algorithm in the analyzed journal papers (Méndez Echenagucia et al.(2015), Wu et al.(2018), Chen & Yang (2017), Yu et al.(2015), Brown&Mueller (2016), Gou et al. (2018), Chen et al. (2018)). Apart from these, genetic algorithm (Zhang et al. (2016), Wang et al. (2006), Implicit Redundant Representation Genetic Algorithm (IRRGA) (Song et al.,2016), Heuristic Algorithm of Simulated Annealing (HASA) (Quaglia et al., 2014), Multi Agent Based Swarm Intelligence Algorithm (SIA) (Agirbas, 2019) were the other algorithms used in the analyzed journals. Moreover, Camporeale et al.(2017) used Grasshopper (GH) evolutionary solver Galapagos which is a genetic algorithm framework. Zhang et al. (2017) and Konis et al. (2016) used Octopus which is based on Strength Pareto Evolutionary Algorithm 2 (SPEA 2). The algorithms used in the studies are presented in Table 1.

Tab. 1 *Algorithms used in the studies*

		Algorithms					Frameworks	
		NSGA-II	Genetic Algorithm	IRRGA	HASA	SIA	Galapagos	Octopus
2006	Wang et al.		x					
2014	Quaglia et al.				x			
2015	Yu et al.	x						
2015	Echenagucia et al.	x						
2016	Zhang et al.		x					
2016	Song et al.			x				
2016	Brown&Mueller	x						
2016	Konis et al.							x
2017	Chen&Yang	x						
2017	Camporeale et al.						x	
2017	Zhang et al.							x
2018	Gou et al.	x						
2018	Chen et al.	x						
2018	Wu et al.	x						
2019	Agirbas					x		

3.2 Optimization Objectives

Méndez Echenagucia et al. (2015) and Chen&Yang (2017) set the optimization objectives as heating, cooling, and lighting to improve energy performance of buildings. Camporeale et al. (2017) aim to minimize heating and cooling demand and maximise Net Present Value. Gou et al. (2018) aim to improve indoor thermal comfort while reducing building energy demand. Yu et al. (2015) aim to reduce energy consumption and increase thermal comfort. While Wu et al. (2018) focus on life cycle energy and life cycle cost (LCC), Wang et al. (2006) focus on life cycle environmental impact and LCC. There are studies which aims to balance structural efficiency with embodied and operational energy (Brown and Mueller, 2016) and energy efficiency (Quaglia, 2014). While some studies aims to improve thermal comfort (Yu et al. (2015), Zhang et al. (2017), Gou et al. (2018), Chen et al. (2018)), some studies aim to maximise direct sunlight (Zhang et al., 2016) and to optimize daylight (Agirbas, 2019). In addition, Konis et al. (2016) and Chen et al. (2018) focus on ventilation and daylighting. Figure 1 indicates the distribution of optimization objectives in the analysed journals.

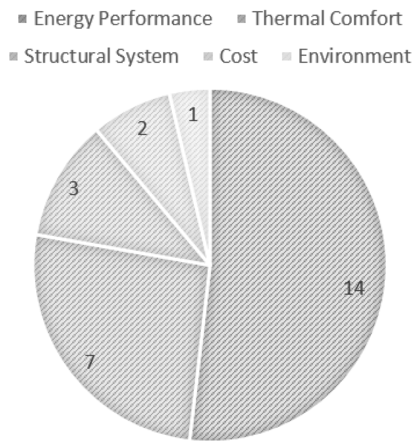

Fig. 1 *Optimization Objectives Applied in the Studies*

3.3 Energy Simulation Programs

Computer simulations are a powerful tool for studying the environmental performance of buildings since they provide useful feedback for the on-going process of design (Touloupaki& Theodosiou,2017).It becomes necessary to use an optimization method coupled with energy simulations to find the optimal building shape that balances the two objectives (Zhang et al.2016). It was seen that Energy Plus is most widely used energy simulation engine in the analyzed literature (Méndez Echenagucia et al.(2015), Chen&Yang (2017), Yu et al. (2015), Quaglia et al.(2014), Camporeale et al. (2017), Konis et al. (2016), Gou et al. (2018), Chen et al. (2018)). Apart from that, Zhang et al. (2016) use Ladybug to calculate the amount of solar radiation gain. Wu et al.(2018) use Design Builder and Matlab. While, Agirbas (2019) uses Diva plugin in Rhinoceros, Zhang et al. (2017) uses Radiance for daylight analysis. Figure 2 presents the energy simulation programs used in the journals. Kheri (2018) made a review on the optimization research. Energy Plus was also used most frequently among the building energy performance assessment methods.

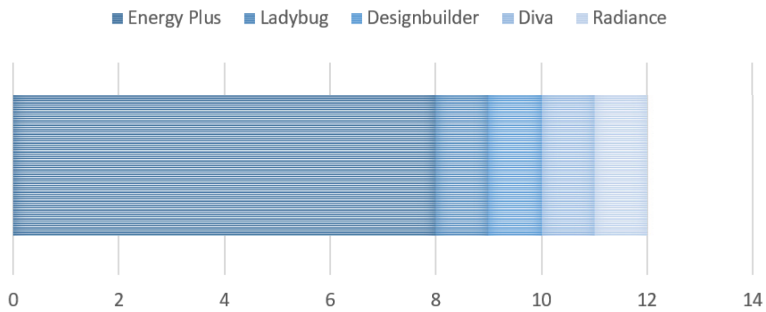

Fig. 2 *Energy simulation programs used in the journals*

3.4 Building Type used in the optimization studies

Majority of the studies used residential buildings in their study such as Cheng&Yang (2017), Yu et al. (2015), Song et al. (2016), Camporeale et al. (2017), Gou et al. (2018), Chen et al. (2018). In addition, office (Méndez Echenagucia et al.,2015, Wang et al.,2006), community centre (Zhang et al.,2016), military and disaster relief housing (Quaglia et al., 2014), and school building (Zhang et al.,2017) typologies are studied. Moreover, Wu et al. (2018) made their study based on a solar decathlon house. Brown & Mueller (2016) studied three case study building with long span roofs and Agirbas (2019) studied a façade of row houses.

4 Conclusions

This study focuses on multi objective optimization studies which deal with building shape to improve energy performance of buildings.15 studies analyzed using Science Direct Database. The findings of the analyses can be summarized as follow:

- NSGA-II which is an instance of an evolutionary algorithm was the major optimization algorithm used in the studies.
- While energy efficiency was the most dominant optimization objective, thermal comfort which included daylighting and ventilation control was the second most widely studied optimization objective. However, the number of studies which focus on thermal comfort was much less compare to energy efficiency.
- Energy Plus was the most widely used energy simulation program in the analyzed journals.
- Majority of the journals focused on residential building typologies in their study.

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Thermal and Visual Performance Analysis of a Low-cost Passive Solar House, South Africa

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Abstract

Low-cost housing in South Africa is characterised as inefficient, owing to their inability to utilise ambient weather factors to enhance indoor thermal conditions. A passive solar house was therefore constructed as an energy efficient low-cost house prototype. This study aims to analyse the thermal and natural lighting performance of the passive solar house. The house indoor and ambient weather parameters were monitored over a year. The indoor illuminance at table level was also obtained. During the winter season which presents the worst thermal performance, 13 and 29% of the ambient air temperature and relative humidity, respectively were in the thermal comfort zone. The indoor temperature had 23% in the thermal comfort zone and 78% of the air relative humidity. Also, an evenly distributed daylighting across the floor area, equivalent to the recommended residential illuminance of 0.2 klux was observed. The favourable indoor conditions are attributed to the north-facing clerestory windows.

Keywords: *passive solar design, low-cost housing, thermal performance, daylighting*

1 Introduction

Over the years, building energy consumption as well as resultant greenhouse gas (GHG) emission is increasing due to building design, occupants behaviour, choice of technology usage, manufacturing and construction processes [1]. Globally, the building sector accounts for half of the world electricity demand, with some region electricity consumption increased by 500% [2]. Energy consumption in the residential sector comprises mainly of space heating, cooling, domestic activities (cooking), and electric lighting. Moreover, the rate of energy consumption varies from one region to another due to energy affordability, energy availability, household income level, energy policies, housing policies, household characteristic, among others. [3]. According to International Energy Outlook (IEO) 2016, residential energy consumption in Organisation for Economic Cooperation and Development (OECD) nations is predicted to increase at an average of 0.6% per annum from 2012 to 2040. For the same period, non-OECD nation's residential energy usage is expected to grow faster, at an average of 2.1% per annum. In addition, residential energy consumption will be responsible for 80% of global energy consumption over the 28 years [4].

Africa accounts for only 3% of the total global GHG emission in 2013 with South Africa responsible for more than one-third of the total [5]. Considering that approximately 90% of South African electricity is generated from coal-fired power plants, residential energy consumption contributes to the country and the continent's carbon footprint. [6]. According to the South African national power utility company, approximately 200 TWh of energy was generated from coal-fired plants between 2017 and 2018. The residential sector with about 12 TWh was the second largest consumer [7]. The high energy consumption in the sector is related to the massive construction of low-cost housing (LCH) in the Reconstruction Development Programme (RDP) and electrification of rural settlements [8]. Since the initiation of RDP in South Africa, over 1.2 million LCH have been built. These houses were designed with no consideration of thermal energy efficiency, as they cannot utilise solar energy for space heating. Also, uncontrollable heat exchange between the inner and outer space of the house due to openings and cracks on the building envelope; leaves the inner space extremely cold in winter. Hence low-cost households consume a significant amount of energy to achieve indoor thermal comfort [9]. Provision of LCH is a positive approach to development in the country, but in-cooperating passive solar design will improve the welfare of occupants, and minimise overall energy consumption in the sector as well as the resultant carbon footprint of the country. In this regards, a single family passive solar house was designed and constructed in SolarWatt Park as an energy efficient low-cost house prototype.

The aim of this study is to analyse the indoor thermal and visual performance of the passive solar house. Hence the indoor air temperature and relative humidity over a given period were evaluated against their respective ambient parameters and analysed base on the South African indoor thermal recommendation. A similar procedure was also adopted in analysing the visual performance of the house.

2 Location and passive solar house description

The passive solar house used in this study is located in SolarWatt Pack in the University of Fort Hare, Alice. The University is located in latitude 32.8° south and longitude 26.8° east at an altitude of 540 m in Alice, Eastern Cape province in South Africa. According to the Köppen-Geiger climate classification, Alice is in the BSh Arid, Steppe, Hot arid climate. Such a climate is characterised by annual precipitation greater than 5 Pth. The annual temperature is greater than or equal to +18ºC [10]. Locally, Alice is classified in the temperate interior (Zone 2) climate of South Africa [11] The Google Earth view of SolarWatt Park and a photo of the passive solar house is given in Fig. 1.

Fig. 1 *Google Earth view of SolarWatt Park indicating the passive solar house*

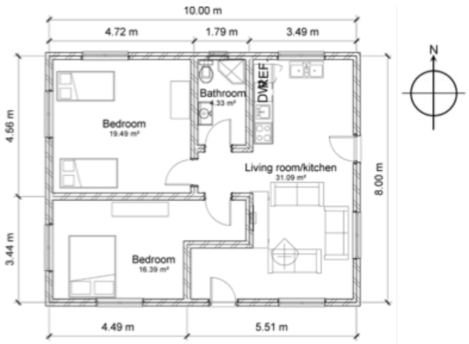

Fig. 2 *Space layout of the passive solar house*

The site as shown in Fig. 1 was found suitable for the house due to its clear north side with no sun rays' obstacle such as tall trees, mountains, and high rise buildings. In line with the energy efficient building design recommendation by SANS 204 and 10400-XA [12], the house was designed with its major glazing area facing north. The selected glazing orientation is to ensure maximum penetration of solar radiation during the winter season. At the same time, the 44 cm long eaves prevent solar radiation from the inner space in summer. Thereby, preventing overheating during the summer season and providing passive heating in winter. In this regard, the clerestory windows were used to release indoor warm air due to convection current to achieve passive cooling [13].

The space layout of the house given in Fig. 2 indicates that the 10 m x 8 m (80 m^2) floor area of the house comprises of three rooms. These include an open plan living room/kitchen, stretching from north to south elevation of the house, a bathroom, north and south facing bedrooms. The rooms were arranged in the house to ensure optimum and uniform admittance of solar radiation.

3 Research method

3.1 Ambient and indoor weather parameters measurement

The indoor and outdoor air temperature, as well as the relative humidity, was measured with an HMP60 temperature and relative humidity probe. The HMP60 probe uses a platinum resistance temperature (PRT) detector to measure air temperature and a capacitive relative humidity sensor to measure relative humidity [14]. The measurement specifications of HMP 60 probe temperature and relative humidity sensor are given in Tab. 1 [15].

Tab. 1 *HPM 60 temperature and relative humidity sensors specification*

Parameters	Measurement range		Accuracy (±)
Temperature (°C)	-40 to +60		0.6
Relative humidity (%)	at 0°C to 40°C	0 to 90	3
		90 to 100	5
	at 0°C to 40°C and +40°C to +60°C	0 to 90	5
		90 to 100	7

Three sets of HMP60 probes were used to measure the indoor air temperature and relative humidity. In the living room/kitchen, south and north facing bedrooms one HMP60 probe was suspended at the height of 0.8 m. This was to ensure that the measured air temperature is nearest to the temperature felt by the occupants, and the probe does not obstruct their activities. The locations of the HMP60 probe in the house are indicated in Fig. 3. Fig. 4 shows the shielded ambient air temperature and relative humidity sensor.

Fig. 3 *Passive solar house space layout indicating indoor thermal sensors*

Fig. 4 *Ambient weather station*

The ambient air temperature and relative humidity measuring probe were housed in a 6-plate natural aspirated radiation shield (dash-line box in Fig. 4). The white painted radiation shield enables it to reflect solar radiation. At the same time, the louvre allows natural free flow of air through the shield. Thereby keeping the probe close as possible to the ambient air temperature (eliminating solar effect) and water vapour [16]. It should be noted that the scope of this paper is limited to indoor and ambient air temperature and relative humidity measurements concerning the sensor indicated in Fig. 3 and 4.

3.2 Indoor illuminance measurement

The amount of light (electric and daylight) in the passive solar house which is determined by the illuminance level was measured using a LI-210R cosine correction photometric sensor. LI-210R photometric sensor uses a precision filtered silicon photocell that is sensitive to visible light to measure the amount of light in a work plane. The silicon photocell is mounted on a cosine-corrected head, thereby measures irradiance from all direction based on Lambert's cosine law. The LI-210R sensor has a sensitivity of 30 µA per 100 klux and a response time of <1 µs [17]. The setup of the photometric sensors in the living room of the passive solar house is presented in Fig. 5.

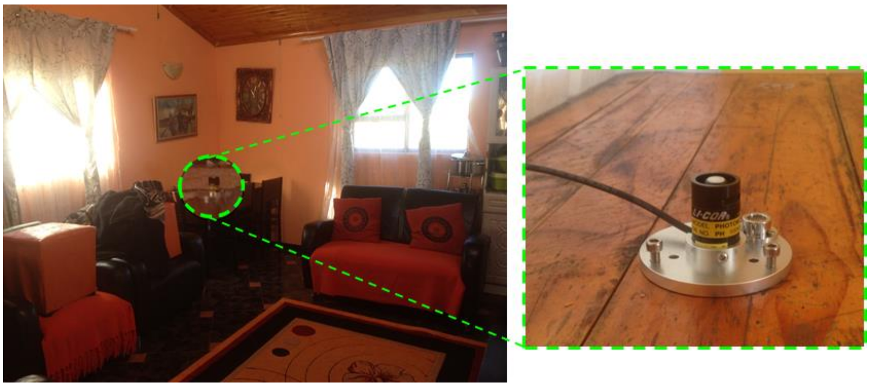

Fig. 5 *Indoor illuminance set up*

Due to lack of sufficient sensors, the illuminance level of the living room was measured only and used as a yardstick for the other rooms in the house. Moreover, the illuminance measurement targeted the maximum light perceived by an occupant performing any activities at table level. To this effect, the photometric sensor was placed on a 1 m high table in the living room and 0.5 m away from an east facing window.

4 Results and discussions

4.1 Thermal performance analysis

Data collection was initiated in September 2016 and continued until September 2017 amounting to a total of 17937 data entries. Uncontrollably, 5% (944) of data entries were lost due to system failure and period shutdown of the data acquisition system. The missing data occurs in November 2016, December 2016, February 2017 and March 2017. The periods of missing data in the affected months were excluded in data analysis going forward. In addition, measured data were analysed and presented in average summer and winter days for simplicity. Therefore, the four seasons in South Africa were classified into summer and winter. Data obtained from 1 September to 31 May were grouped as summer while 1 June to 31 August was treated as winter season.

4.1.1 Zonal air temperature and relative humidity variation

The floor plan of the house (see Fig. 3) was virtually partitioned into three thermal zones for analysis purposes. The living room/kitchen was represented by Zone 1 while the north- and south-facing bedrooms were zones 1 and 2 [13]. The effect of the various activities and orientation of the zones on the whole building air temperature and relative humidity were considered. Hence, the air temperature and relative humidity in each zone of the house were measured separately. Seasonal daily indoor air temperature and relative humidity profiles of the various zones in the house are given in Fig. 6 and 7. In both Figures, the vertical bar charts; below and above respectively represent the air temperature and relative humidity percentage difference between the three zones in the house.

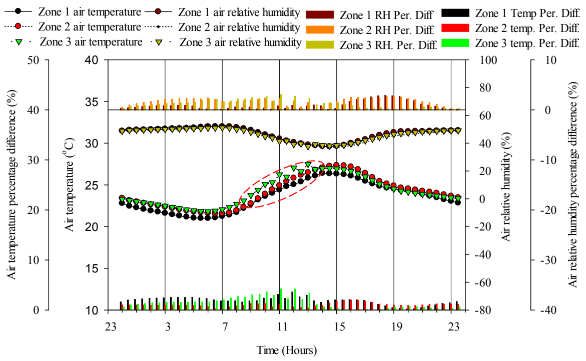

Fig. 6 *Typical summer day air temperature and relative humidity distribution in the various zones*

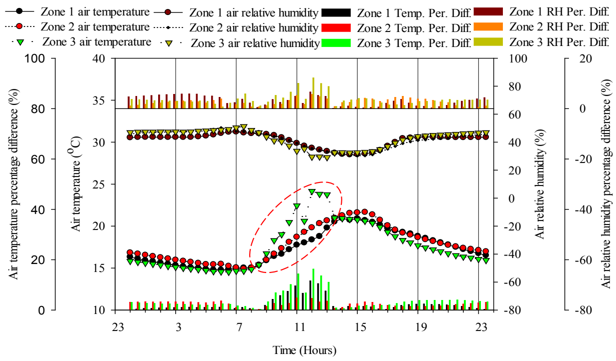

Fig. 7 *Typical summer day air temperature and relative humidity distribution in the various zones*

On a typical summer day, the air temperature percentage difference was 4% at 12h00 and a corresponding relative humidity of 3% at 11h00. A higher percentage difference was observed in winter at the same time, the air temperature and relative humidity percentage difference were found to be 16% and 12%, respectively. Further findings are populated in Tab. 2 and 3.

In both Tables, the daily swing refers to the difference between the daily maximum and minimum air temperature and relative humidity obtained. In Tab. 2, a fairly constant daily air temperature swing of an average of 5.6°C was observed, although the relative humidity swing in each zone varies. This was expected given that the presence and activities of occupants in a room are a contributing factor to the air relative humidity.

Tab. 2 *Typical summer day indoor air temperature and relative humidity variation in the house zones*

Zone	**1**		**2**		**3**	
Indoor weather parameter	**Temp. (°C)**	**RH (%)**	**Temp. (°C)**	**RH (%)**	**Temp. (°C)**	**RH (%)**
Daily swing	5.4	14.4	5.8	16.1	5.7	13.5
Max. Per. Diff. (%) (Equiv. Temp.)	4 (0.9°C)	2.9 (1.3%)	2 (0.5°C)	2.7 (1.2%)	4 (1.1°C)	3.1 (1.3%)
Peak Time	12h00	18h30	16h00	18h30	11h00	11h00
Average Per. Diff. (%) (Equiv. Temp.)	2 (0.4°C)	0.9 (0.4%)	1 (0.2°C)	1.7 (0.8%)	1 (0.3°C)	1.1 (0.5%)

Tab. 3 *Typical winter day indoor air temperature and relative humidity variation in the house zones*

Zone	**1**		**2**		**3**	
Indoor weather parameter	**Temp. (°C)**	**RH (%)**	**Temp. (°C)**	**RH (%)**	**Temp. (°C)**	**RH (%)**
Daily swing	6.1	16.3	6.7	20.0	9.6	22.2
Max. Per. Diff. (%) (Equiv. Temp.)	11.6 (2.4°C)	6.5 (2.2%)	4.8 (0.9°C)	5.7 (1.9%)	16.2 (3.4°C)	12.2 (4.1%)
Peak Time	12h00	12h00	11h00	12h00	12h00	12h00
Average Per. Diff. (%) (Equiv. Temp.)	2.2 (0.4°C)	3.1 (1.3%)	2.3 (0.4°C)	2.5 (1.0%)	3.9 (0.7°C)	3.6 (1.5%)

Furthermore, varying air temperature and relative humidity were observed in each zone during winter days. This implies that a relatively high diurnal temperature variation was experienced during the winter season. Also, zone 3 had the maximum daily air temperature swing of 9.6°C, which was as a result of the north facing clerestory windows. Recall that the house was designed to optimise even air temperature indoors. Hence, the clerestory windows were installed to distribute solar radiation to the south floor area of the house. The red highlighted dash circle in Fig. 9 and 8, indicates air temperature increase in zone 3 (south facing room) due to penetrated solar radiation; consequently increases the day and night air temperature difference in the zone.

4.1.2 Whole building weather response to ambient air temperature and relative humidity

The average air temperature and relative humidity in each zone of the house were obtained and used as the whole building air temperature and relative humidity, respectively. Summer season frequency distribution of the whole building and ambient air temperature is given Fig. 8 and relative humidity in Fig. 9.

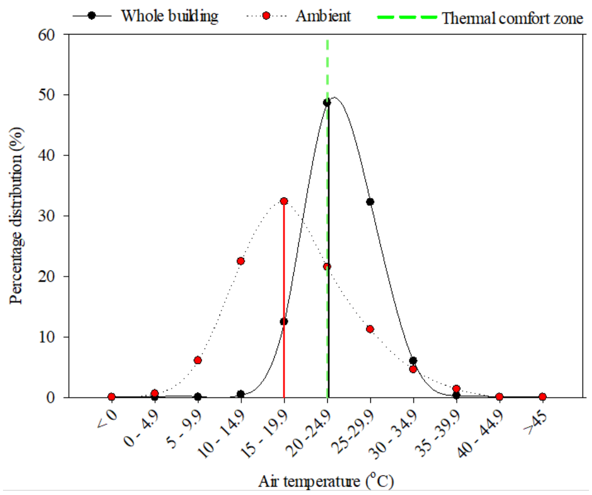

Fig. 8 *Whole building and ambient air temperature summer season distribution*

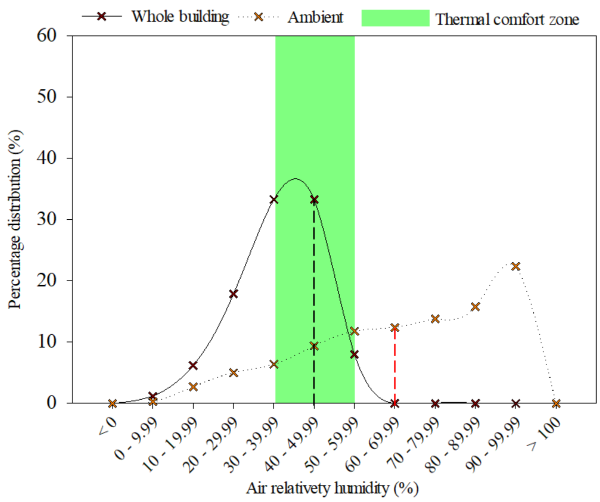

Fig. 9 *Whole building and ambient air relative humidity summer season distribution*

A total of 12607 data entries were used to develop the summer whole building and ambient air temperature and relative humidity distribution profile. In Fig. 8, the whole building and ambient air temperature distributions were divided into nine classes of 4.9°C width. The air relative humidity frequency distribution curves in Fig. 9 are made of 11 classes of 9.99% width. Statistically, the whole building and ambient air temperature are not normally distributed.

In both figures, the broken green line and band respectively indicate the indoor air temperature (20°C and 24°C) and relative humidity (30% and 60%) thermal comfort zone [18]. In this regards, 49% of the whole building air temperature as well as approximately 85% of its corresponding relative humidity were found within the thermal comfort. Whereas, only 21% and 28% of the ambient air temperature and relative humidity, respectively were in the thermal comfort zone.

In the winter season, a total of 4386 data entries were used to develop the whole building thermal condition, ambient air temperature and relative humidity distribution. Fig. 10 shows the measured winter season ambient and whole building air temperature as well as the resultant relative humidity in Fig. 11.

From Fig. 10 and 11, the mean of the whole building air temperature drifts away from the thermal comfort zone; leaving only 23% of the whole building air temperature distribution in the thermal comfort zone. However, the percentage of the ambient air temperature in the thermal comfort zone deviates by 10%. Whereas, approximately 78% and 29% of the whole building and ambient air relative humidity, respectively were inside the thermal comfort zone.

Furthermore, average daily seasonal whole building air temperature and relative humidity distribution concerning the indoor thermal comfort zone were generated and presented in Fig. 12 and 13.

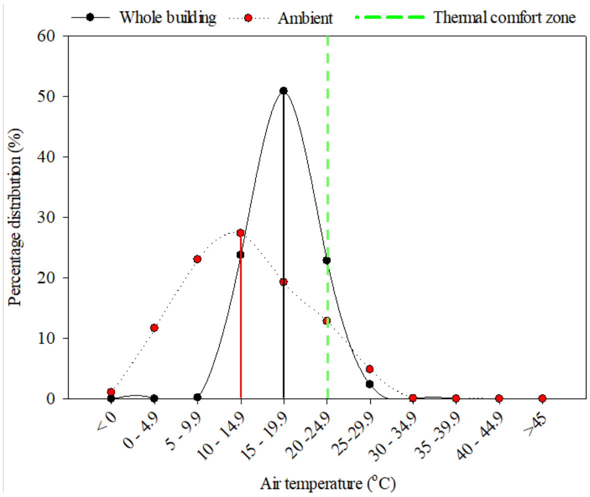

Fig. 10 *Winter season whole building and ambient air temperature distribution*

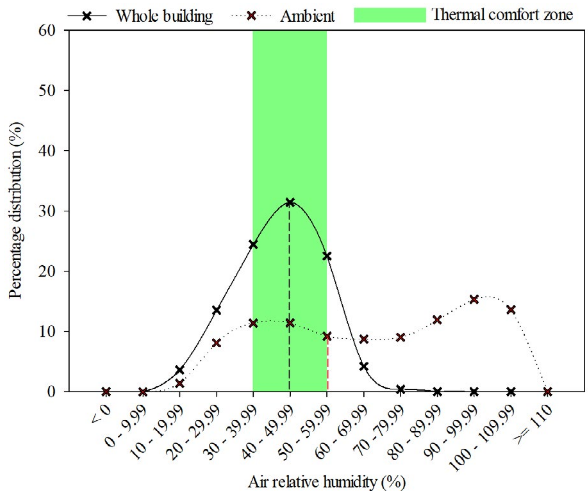

Fig. 11 *Winter season whole building and ambient air relative humidity profile*

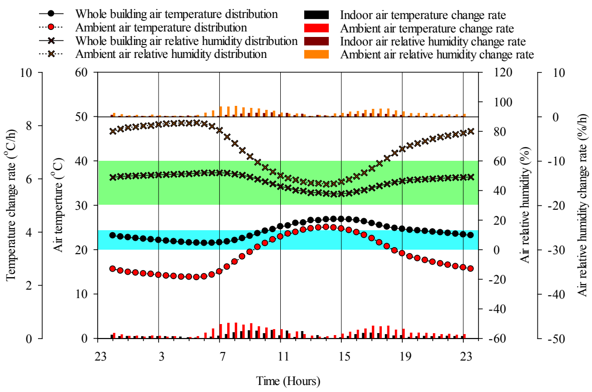

Fig. 12 *Average summer day whole building indoor weather condition response to ambient air temperature and relative humidity*

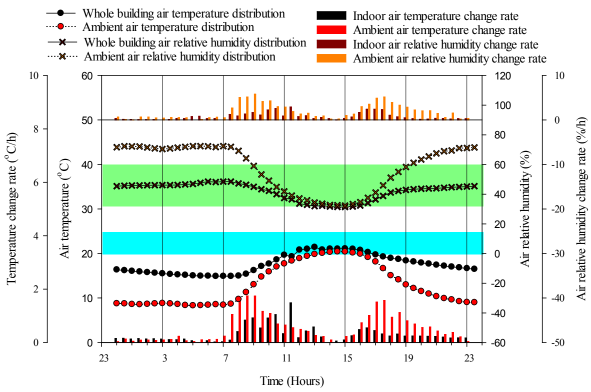

Fig. 13 *Average winter day whole building indoor weather condition response to ambient air temperature and relative humidity*

The whole building relative humidity was entirely within the thermal comfort zone in the summer season but the ambient air relative humidity in the thermal comfort zone for only 38% of the day. In teams of temperature, the whole building and ambient air were found to be out of the thermal comfort zone 46% and 77% of the day, respectively. On an average winter day, the ambient air temperature was found to be in the comfort zone for only 5% of the day. Its resultant air temperature was in the thermal comfort zone for 21% of the day. On the other hand, the whole building relative humidity was completely in the thermal comfort zone once again. However, 21% of the distribution was found to occupy the lower (30 to 35%) level of the thermal comfort zone. The ambient air relative humidity was however within the thermal comfort zone 44% of the day.

Regarding the daily air temperature and relative humidity variation, a relatively vigorous behaviour was observed in the average winter day. The average winter day had the maximum daily temperature and relative humidity change rate with the whole building temperature change rate of 0.59 °C/h and 1.48 %/h relative humidity. The ambient temperature change rate of 1.03 °C/h while its corresponding relative humidity was 3.53 %/h. Regardless of the seasons, the ambient temperature and relative humidity change rate were found to be approximately twice the whole building temperature and relative humidity, respectively. In both seasons, the level of thermal comfort achieved indoors agrees with the findings of Golden [19].

4.2 Visual performance analysis

In addition to the indoor space heating through optimum solar admittance, enhanced indoor daylight is also achieved through the transmission of the sun's rays. Hence, the clerestory windows transmit solar radiation to the southern floor area of the house while the two large north facing windows provide solar radiation to the north facing area (see fig. 3). Thus, uniform and maximum daylight illuminance can be achieved indoors. The indoor illuminance level which includes daylight and electric light over a week is shown in Fig. 14.

The indoor illuminance distribution in Fig. 14 can be classified into clear and cloudy sky days based on the maximum daily illuminance obtained. In other words, days with maximum illuminance greater than 0.2 klux were considered as clear sky days while days with maximum illuminance less than 0.2 klux were cloudy sky days. In line with the above assumptions, 21 to 26 May were clear sky days, and the average maximum illuminance was 0.30 klux. Whereas, 27 and 28 May with average maximum illuminance equal to 0.19 klux were considered as cloudy sky days. An average clear and cloudy sky day's illuminance profile of the house is presented in Fig. 15.

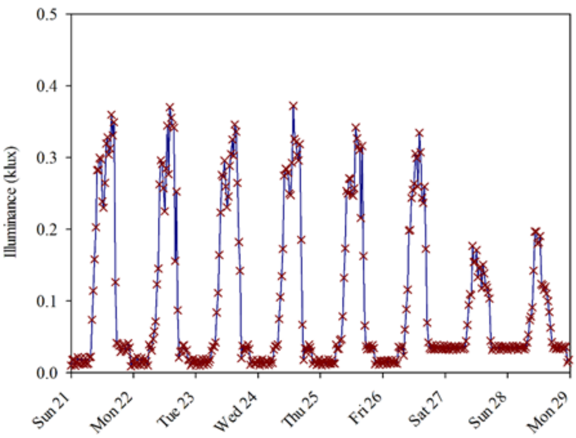

Fig. 14 *The passive solar house indoor illuminance distribution*

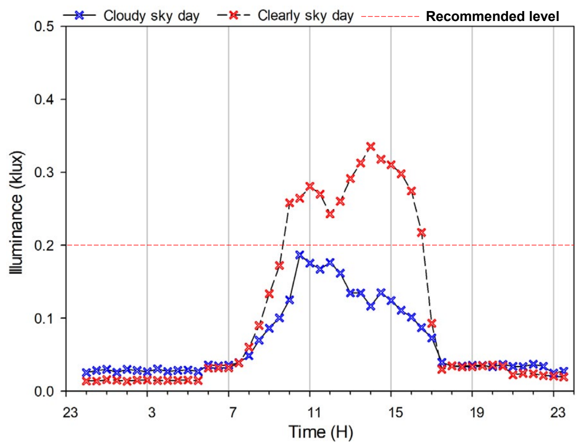

Fig. 15 *Typical clear sky and cloudy sky day's indoor illuminance distribution of the passive solar house*

The average maximum illuminance obtained during the cloudy sky day was equivalent to the recommended illuminance for an occupant in the kitchen, dining room or performing major domestic activities at table level [20]. The average illuminance before and after the peak illuminance period (08h00 to 17h30) on a cloudy sky day was 0.04 klux and 0.01 klux on a clear sky day. The obtained illuminance during the period mentioned above was due to electric lights, ambient street lights and moonlight. It should be noted that both cloudy sky days were weekends. It was observed that during the weekends, the occupants were often out of town and switched on the electric light all through the day for security reasons. Between the peak illuminance period (8h00 and 17h30), an average of 0.23 and 0.12 klux was respectively observed indoor on a clear and cloudy sky day.
From Fig. 15, it can be said that daylighting is sufficient for visual activities in the house on a clear sky day during peak illuminance period. However, electric light will be required to perform visual tasks comfortably. Therefore, energy savings can be achieved by switching off of electric lights during peak illuminance period. Integrating the electric lights with an adjustable photocell switch, which automatically switches off the electric light at a pre-set indoor illuminance, is recommended for effective lighting energy saving; since the human eyes cannot reliably determine illuminance level.

5 Conclusions

The aim of this study is to analyse the indoor thermal and visual performance of a passive solar house. The whole building average air temperature was found to be in the thermal comfort zone for 54% on a typical summer day and for only 5% on a typical winter day. Moreover, the whole building relative humidity was entirely in the thermal comfort zone in both seasons. It was also found that on a clear sky day, daylighting is sufficient for visual activities in the house. However, electric light is required on a cloudy sky day to perform visual tasks comfortably. Based on the findings of this study, passive solar design can reduce excessive energy consumption in the South African residential sector through passive cooling and daylighting. However, further studies on passive solar house design are recommended to enhance passive heating.

Acknowledgement

This work was based on the research supported by the National Research Foundation (Grant number 116763) of South Africa, Department of Science and Technology and Govan Mbeki Research and Development Centre.

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Buildings and Climate Change

Parametric Optimization of Carbon Footprint

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Abstract

Carbon footprint is a form of estimating the environmental impact of an object. It is desirable to develop time-efficient methods for evaluation of early design phase decisions. One possible way is the usage of simplified Life Cycle Assessment. The study considers the product phase (A1-A3) – „embodied carbon" and operational energy use stage (B6) – „operational carbon", as those are typically the main impact factors. There is possibility to optimize building's carbon footprint via evolutionary algorithms in connection with generating different possible combinations of building shape, materials, and other architectural elements like windows. Each case is being evaluated by the energy use during lifecycle – which is then calculated into carbon dioxide emissions, and by the CO_2 emissions from the selected materials. Then next generation of possible solutions is generated – typically with lower lifecycle emissions. This approach can be used to optimize and compare projects versions on a specific site. The method has been used to asses best proportions of the building shape, optimal insulation levels and window amount and position for the multifamily building for the lowest carbon footprint. The lowest carbon footprint result has been selected from a list of generated options. The results show that the optimal solution with lowest carbon footprint is neither the lowest embodied carbon case, nor the lowest operational carbon case. This shows that we cannot focus on embodied or operational carbon, but we must consider both of them in a holistic decision process.

Keywords: *parametric, architecture, CO_2, emissions, LCA, optimization*

1 Introduction

Built environment contribute to 40% of energy consumption and 40% of CO_2 emissions in the European Union [17]. With the rising problem of carbon dioxide emissions it is important to develop strategies and design approaches that minimize the environmental impact and carbon footprint of buildings. The architectural design process follows typically similar stages: early sketching, concept development, building drawings and execution drawings. This is followed by construction process. The ability to change the design is usually high in the early phases, and very low in the later phases. This leads to a conclusion that early design decision have very broad area of possible choices, while at later stages it is almost impossible to do bigger changes. This influence both costs and environmental impact. This can be shown on a simple case: "On the first day, management has a 100% level of influence in determining future expenditures. (..) To build or not to build?" [11]. This strictly transfers into the environmental aspects of the project. The early decisions carry the most weight on the future characteristics of the building. The early design phase is the most important phase in sustainable architectural design [15].

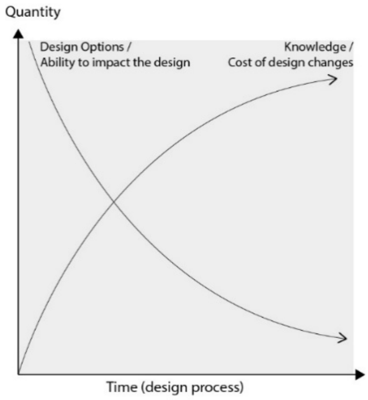

Fig. 1 *The design process – impact of the knowledge availability on the design options (based on [3],[11])*

2 Life Cycle Analysis

One of the common evaluation tools used to analyse building's environmental impact is Life Cycle Analysis. The method is a detailed analysis tool for analysing environmental impacts of products, objects, buildings and processes [5]. The procedure of applying LCA method to the built environment has been described in an EN 15978 [10]. Life Cycle Analysis demands a very detailed knowledge on the object analysed, which means that it is usually done at the end of the design process – and is not being used as a design tool, but typically as an evaluation tool. This subject has been already studied in different variations in various research projects. Säynäjoki et al. presented a study that compared 49 different LCA analyses [16]. The comparison showed that even for similar buildings with similar conditions the studies can show highly different results. The study showed that comparison can be made between LCA analyses made by the same authors, but the comparisons of different LCA studies conducted by different authors losses the consistency due to many different factors. The most important conclusion from the study was that the pre-use phase emissions are tied to the later use phase emissions, which means that only a holistic approach to the life cycle analysis can lead to the real reduction in GHG emissions. The problem with LCA in practice is that the data availability follows similar curve as the previously cost of design changes graph (figure 1) [11]. In the early design phase the ability to change the design is vast, but the data on the design decisions is limited. The detailed LCA can only be made in the later design phases, when the ability to influence the building design is very low.

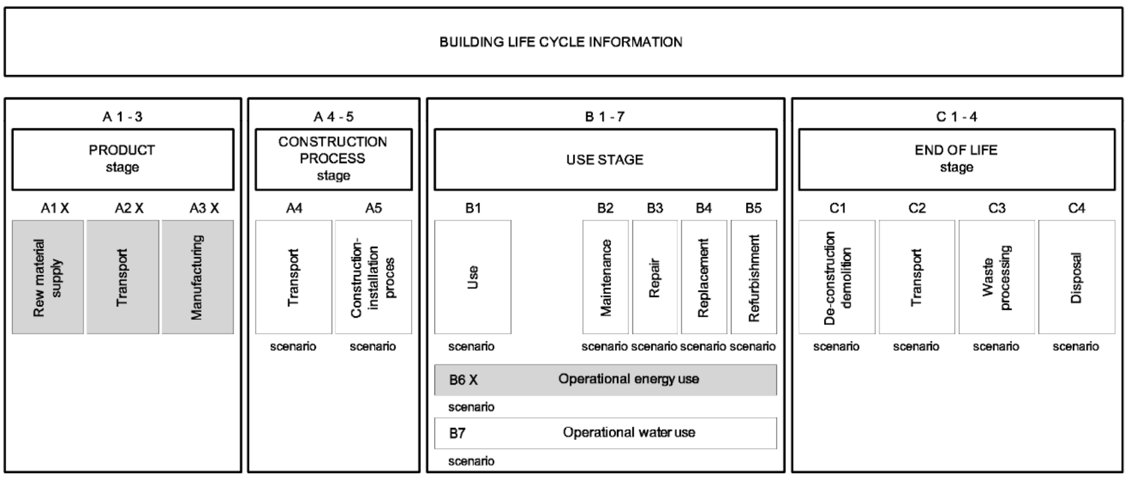

Fig. 2 *Building Life Cycle Phases, Phases marked with X (Grey background) have been considered in this study, (based on [10])*

Those two assumptions leads to the reason behind this study. In order to reduce architectural impact on the environment it is important to develop design strategies that can be applied early in the design process. The early design decisions could lead to high reduction of environmental impacts. This means that there is a need for a simplified lifecycle building analysis that can be applied in early stages of project development. The data used for Life Cycle Analysis is region specific which means that similar studies done in different location could result in very different results, which can be explained by for example different climate conditions, but also on different product availability and different energy mix of a specific location. The example LCA studies of importance of architectural decisions on LCA results in polish context have already been conducted in Poland [13]. The problem of the optimization of decision process in terms of architectural environmental impact in Poland has been studied by Arkadiusz Węglarz and Piotr Ziembicki [18]. To be able to conduct Life Cycle Analysis in the early stage of the design process, there is a need for some simplifications. A case study for simplified LCA method has been presented by Bonnet et al. The study showed that using statistical averages for elements like structure, or for specific building material amounts can be applied to simplified LCA method on a "per square meter" basis. The results of a comparison between full LCA and simplified LCA method showed that results for most LCA indicators had less than 10% margin [2]. The approach of using "per square meter" values for elements that are hard to quantify and design at early design stages can vastly improve time efficiency of the method.

3 Parametric modelling

In the recent years there is a visible shift towards parametric design tools, that allow the users to easily generate big amounts of different design alternatives. The ability to generate, analyse and compare big amounts of design concepts gives the possibility to search for most efficient parameter configurations that optimize specific result, for example lifecycle carbon footprint. An example of such parametric tool is Grasshopper, a plugin for a program Rhinoceros3d. The tool is a graphical scripting software that allows the users to easily manipulate with the parameters that define the building model, and generate many variations. Lobaccaro et al. has presented an overview that compared a range of studies that focused on parametric life cycle analysis in the recent years [6]. It showed that various software have been used to conduct the analyses. The energy simulation is starting to be included during the early design process [8]. A Parametric Life Cycle Analysis method (PLCA) has been proposed by Hollberg. The method calculated both the embodied and operational impacts. The operational impacts have been based on the energy calculation using the Quasi-Steady State Method. The tool has been designed to reduce the time needed to do Life Cycle Analyses in the early design phases, allowing to implement the environmental impact assessment into the architects' workflow [4]. A similar approach to parametric calculation of Life Cycle Analysis have been proposed by Negendahl, Otovic and Jensen. In this case also both the embodied and operational impacts have been considered. The energy simulation is done using Dynamic Building Performance Program [9].

4 Optimization

The parametric generation of various design alternatives is not useful if we do not have methods for time-efficient analysis of the designs. With just a few parameters that can be changed the search space of possible combinations rises exponentially. Naboni et al. analysed the influence of building's form, facade design and material on the building's energy consumption. In the study more than 10 building parameters have been declared as variables. The search space consisted of over 25 million possible combination. The optimization process has been based on a genetic algorithm to reduce the time needed to perform the analysis [7]. The final results showed that different building shapes, components and materials are preferred for minimizing the energy need in different locations and climate conditions. The Evolutionary Algorithms have the possibility to improve the time-efficiency of the searching process for optimal solution.

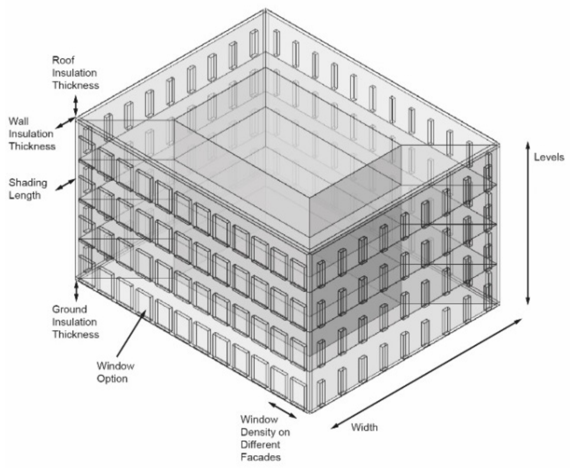

Fig. 3 *Thermal Zone model with Simulation Parameters presented*

5 Study Background

One of the goals of the study was to conduct all steps of the analysis in a single program. This lowers the entry level threshold on the method, and allows for easier application in different conditions. Demanding from an user to move between many different programs could lead to discouragement and finally aborting the method. The Grasshopper environment has been the basis for creating the script. All the building dimensions visible on the image had the possibility to be changed: building height, width, length and window ratio. The building area has been selected to be constant 1600 m^2.

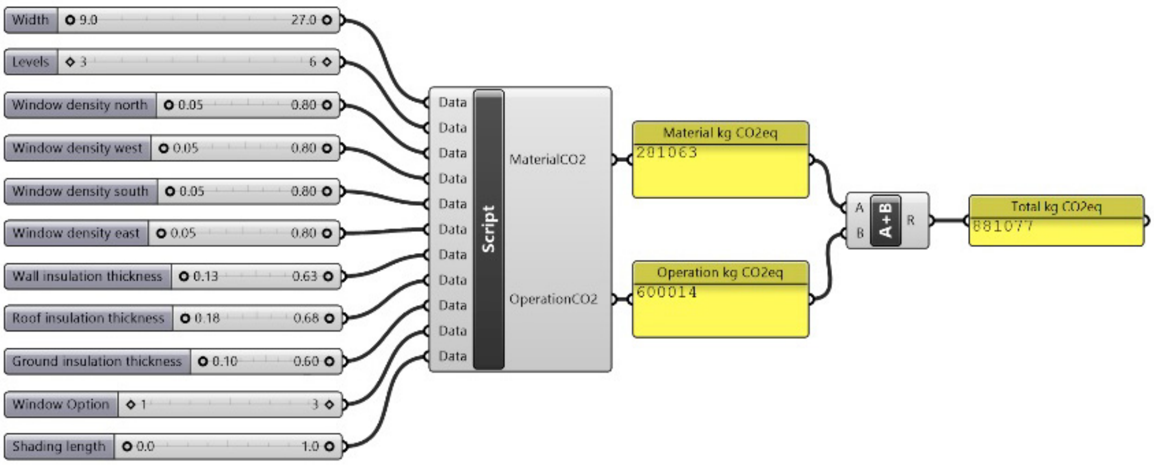

Fig. 4 *Simulation parameters with presented minimum and maximum values*

Even with a simple building shape the amount of possible combinations is enormous. In this case the possible combinations of the proposed parameters give over 64 quadrillion possible solutions. This shows that it is impossible to analyse all the combinations, and that it would be more time efficient to use an algorithm that optimizes the search process.

The basis for the calculations has been the Ladybug and Honeybee (LB+HB) plugins that allows to perform energy analyses using Grasshopper. Ladybug is used to import weather data and visualize the information regarding climate conditions, while Honeybee connects the Grasshopper environment to validated simulation engines. The study used a Dynamic Building Performance Program – EnergyPlus with OpenStudio – which evaluate building energy consumption [14]. The building definition has been created parametrically with the possibility to change the various features of the building. The thermal zones definitions followed the guidelines from ASHRAE Standard 90.1 – with 4.6m zones for the each side of the building and a common core, with separate zones for each level [1]. The HVAC system has

Tab. 1 *Description of the simulation parameters*

Parameter	Range	Description
Width	9.0–27.0m	width of the building, together with Levels determines the Length of the building, as the area is kept constant at 1600 m2
Levels	3-6	the amount of levels of the building, also describing the height of the building (which equals to 3,3m x Levels)
Window density north, west, south, east	0.05–0.80	the glazing ratio of the windows on different facades
Wall insulation thickness	0.13–0.63m	the insulation thickness of the external walls (the lower range bound has been selected according to the minimum insulation level in Poland, while the higher is the minimum +0.50m)
Roof insulation thickness	0.18–0.68m	the insulation thickness of the ground floor (the lower range bound has been selected according to the minimum insulation level in Poland, while the higher is the minimum +0.50m)
Ground insulation thickness	0.10–0.60m	the insulation thickness of the ground floor (the lower range bound has been selected according to the minimum insulation level in Poland, while the higher is the minimum +0.50m)
Window option	1–3	chosen option from a list of 3 possible window options (options: 1 – Passive house window with Uw=0.62 W/m2K, g=0.5, Lt=0.7; 2 – Old window for comparison Uw 1.4 W/m2K, g=0,63, Lt=0,83; 3 – Window with maximum U value according to regulations Uw=1.1 W/m2K, g=0,63, Lt=0,83)
Shading length	0.0–1.0m	describes the shading placed around the windows with a possible reach of maximum 1m in front of facade

been modelled using Ideal Air Loads – representing the needed energy, not the actual use. The embodied carbon from A1-A3 phases is calculated by "LCA Tool", a Grasshopper script developed by Negendahl, Otovic and Jensen [9]. The Life Cycle Analysis results depend greatly on the data quality used to perform the study. As the study focuses on embodied carbon (A1-A3 phases), and operational carbon (B6), it is important to specify the data used for the analysis. There are different levels of data available for building analysis. For the embodied carbon the highest level of detail is available in Environmental Product Declarations. On the polish market there are some materials and building products with EPDs created by ITB. There is however no single database compromising the building materials available in Poland. To conduct the study a database of available materials has been created. The preference has been put on materials and products available on polish market, for which an EPD was available. In the case of no availability of EPD for specific building component and material, the author tried to find similar products available abroad with declared EPDs. The operational carbon data is based on the polish energy mix for electricity data. The data for fuel combustion for district heating is based on information from National Centre for the Emissions Equalization and Management (KOBIZE). The operational phase is also highly dependant on the local climate data. The case study is a proposed apartment building located in Warsaw, Poland, wich is considered to be Dfb according to the Köppen-Geiger climate classification [12]. This means that the local conditions will demand both heating and cooling, although the heating need tend to be higher. The local weather data comes in form of .EPW file, a commonly used weather data format for EnergyPlus (exact location for weather data is Warszawa Okęcie 123750 (IMGW)). The reference study period have been set to be 20 years. The final result of each analysis has been recorded into excel database using Colibri, a plugin for data export for Grasshopper. Then if the generation was over the evolutionary algorithm plugin Octopus generated a new set of possible solutions and the process started again to analyse each of them (figure 5). The study considered only part of embodied carbon that could be analysed in a full scope LCA. The main building elements analysed were the external envelope – walls, roof, and ground floor; the internal floors and walls (the internal walls and staircases have been considered as a factor of specific amount of kg per square meter area rather than modelling specific layout – as this approach allows for better comparison between various options) and external windows. The calculation of the HVAC system embodied carbon could also be an important part.

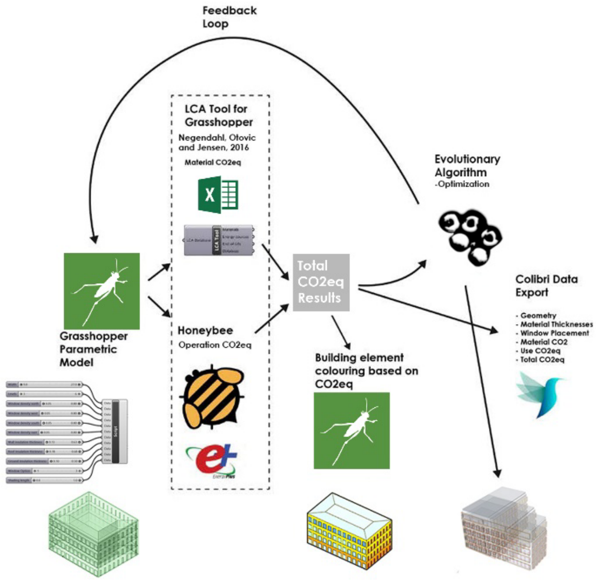

Fig. 5 *Optimization process*

6 Results

This chapter presents the results of the case study and discusses the applicability of this method. The script has been running for about 40 hours generating around 400 design solutions. Each run took between 3 and 10 minutes. The genetic algorithm Octopus in the first generations selected random parameters to slowly come closer and closer to the optimal solutions. Figure 7 presents the optimization process. The bars shows the average value of Total CO_2eq emissions (Material A1-A3 + Operation B6), while the black error bars represent the range of all results. The first generation of 20 cases shows an average of 1 304 240 kg. The average data for all of the simulations shows the value of 1 056 535 kg. The data for the best 20 cases shows the average of 878 689 kg. This shows that the optimization process resulted in lowering the carbon footprint of the building by around 32% (if comparing first generation of 20 cases to the best 20 cases). When comparing the averages of all the cases the script resulted in the reduction of the carbon footprint of around 19% (compared to best 20 cases).

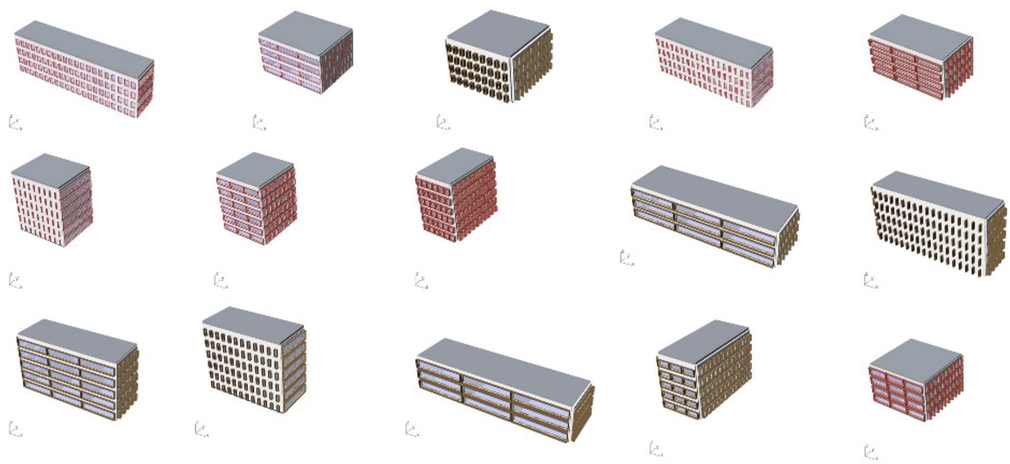

Fig. 6 *Overview of randomly selected cases from the list of 400 generated combinations*

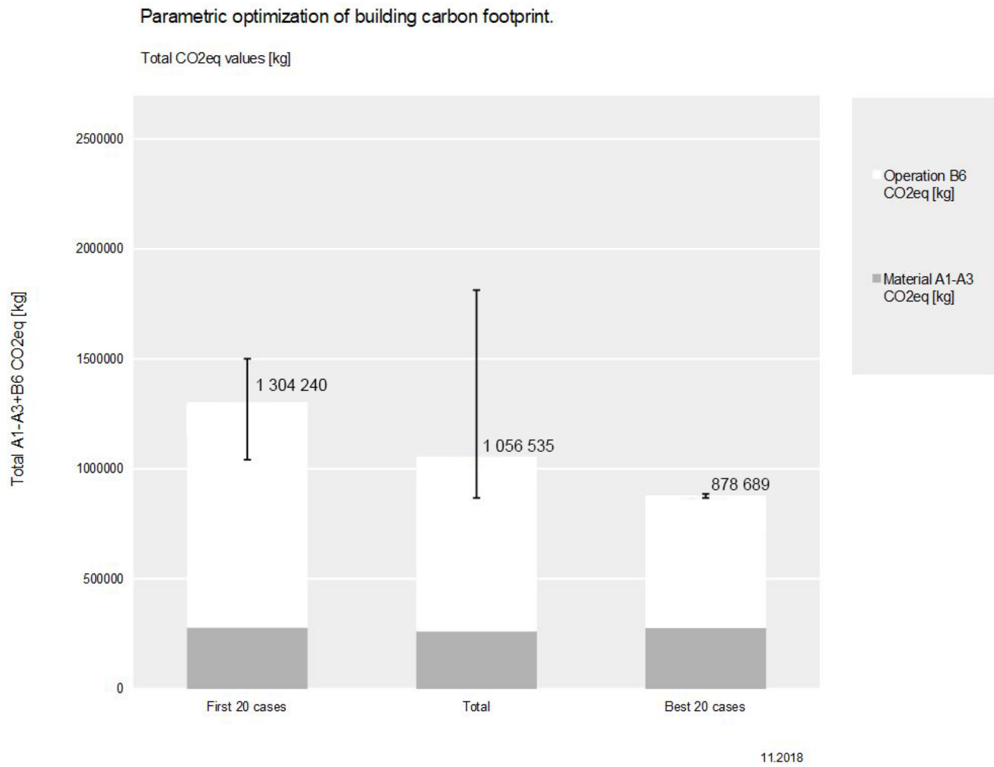

Fig. 7 Average values of 20 first cases, all cases and best 20 cases

It can be observed that the variance of the Material A1-A3 results cannot be seen from figure 7. The Embodied Carbon phase results seemed to influence the final result in smaller scale than the Operational Carbon.

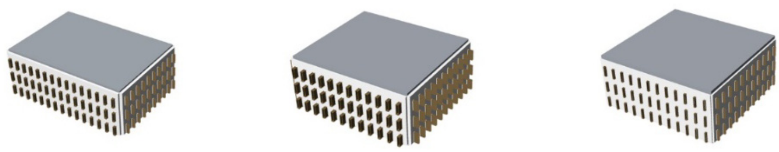

Fig. 8 Visualization of 3 out of 20 best cases

This can be seen on the figure 9 which shows the scatterplot of the all 400 simulations. The x and y axes represent Material CO_2eq and Operation CO_2eq results. Additionally the color plot represent the insulation thicknesses selected in the specific cases. The result shows that the lower Material CO_2eq results typically have higher Operation CO_2eq. This can be explained by the insulation material thicknesses shown by the colors. The lower Operation CO_2eq have typically higher insulation levels although the optimal solution do not have the maximum insulation levels. It can be observed that solutions with higher insulation thickness than the optimal solution (marked with an "X") tend to have higher Total CO_2eq or higher Operation CO_2eq and Total CO_2eq (figure 9). This can be explained by two situations. In some cases with higher insulation levels probably overheating problems can be found. The other explanation is that there is an optimal insulation thickness level. At some point adding more insulation reduce the Operation CO_2eq slower than the Material CO_2eq gets higher.

The best 20 solutions shows a few important facts about the optimization process. Figure 11 shows the values of the parameters of 20 best cases. The genetic algorithm had preferred the shapes close to the square, but with slightly longer southern facade.

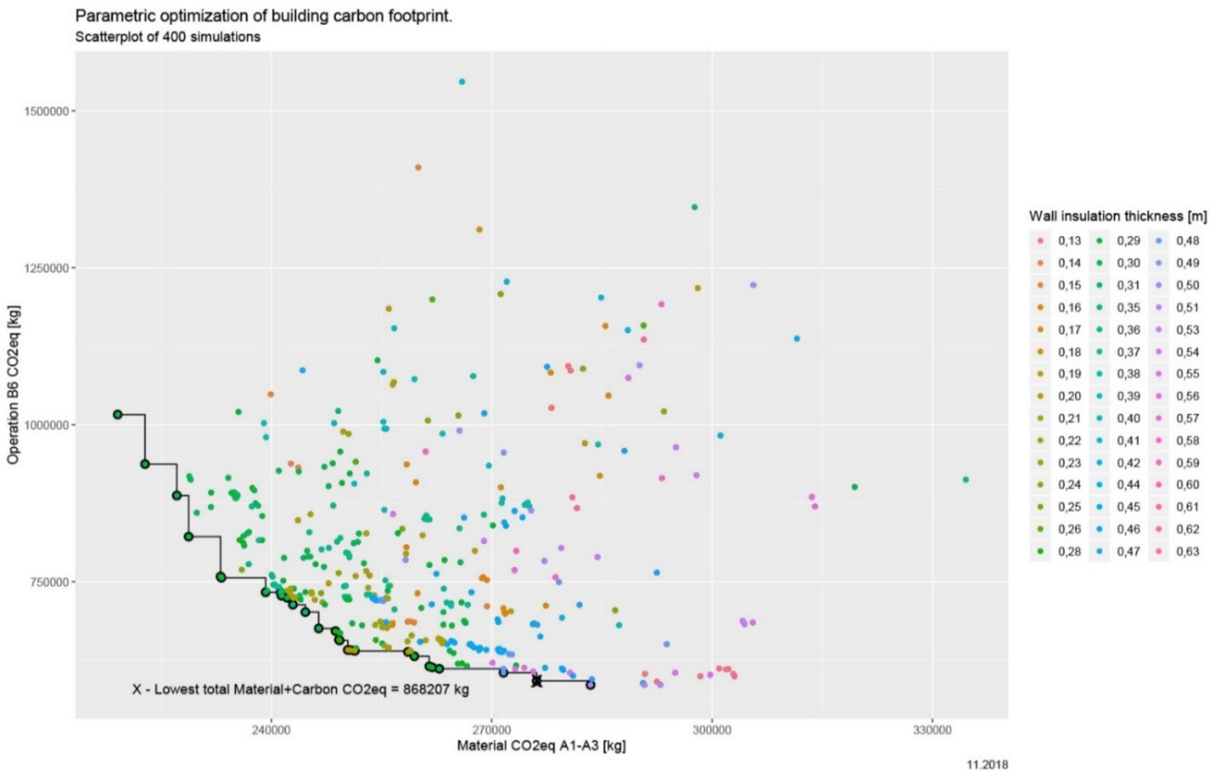

Fig. 9 *Scatterplot of all the simulations. Operation vs. Material CO_2eq [kg]*

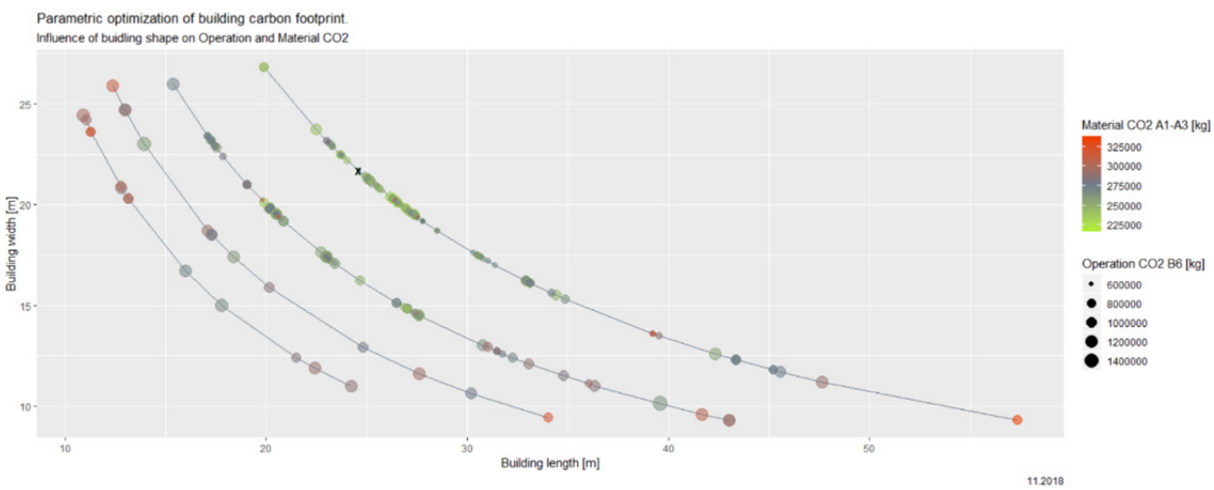

Fig. 10 *The effect of varying building dimensions on the Building Operation and Material related CO_2 emissions (the lines from the left to right represent Levels: 6 to 3 levels respectively; the "x" marks the optimal solution)*

Figure 10 shows the effect of varying building dimensions on the Building Operation and Material related CO_2 emissions. It is visible that the area with the best results corresponds with the area of building width between 18 and 24 m, and length between 20 and 27 m. This could mean that the solar gains were important factor, but at the same time the algorithm has selected glazing ratios in the lower end of the possible search space. The southern and western facade received larger glazing areas, while the northern and eastern facades were selected to be smaller. The script selected almost only 3 level

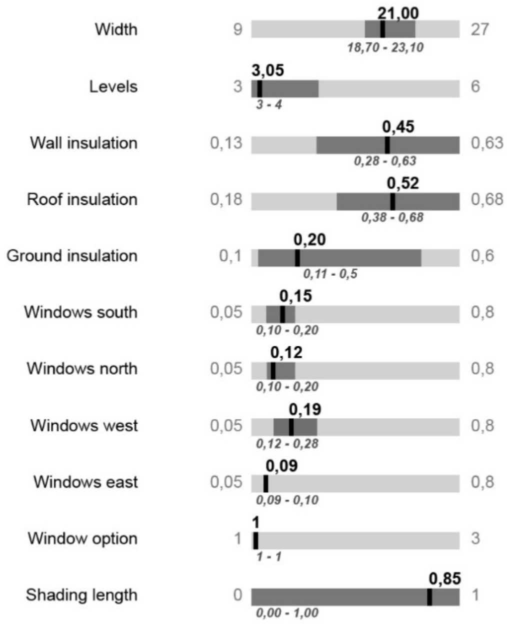

Fig 11 *The parameters of 20 best cases. Light grey shows the possible values. Dark grey shows the range of selections in the best 20 cases. The black tick represents the average value of the 20 best cases – "optimal" solution*

high options (1 out of 20 best cases is 4 levels high), while there was possibility to generate a building between 3 and 6 stories. This could be affected by the staircases that need to be higher, and as they are made mostly out of high CO_2 emitting material (concrete) this could limit the height of the buildings.

The insulation thicknesses had varying behavior. The wall and roof insulation seem to be important as the thicknesses are in the higher part of the possible variants. The optimal spot for both of them seems to be around ¾ of the scale – 0,45m for the Wall Insulation and 0,52 for the Roof Insulation. At the same time the Ground Floor Insulation seems to matter much less, as the possible options in the best 20 cases occupy the most of the scale, and the average is at the 1/5 of the possibilities – 0,20m. Finally the window option is constantly selected to be the Passive Window. It seems that the slightly lower g-value that lowers the solar gains is preferred as this window has also much lower U-value. The shading element length shows that it is better to install the shading – the average is 0,85m, but there are possibilities at which we can optimize the building without shading systems (the 20 best variants have values between 0,0 and 1,0m).

7 Conclusions

The results showed that early design decisions carry big impact on the final carbon footprint. The method could easily be applied to study different building design in a different location and climate condition. The method has however some limitations that were discovered during the study. Selection of the starting parameter range carry a big impact on the results. For example the decision to model shading as an element that is not only positioned over the window but around the whole window could have impacted the analysis. In the final results the algorithm actually picked the options with big shading elements (between 0.6 and 1.0m), but the study do not show if it is better to cover the window only from the top, or actually around the windows. Important study limitation is the simplified character of the LCA used. It would be important to perform a full-scope Life Cycle Assessment on the same building dimensions, however it would be expected that the results are not more than 10% different according to the study performed by Bonnet et al. [2].

The parametric optimization method gives the option to the designers to explore the environmental impacts in a vast design space. The architect can use this method to either generate different variants of a design concept, or to compare different outcomes of predefined design options. The study only considered elements that change the architectural design of the building.

The important extension to this study would be incorporating the method into actual architectural practice. It would give the possibility to test the process in real working conditions and see how easily such optimization could be done with strict time and economic constraints.

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An Empirical Analysis of Strategies to Reduce GHG in the Canadian Building Sector

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Abstract

In 2017, Canada and 195 other countries signed an ambitious agreement to fight climate change. In the Paris agreement, Canada committed to reduce its Greenhouse Gaz (GHG) emissions by 30% from 2005 levels in thirteen years. In this study, we evaluated how three strategies (mandatory energy codes, integrated design processes, and green certifications) are helping Canada to reduce GHG emissions in the building sector. We investigate three LEED® certified buildings in Canada. Results show a 21% reduction in global warming potential and a 35% reduction in energy consumption in the three projects. However, the buildings failed to achieve the reductions anticipated during the design phase (-7% for GWP, -19% for energy savings). The study reveals three challenges that practitioners must overcome to effectively reduce a building's GHG emissions. The results can help develop new energy standards and building codes, and thus help Canada meet its environmental target.

Keywords: *Energy and GHG reduction, Environmental performance, Sustainable construction*

1 Introduction

In 2016, Canada's GHG emissions were 704 megatonnes of carbon dioxide equivalent (Mt CO2 eq). This represents a modest 3.8% – or 28 Mt – reduction from 2005 emissions [1]. Thus, these reductions are far from the commitment made by Canada in 2017 in Paris: to reduce its Greenhouse Gaz (GHG) emissions by 30% below 2005 levels by 2030. The building sector has potential to help Canada meet its emission reduction target. The sector accounts for 40% of energy consumption and 17% of GHG emissions [2]. However, the traditional silo-type, linear, and fragmented processes of designing, constructing, and managing buildings have been identified as a significant barrier to collaboration [3]. And scholars and practitioners agree that this collaboration is needed to produce innovative solutions to reduce a building's impact on the environment [4].

A literature review, including 26 research and policy documents, helped us to identify three strategies adopted in Canada to reduce a building's environmental impacts: 1) implement mandatory energy codes; 2) encourage collaborative and multidisciplinary processes in building design; and 3) stimulate the use of green certifications. Yet, the effectiveness of these strategies in reducing GHG emissions in the built environment is sometimes contested [5, 6]. After project completion, the strategies and approaches applied, and the actual building performance data are rarely made public [7]. Having access to these results would help stakeholders to improve their activities to reduce a building's GHG emissions. This study aims to evaluate how these three strategies are helping Canada to reduce GHG emissions in the building sector. Specifically, it assesses the real value of innovations within projects in terms of Global Warming Potential (GWP) and energy consumption.

The originality of this study is that the design processes, materials used (embodied energy), and strategies mobilized during the building design phase have been studied throughout the construction and operation phases, thus avoiding the drawbacks of several studies that have focused only on expected performances during the design phase.

1.1 Key terms to understand climate change

Greenhouse gases (GHGs) are gas molecules that absorb and radiate thermal infrared radiation back to the earth's surface. The increase of GHG molecules increases the planet's surface temperature, provoking a ‘‘greenhouse effect’’. Greenhouse gases have different effects on the environment. Each gas molecule has a unique atmospheric lifetime and heat-trapping potential. This creates the need for a way of comparing the net effect of emissions of different greenhouse gases, which has led to widespread use of the so-called Global Warming Potential GWP [8]. GWP is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO2) [9]. Global warming – one aspect of climate change – refers to the rise in global temperatures due to the increasing concentrations of GHG in the atmosphere. Climate change, however, includes other effects of human activities on nature. It also refers to long-term changes in wind patterns, ocean currents, rain and snowfall, and extreme weather events [10].

1.2 Canadian energy code for buildings

Governments around the world have recognized the need to intervene in the building sector by implementing mandatory energy codes [11]. Energy efficiency in the building sector is essential to address climate change. In Canada, buildings represent 40% of total energy consumption, and 17% of total GHG emissions, that is 126 Mt of CO2 eq. [2]. In 1997, Canada launched its first national energy standard – or energy code. It focuses on aspects of building design that affect energy consumption, such as building envelope, electrical lighting, mechanical heating, cooling, ventilation, and hot water systems [12]. The standard is called the Model National Energy Code for Buildings (MNECB).

In 2011, the standard was revised and renamed the National Energy Code for Buildings –NECB 2011. The NECB 2011 is stricter (25% as much in most measures) than the MCEB 2007 energy code [12]. In 2017, Natural Resources Canada (NRCan) launched the high-performance building community of practices (HPB-CoP). NRCan is a department of the Canadian government and is responsible for developing strategies and programs to enhance the contribution of the natural resources sector to the economy and to improve the quality of life for all Canadians. HPB-CoP's objective is to gather together effective ideas for the development of a new, stringent energy and GHG codes for 2020. For 2030, the HPB-CoP's goal is to launch a “net-zero energy ready” model building-code for all Canadian provinces and territories.

1.3 From fragmentation to multidisciplinary and collaborative approaches

Two decades ago, Egan (1997) identified the fragmentation between construction phases and suppliers as an important barrier to the improvement of quality and efficiency in the building sector [13]. This conventional approach is known as the “over-the-wall” syndrome, wherein design documentation is produced in a fragmented, sequential and isolated manner [14]. This inefficiency in the design phase inhibits optimisation in the building sector [15]. Leoto and Lizarralde [16] identified six different types of fragmentation during the building life cycle: design fragmentation, procurement fragmentation, construction fragmentation, labour fragmentation, supply chain fragmentation and facility management fragmentation.

Increasing attention toward sustainability, however, has led governments and design professionals to seek alternative and more effective building design processes [17]. One response in Canada is the emergence of more collaborative and multidisciplinary processes, such as the Integrated Design Process (IDP) [18]. IDP aims at integrating otherwise fragmented outputs and processes to improve a building's energy and environmental performance. The process invites all experts and stakeholders (professionals, builders, operator specialists, users, and owners) to work together during the early stages of the project through intensive work sessions (dubbed design "charrettes"). Green building certifications foster IDP adoption and the belief that decisions taken collectively can reduce fragmentation and enhance industry efficiency to deliver sustainable projects [19]. The team is called upon to consider, for example, the whole life cycle of the building, not just the initial capital investment in construction [20]. By developing and sharing new knowledge, stakeholders generate added value in the process and to the final product.

1.4 Green Building Certifications

Green Building Certifications emerged in the early 1990s as a methodological framework to measure and monitor the environmental performance of a building [21]. They have helped to create awareness among stakeholders and users [22] and have become a powerful way to show stakeholders' commitment to sustainable development [23]. Building Research Establishment Environmental Assessment Methodology (BREEAM), developed in UK, was one of the first methodological frameworks implemented. Since then, other methods and tools have emerged, for example: HQE (Haute Qualité Environnementale) in France, CASBEE (Comprehensive Assessment System for Built Environment Efficiency) in Japan, Green Star in Australia and DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) in Germany.

Four certifications are common in Canada: LEED® (Leadership in Energy and Environmental Design), BOMA BESt (Building Environmental Standards), Living Building Challenge and SBTool (Sustainable Building Tool), a framework developed by iiSBE (International Initiative for a Sustainable Built Environment). Among these, LEED® is the most popular with almost 3 000 LEED® certified buildings in Canada. It is a point-based system where building projects earn points in seven impact categories: 1) reverse contribution to global climate change; 2) enhance individual human health and well-being; 3) protect and restore water resources; 4) protect, enhance, and restore biodiversity and ecosystem services; 5) build a greener economy; 7) enhance social equity, environmental justice, and community quality-of-life [24].

2 Research Methods

We adopted a case study approach "that investigates a contemporary phenomenon within its real-life context" [25] (p.13). Three case studies were chosen that met the criteria previously identified: a) adoption of a green building certification –LEED®, b) adoption of a collaborative and multidisciplinary processes in building design; b) projects that exceeded the current Canadian energy code; and d) accessibility to access full data, reports, and the projects' stakeholders. **Table 1** describes the three cases.

Tab. 1 *Main characteristics of the three case studies.*

Charact.	Case study A	Case study B	Case study C
Client	NGO	Space for Life	Ministry of Sports and Recreation
Main use	Offices	Museum and entertainment	Soccer stadium
Floors	5 storeys	3 storeys	2 storeys
Functional programme	Offices, meeting rooms, amphitheatre, and a cafeteria	Theatres, admin. offices, auditorium, and a boutique.	2 soccer fields, a cafeteria, admin. offices, and retail space.
Built area	6,500 m² on five levels	8,000 m² on three levels	12,600 m² on two levels
LEED®	LEED® Canada NC 1.0	LEED® Canada NC 1.0	LEED® Canada NV 2009
Certification	LEED® Platinum	LEED® Platinum	LEED® Gold
Obtained	2013	2015	2017

We collected and analysed primary data, including 150 architectural plans and more than 100 documents, LCA reports, energy simulations and articles. The use of multiple sources of documentation in the case study enhanced validity. Consequently, and following Yin [25], we examined and assessed documents in terms of their purpose, coverage, and quality. In each of the documents, we identified mitigation strategies and analysed elements that indicate intentions and actions related to decision-making processes during the IDP charrettes. The second step included 30 semi-structured interviews with professionals, clients, and stakeholders involved in all of the project phases of the IDP.

In the last step we compared the building performance results from each case. To do that, we created: 1) a project baseline – used as benchmarks – named reference building (RB), 2) a construction documentation (CD) which is the result of the case study's IDP charrettes, and 3) an Actual Performance (AP), that considers measured/real consumption (real energy consumption and GHG emissions). The characteristics and parameters of each model are detailed in **Table 2** and are valid for all evaluations presented in this study. We then applied an LCA tool – ATHENA® Impact Estimator for Buildings (IE2B) v5.2.0119 – to evaluate the environmental impact for each scenario. The quantitative results from the LCA and energy consumption analyses helped to contextualize the qualitative information obtained from the documents. The results are presented in the following section.

Tab. 2 *Details of Reference Building (RB), Construction Documents (CD) and Actual Performance (AP)*

Case Studies		RB	CD	AP
A	Methodology	ASHRAE 62.1	EE4 v1.7-2	First 3 years of consumption
	Characteristics	MNECB 1997	LEED® strategies (Table 3)	LEED® Platinum 59/70 points
B	Methodology	ASHRAE 90.1	HAP v4.51	First 3 years of consumption
	Characteristics	MNECB 2007	LEED® strategies (Table 3)	LEED® Platinum 55/70 points
C	Methodology	ASHRAE 90.1	eQuest v3.64	First 3 years of consumption
	Characteristics	MNECB 2007	LEED® strategies (Table 3)	LEED® Gold 64/110 points

3 Results

3.1 Anticipated measures

For each case study, we first examined the project documentation to identify mitigation strategies to reduce energy and GHG. The results are presented in **Table 3**. The results in the second column of each table – the anticipated reductions – come from the LEED® documentation and/or the simulation results (LCA and BES).

3.2 Achieved building reductions

In the next step, we compared targets defined during the design charrettes with actual data measured over three years of operation. A Building Energy Simulation (BES) is a tool used to predict the RB and CD energy performance [26]. **Table 2** details the BES's used in the design phase to analyse and optimise building performance for each case. The AP represents the average of the first three years of operation. **Table 4** shows the results. The *anticipated reduction* column shows the predicted energy consumption reduction (in percentage) that the design team projected to achieve with the construction documentation (CD), compared to the reference building (RB). The column *achieved reduction* compares the RB and the actual performance (AP). The last column shows the *gap* between the predictions of the buildings' energy reduction at the design stage and the actual, subsequent performance.

Tab. 3 *Strategies used and benefits in case studies.*

Mitigating strategies reduce buildings' impacts on nature	Anticipated reductions		
	Case A	**Case B**	**Case C**
Gearless and room-less elevators	30% energy reductions		
Raised Floor	13% energy reductions	17% energy reductions	
Hybrid natural ventilation		30% energy reductions	
Air dehumidification		35% energy reductions	
Natural light		25% energy reductions	
Green roof	794.75 m^2 – 67% of the roof area – RSI 5,7	794.75 m^2 – 67% of the roof area – RSI 5,7	
White Roof			794.75 m^2 – 67% of the roof area – RSI 5,7
High-performance envelope	RSI 3,7 to RSI 4,2	RSI 4,6	RSI 3,7
Triple-pane windows	SC 0,27	SC 0,27	
Doubled ceramic f. glass			RSI 0,65
Exhaust energy recovery	85% energy recovery	93% energy recovery	90% energy recovery
Geothermal system	79% energy reductions 3.880 GJ/year	90% energy reductions 4.750 GJ/year	75% energy reductions 3.550 GJ/year
Efficient lighting system	20% energy reductions 170 GJ/year	30% energy reductions 120 GJ/year	40% energy reductions 250 GJ/year
CLT wooden structure			64% GWP reduction
Fly ash replacing cement	25 % less cement use		
FSC-certified wood	95,29 % (by value)	80 % (by value)	
Recycled content products	18.53% (by value)	15% (by value)	40% (by value)
Reused materials		25 % less cement use	
Rainwater for toilets	23% reduction 343.000 l/year	20% reduction 263.000 l/year	23% reduction 200.000 l/year
Waterless urinals	100% reduction 411.000 l/year		
Dual- and low-flush toilets	20% reduction 305.000 l/year	15% – 255.000 l/year	85% – 328.000 l/year
Faucets - infrared sensors	85% reduction 722.000 l/year		
Vertical living wall	Eliminates air pollutants		
Low VOC and no formaldehyde	Reduce air toxics emissions		
CO^2 control	Eliminates air pollutants		

Tab. 4 *Consumption of Reference Building (RB), Conceptual Design (CD) and Actual Performance (AP)*

Cases	Energy Source/Unit		RB	CD	Anticipated reduction	AP	Achieved Reduction	Gap
A	Electricity	kWh	1.121.928	721.954	64%	1.431.270	128%	63%
	Gas	m^3	117.645	4.206	4%	21.638	18%	15%
	Total	MJ	8.321.222	2.757.523	33%	5.967.908	72%	38%
	EUI	kWh/ m^2/year	356	118	33%	255		
B	Electricity	kWh	2.109.463	1255278	60%	1.500.000	71%	12%
	Total	MJ	7.594.070	4519003	60%	5.400.002		
	EUI	kWh/ m^2/year	264	157	59%	188		
C	Electricity	kWh	1.470.574	1.104.861	75%	1.401.790	95%	20%
	Gas	m^3	254526	64.665	25%	67.295	26%	1%
	Total	MJ	14.884.923	6.414.142	43%	7.582.205	51%	8%
	EUI	kWh/ m^2/year	328	141	43%	167		

The LCA tool called ATHENA® IE2B (as presented in the methods section) was used to compare the environmental performance of the three case studies. The characteristics used for each building are detailed in **Tables 3** and the real energy consumption applied is detailed in **Table 4** (total consumption in MJ). The LCA results are presented in **Figure 1** – for the Embodied Energy results – and **Figure 2** – for the Operational Energy results. In both cases, we take into account, for AP, the first three years of operation. These quantitative results – energy consumption and LCA – contextualize the information obtained from the analyses of the mitigation strategies for each case study (**Tab. 3**). The discussion of both results is presented in the discussion section.

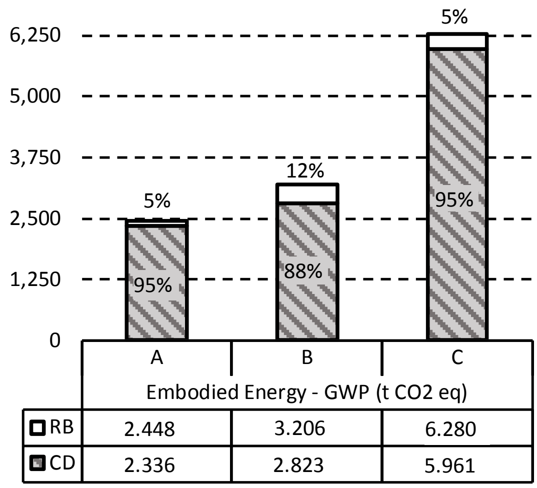

Fig. 1 *Embodied Energy results (Construction and five years maintenance)*

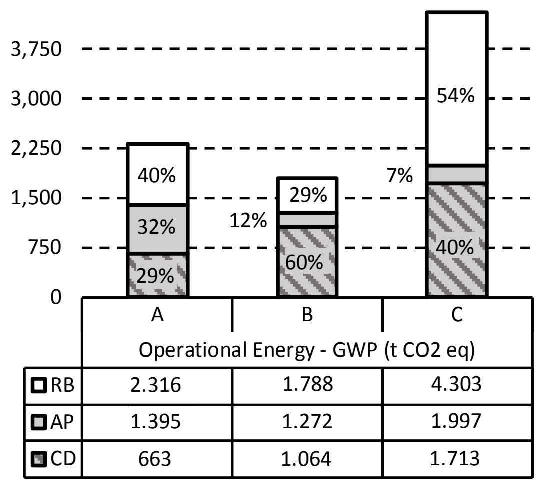

Fig. 2 *Operational Energy results (five years operation)*

3.3 Collaborative and multidisciplinary design practices

The three cases applied the Integrated Design Process. IDP was primarily developed in the NRCan C-2000 program. IDP brings together interdisciplinary experts and key stakeholders through intensive charrettes concentrated in time and space (**Tab. 5**). In practice, however, no consensus exists on how to operationalize the "charrettes" [4]. The three cases applied IDP differently (**Tab. 6**). Case A started from day one with a pre-selected design team, the client and contractor. In Case B, the design team (architect and engineers) were chosen after a design competition. The client joined the charrettes after the results of the design competition. In case C, only the architect was chosen after a design competition. The others design professionals were hired based on the lowest bidder.

Tab. 5 *Professionals and specialists involved in project charrettes during the design phase of the case study projects.*

Stakeholders involved in charrettes		**A**	**B**	**C**
Experts who typically participate in traditional project design	Clients, architects, civil engineers, structural engineers, electrical engineers, mechanical engineers, project managers, and landscape architects.	X	X	X
Additional experts who participate in IDP processes.	Commissioning team, users, contractor, LEED® consultants and geothermal energy consultants.	X	X	X
	Users, energy efficiency specialist, Green roof, operation team, and museologists	X	X	
	Building envelope consultants, researchers, Green wall, and ergonomist	X		
	Leak detection specialist, Planetarium theatres, and scenographer		X	
	BIM manager and engineered wood consultant			X

The results show that, during ID charrettes, the professionals perceived LCA as an overly complicated tool. In cases A and B, clients hired a consultant to compile LCA reports only to compare options for specific solutions (i.e. facade: brick x fiber cement). Case C hired an LCA consultant to participate in almost all IDP charrettes. In none of the case studies made use of the environmental assessment tools (LCA) to calculate the whole GHG impact of the building.

Tab. 6 *Charrette themes and professionals' participation (**NC**-Number of charrettes; **NP**-Number of experts and professionals' participation; **PP**-Percentage of experts and professionals' participation).*

Charrette themes	Case A Total of 22 professionals			Case B Total of 12 professionals			Case C Total of 16 professionals		
	NC	NP	PP	NC	NP	PP	NC	NP	PP
Brainstorming	5	17	77%	3	4	33%	2	2	13%
Design charrette	3	16	73%	3	4	33%	4	8	50%
Coordination	4	17	77%	4	10	83%	7	12	75%
Value engineering	1	22	100%	1	6	50%	1	10	63%
LEED®	1	17	77%	2	6	50%	1	12	75%

4 Discussion

The previous section measured achieved energy consumption and GHG emissions reductions in three cases in Canada. Results show a 21% reduction in global warming potential (GWP) and 35% in energy consumption (MJ) in the three case studies. The results also revealed that the projects failed to reach the GWP and energy consumption reductions predicted in the design phase. An important gap emerged between the anticipated (construction documentation – CD) and achieved (Actual Performance – AP) exists, – 7% for GWP and 19% for energy savings (on average in the three cases). Results revealed at least three challenges that practitioners face during the process.

4.1 Fragmentation between project phases

In the three case studies, stakeholders dedicated two to six charrettes to research for new technologies and brainstorming (**Table 6**). However, we identified that practitioners chose innovative strategies based on little or non-existent performance data. In Case A, the raised floor chosen promised 13% energy reductions. After 5 years, the researchers returned to the building. They found improvements in air quality, but the strategy did not reduce energy use. In Case B the hybrid natural ventilation promised to reduce air conditioning needs. In practice, the system proved to be tricky to manage and was deactivated. The rainwater recovery for toilets is not operational. The pipe for transporting rainwater to the tank does not have the proper inclination and the system has been deactivated. All these problems could have been avoided if the facility team had been present during the brainstorming and design charrettes.

The facility team have know-how from previous projects and know the actual performance data and potential problems with each strategy. Their experience and feedback with regards to implemented strategies performance can empower professionals in the decision-making process during the design phase [27]. The facility team might also benefit from better integration with the design team. The results show that the three projects failed to achieve the anticipated performance (**Fig. 2**). The design team had all the theoretical data and could have helped operators to foresee eventual problems managing the building. The design team could have helped in the fine-tuning of the building, which would have generated valuable information for new projects.

4.2 Building cost and actual performance data

Table 3 shows the expected economies provided by each strategy established during the IDP charrettes. It was relatively easy to obtain the *total final cost* and the *real total consummation (water* *and energy)* in all case studies. These data, however, could not be used to individually analyze the strategies' performance [6]. In terms of costs, we were unable to isolate the investment by strategy. In terms of performance, all three cases did not install equipment to measure real energy or water consumption separately by strategy. We found equipment to measure temperature and CO_2, but we were unable to verify COV emissions in any of the projects. According to the client in case A: "It's just last year that we hired an expert to measure COV before and after the green wall, and the results showed little benefit. This performance information will help in new projects." The energy consumption, in case B, was more difficult to calculate. As the building operator explained: "The equipment measures our consumption and that of the neighboring building. In order to have only our individual consumption, we calculated the increase in consumption after the implementation of the new building."

The case A client admitted: "I do not know the return on investment (ROI) of each strategy. For example, rainwater recovery. How much did it cost in concrete [for the retention basin]? And to have two separate pipes for the system? And yet, how much do I save on water each year? It is frustrating not to be able to have this data today." In addition, some strategies applied – as for example the green wall or the CLT wooden structure – are innovations being used for the first time, and so it is extremely important to access real data performance. The real data – in total investments and actual consumption - is crucial for transparent decisions in low-carbon projects [28].

4.3 Reducing building's embodied energy

Current Canadian building codes have primarily targeted energy savings [7]. All three case studies achieved significant operational impact reductions when compared to reference buildings. However, all cases neglected the embodied potential impact (i.e. the energy embodied in the manufacture and transport of building components). Other studies have also identified insignificant embodied impact reductions in green buildings. Sometimes, green buildings have increased embodied impact compared to reference buildings [29]. Embodied impact – mostly materials used in the construction phase – represents 8 to 17 years of operation in the three cases (**Fig. 1 and 2**). Therefore, new buildings codes should consider not only the energy reduction during operation but also the embodied energy used in the construction phase. This new standard, according to our results, will face resistance from professionals who find LCA a very complicated and imprecise tool. To overcome these barriers, user-friendly LCA tools – that professionals can use without having complex measurement skills – are necessary. Although they are not widely used, several LCA-based assessment software tools are already available: Athena Impact Estimator for Buildings (IE4B), Athena EcoCalculator and BEES [30].

5 Theoretical and practical implications

This study has some limitations that should be highlighted. First, the research focused on LEED® certification projects (gold and platinum). Other types of green buildings certifications should also be analysed (e.g., Living Building Challenge, WELL, BREEAM). Second, the case studies were concentrated in Montreal/Canada and were institutional projects (funded by government or an NGO). Future research should evaluate the conclusions drawn here in the context of other cases (e.g., private real-estate projects) and locations. Yet, this research reveals three challenges that practitioners must overcome to effectively reduce a building's GHG emissions: 1) the fragmentation between design, construction and operation phase, 2) the difficulty gaining access to building cost and actual performance data, 3) achieving embodied energy reductions in high-performance buildings.

From a practical perspective, this study revealed the importance of measuring innovations' ROI (investment x benefit in GHG, cost and energy) to generate data. The real data will help professionals to identify ways of reducing a building's impact - material, energy, and water use. All data serve as a benchmark – how much material, energy, and water the buildings currently use – for future projects. From a theoretical point of view, the results show the importance of post-occupancy evaluation as a way to learn from failure and success. The data gathered can help to develop new indicators for carbon-efficiency labelling for buildings. Carbon efficiency is derived from the output of GHG emissions from the production phase of the building and operative energy demands [28]. The results are also important to improve current energy-efficiency standards and building codes, and thus help Canada meet its target for the Paris Accord.

6 Conclusion

This paper analysed current strategies used in Canada to reduce GHG emissions in three case studies. Three strategies are currently used in building sector in Canada: 1) to increase energy reduction standards; 2) to encourage collaborative and multidisciplinary processes in building design; and 3) to stimulate the use of green certifications. The results show a 21% reduction in GWP and a 35% reduction in energy consumption in the three case studies. However, all three projects failed to achieve the anticipated reductions defined during the design phase – a 7% gap for GWP and 19% for energy savings. The discussion section revealed three challenges that practitioners must overcome in order to be more effective in reducing GHG emissions in buildings.

First, they must reduce the fragmentation between design and operation teams. Both teams will benefit from more integration between the design and operation phases. The *Design team* will be able to access valuable information – follow and verify the true building performance – to improve the performance in new projects. By participating in the early stages of the project, the *facility team* will help – with their knowledge – to minimize errors and enable the project to achieve the expected performance. Second, they must install equipment to monitor buildings' performance - and all energy and GHG mitigation strategies applied. Buildings, as they are currently being built, do not integrate measurement equipment to evaluate the energy and GHG implemented-strategies' performance. A building's actual data are especially important when innovations are being used for the first time. The real performance information, compared with the real cost, can be used to evaluate carbon mitigation strategies. Third, they must consider embodied-energy reductions in the construction phase in new buildings codes. A major barrier for professionals will be the lack of LCA knowledge and skills. Training and special courses need to be developed, especially in universities, to train future architects and engineers to develop knowledge deploying user-friendly LCA tools.

Acknowledgements

The Authors would like to acknowledge the financial support of the Institute of the Environment, Sustainable Development and the Circular Economy – EDDEC – Scholarship Program.

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Roads to Architectural Adaptation: Strategic Approaches to Climate Change Adaptation of Sustainable Residential Architecture in Oceanic Climates

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Abstract

Climate change adaptations in new buildings must reconcile mitigation with resilience and adaptation, to obtain a truly sustainable architecture.

Extensive literature studies reveal a multitude of approaches to climate adaptation worldwide that has been defined as either hard or soft based on the flexibility and economy of their implementations, or as human adaptations, based on behavior and physiology.

This paper investigates architectural and engineering approaches to climate change adaptations in oceanic climates and rationalizes them within a framework that may serve as point of departure for future residential architecture. Overall approaches fall into either defensive, reactive or embedded strategies.

Defensive strategies are mostly passive solutions that entrench the building from the extremes of climate change. Reactive solutions actively engage the climatic impacts and dynamically change the architecture to respond accordingly. Embedded architecture engage with ecology and landscape to enhance the natural resilience of the site and adapt in depth.

Keywords: *Climate Change, Adaptation, Sustainable architecture, Residential Architecture*

1 Introduction

Adaptation to- and mitigation of climate change is one of the most pervasive issues in architecture today. The focus on sustainable architecture have been the main driver in a large part of new architectural design for the last couple of decades. Climate change adaptation has just recently started to become an entity in architecture. Disasters and new challenges have arisen because of climate change, therefore, the buildings we inhabit must conform to the new reality by being resilient to extreme events and adapt to the changes.

This article attempts, based on the literature in the field, to define three different positions that categorizes adaptation to the impact of climate change in architecture; these are defensive, reactive and embedded strategies. Furthermore, the article will describe three tiers of the adaptive strategies; hard, soft and human.

Each of the strategies described are illustrated with examples of architecture and building designs that embody these strategies.

The article concludes with a discussion on the relevance and utility of categorizing and employing adaptive solutions as long-term strategies in architectural design. What potential implication this would have on the field of architecture. Further avenues of research directly resulting from this study is discussed as well.

1.1 Background

The field of architecture have been approaching climate change for the last decades as a problem solved through mitigation. Energy consumption must be lowered since the building sector is the source of a disproportionately high amount of the greenhouse gas emissions [1].

This has overall led to increasing energy standards and better practices in building design. In some countries, like Denmark, the regulatory standards are thus moving close to Zero energy in the near future [2], [3].

As the climate crisis has evolved, it has become apparent that only mitigating climate change is no longer enough. Climate changes are happening at an increased rate, and resultant extreme weather events are occurring in most of the world. Future buildings should therefore be adapted to climate change and not only help mitigation. Adaptation to climate change have in many countries been left as a response in the realm of urban planning, separating sewer systems and developing retention systems and urban greenery to adapt cities to the extreme weather of the future [4], [5].

While developing urban adaptations is helpful on the large scale, the economical investments are also massive[6]. The buildings in cities can be worsening the problem of the climate change impact, by producing runoff water and excess heat [7]. With increasing cooling needs and rainwater especially in the form of cloudburst, there will be a need to look at how the individual building design can remain inhabitable during changing climate but also how their adaptation may contribute to large-scale resilience of our cities, towns and neighborhoods.

2 Methods

2.1 Literature Studies

The main content of this paper has been written based on a literature review made in online databases on adaptive architectural design. The goal was to provide a state of the art of the literature on subject. This paper builds upon the review by further analyzing and expanding upon the results, and by structuring the state of the art into tangible adaptation design strategies in architecture [8], [9].

The literature is found from a wide array of fields related to architecture and climate change. Most come from architecture and building engineering, but urban design and landscape architecture provide some insights as well. The systematic method of selecting the literature from the databases is elaborated in the preliminary state of the art. The focus of the literature were the adaptation measures within temperate climates published since 2007 [8]. 2007 have been chosen as the starting year, since going further back would yield sparse literature, where the research have been made on less severe climate predictions.

2.2 Case Studies

To exemplify the presented design strategies, analysis of cases of adaptive architecture or building methods will be presented alongside the description of the methods. The cases will form a tangible base to ground the research [9].

The cases will also help reveal where this study draw the demarcation lines between different strategies, and exemplify how to use the strategies as an overall approach.

3 Adaptive strategies

Solutions to climate change adaptations comes in wide array of solutions that can synergize and combine in a multitude of constellations [10]. The focus in this study is mainly on adaptations on building scale, while some landscape architecture and vegetation strategies are considered since these can be scaled down and can interact with the architecture on a smaller scale.

This section is the result of previous literature studies on architectural climate change adaptation. The results are divided into three main approaches to adaptation: Defensive, reactive and embedded strategies. This section describes each strategy and its viability followed by examples of the three approaches in architectural design.

4 Defensive

Defensive design is fortification of architecture against the effects of climate change. These mostly passive solutions entrench the building against outside interference. The defensive adaptation seeks to protect the building from the external effects.

Defensive strategies aims for a sharp division between the exterior and the interior. The indoor environment exists separately from the exterior through conditioning and insulation. This create a stable interior environment that keeps most inhabitants satisfied. The controlled environment can offer excellent answers to the question of overheating in the individual houses in current climates, at the cost of increased energy use and thereby a lack of resilience to long-term climate change if reliant on electrical cooling [11]. Otherwise, in the perspective of temperature rise, defensive designs would act like a cool cave, thermal mass and shade interacting to create a stable indoor environment that barely interact with the exterior.

Employing defensive strategies towards floods is about designing buildings that withstand the water, either by raising the building above it or by using robust materials and constructions that survive being submerged in flood- or seawater [12], [13]. The robustness of the materials will then play a major role in the resilience towards changing precipitation and humidity patterns as well. Winters with more precipitation and temperature swings around the freezing will also wear on the buildings [14].

Defensive solutions have been the common response to floods in most of human history: Building dikes, raising houses on poles or using materials that can withstand the water are examples of defensive solutions[15].

It is important to note though that passive solutions are not necessarily defensive by definition; some might be better classified as embedded strategies. The defining feature of the defensive design is that the building's interior state remains in status quo during climate changes and extreme events, or returns to baseline quickly without changing the state of the building and with minimal interference from the inhabitants. The architectural design is resilient enough to withstand impacts in itself [14].

Passive house-designs will often employ a defensive approach to indoor environment, by tightening the envelope between the interior and exterior [16], [17].

4.1 Reactive

Reactive architecture actively responds to changes in the climate to accommodate the inhabitants while reacting to extreme events through dynamic mechanisms.

Similar to the defensive strategies the architecture is primarily using manmade adaptation solutions, while plants may be integrated in some solutions. Reactive architecture can primarily be achieved through the use of high-level technology and interconnectedness in the building design [18].

Reactive design strategies will be able to adapt as changes occur. They will help the building change along the climate. This can happen through small incremental changes over a large span of time or major sudden adjustments. The larger the reactions the more radical the design must be.

Many of the reactive designs have yet to develop fully with especially the field of robotics playing an important role in active façades and censors that interact with the users on an individual basis [18].

Most active house-designs will fall under the reactive category. While they are designed primarily with mitigation in mind, the monitoring and constantly adjusting automatic system reacts to changes in the environment and temperature, which changes the interior climate for the inhabitants to accommodate a status quo with a minimal expenditure of energy [19]. The interior environment is also in this case separated from the exterior like in the defensive solutions, but the building actively interacts with the exterior to maintain the baseline, which is the demarcation of the reactive strategies: They need to actively engage and interact with the exterior and extreme events.

4.1.1 Amphibious architecture

Amphibious architecture is an archetypical reactive design strategy, since the entirety of the building moves with the water level protecting the house from flooding. While few amphibious houses remain fully useable during flood events, they still maintain the baseline of the building more or less immediately after the flood when they return to resting position.

Architecture with amphibious features is compromised of mainly passive design choices, the main goal is to let the building be lighter than the water it displaces and therefore gain buoyancy. Installations must be designed to disconnect reasonably in and the building should be constraint to vertical movement only, thereby minimizing damages. This makes the building fully reactive allowing the building to change along extreme events immediately and return to baseline at the same speed. By integrating every part of the building to accommodate the buoyance, the amphibious properties and reactive strategy is achieved [15].

4.1.2 Continuous and modular construction

Adaptability in nature is also the ability to change. Likewise, buildings that face a changing climate might not be suited for the climatic challenges they will be facing in their entire lifetime. The downside to engineering for all possible scenarios from the beginning is that due to the probabilistic nature of climate change buildings might end up being ‘over-engineered’, too expensive and too complex. Therefore, an alternative solution is the ability for buildings to change throughout its lifetime by continued renovation and construction. This can be simplified by using modular design that can easily be assembled and disassembled at will [14], [20].

The ‘continuous construction design’-method is reactive without any moving parts and requires incremental changes of the architecture over a long span of time by the inhabitants of the building. It is akin to the natural development and refurbishment that inhabitants will do to a dwelling over time, but the continuous design is either preplanned by the architects or made easy to adjust by design [21].

4.2 Embedded

Embedded architecture as the term suggests embed itself within the local landscape and ecology; it is embodied through regenerative design. The design of the building focuses on the benefitting local ecology and on harvesting the benefits of ecosystem services.

The building design is therefore intrinsically linked to site, ecology and microclimate. Design must accommodate adaption in depth by regenerating ecosystems.

The designs integrate natural features. This might need to happen on a larger scale than the individual building can accommodate. Buildings utilizing an embedded strategy therefore lean in on the surroundings, and gain resilience by working together with the surrounding sites. Ideally, embedded designs could be evolving through multiple designs on larger developments to unlock its full potential [22]–[24].

Designing low rise-residential architecture as embedded into ecosystems is a daunting task, when the product is individual buildings in an urban context. However, employing embedded adaptation strategies in building design might actually prove to be a low hanging fruit compared to the other strategies mentioned here, since the basis for the ecosystem will be present at site already.

Residential developments in suburbia could be excellent areas in which to employ embedded adaptations, since they in most cases already have gardens or other features to nurture natural landscapes around them. Designing houses and residential developments in suburban context with embedded strategies could probably become a net positive for the local neighborhood, since the bettering of waterways, soil and biodiversity will be a positive for the surroundings outside the immediate building site [12], [25].

4.2.1 Vernacular, traditional and bioclimatic design

Bioclimatism is a term that describes architecture that is adapted to its local macro- and microclimate. These methods have often evolved over generations as local building tradition also called vernacular design, often from simple forms becoming more complex over time yet attainable and efficient utilizing local materials at hand [26]. These buildings are inherently adapted to their local environments using passive strategies to regulate the temperature within the buildings and preventing or surviving flooding [27], [28].

Vernacular architecture has evolved and adapted to the climate through generations, implying a slow and gradual change. While there certainly are plenty examples of climatic change throughout the history of humanity, what we face today is unlike anything faced before regarding the speed of change, and looking at what was once adaptable architecture may not be sufficient in the future [14] .

Nonetheless, bioclimatic designs are fit for the environment that it was built in; what the buildings of the future are going to face will in some cases be exaggerated versions of the climate the buildings are designed for today. Therefore, the elements of traditional and bioclimatic designs might still be relevant within especially the embedded class of adaptive strategies.

4.2.2 Biomimicry

The notion that humans should learn from nature is ancient, but technological advances and the growing importance of the sustainable paradigm have given life to biomimicry.

Biomimicry is the emulation of natural functions or processes in manmade objects, not merely the aesthetics of biology which is defined as biomorphic design [29]. Biomimicry requires insight in the biological processes and functions that the design wants to achieve and is thus raised somewhat over the expertize of individual designers, whom may require assistance from biologists or other professionals with a similar knowledge of the natural world [30].

Examples of biomimicry would in the field of housing often through inspiration from plants since they are stationary; façade systems could mimic properties of leaves or overhangs could mimic the behavior of certain plants in changing conditions [30]. On larger scales full ecosystems or organic systems could be mimicked, like the Eastgate Centre’s mimicry of termite mounds [29].

Employing biomimicry could very well go into all described strategies. However, it is most applicable to the embedded design strategy, especially ecosystem mimicry [22].

4.3 Hybrid Strategies

While the previous sections describes the three main approaches to climate change adaptation in sustainable architecture, there are also hybrid strategies combining the three. In the next sections, tiers of adaptation are described; they are what determines the possible implementation of the adaptive design.

Hybrid strategies will most likely be the most widespread if climate change adaptation begins to spread into mainstream housing design. Different categories excel at different impacts and particular sites may make better use of embedded strategies, while others have to rely on the defensive and reactive approaches as the main design drivers.

Hybrid designs could also denote the interplay between building and landscape design, where symbiosis between solutions in the two fields could become more than the sum of their parts [10], [11].

4.4 Summary

- **Defensive:** Protects the building from extreme events through resilient solutions that are immutable in the building design.
- **Reactive:** Reacts to extreme events by changing the building along the event.
- **Embedded**: Protects the building and aids the surroundings by embedding in natural landscape and surroundings.

5 Tiers of adaptation

5.1 Hard

The hard adaptions are the ones that are often deeply imbedded in the architectural design, these can be the structural or envelope designs that increase the resilience of the design [11].

These can provide a basic level of resilience and adaptation to climate change. Through their relatively immutable nature and higher cost to change, the hard adaptions should only respond to the most critical climate change effects and to the lower range of future projections.

Hard adaptations are fully integrated in the building design and is either hard or impossible to change during the buildings lifetime. Therefore, the hard adaptations are best suited to engage the most likely and pressing climate change issues. Thereby, the investments are likely to earn themselves back. Adapting architecture to the worst future projections might be overcomplicating designs and over-expensive. In the worst case, over-engineered hard adaptations might lead to maladaptation, if climate change should take another route than currently predicted. The economic circumstances surrounding hard adaptation will in most cases make them unfeasible for anything but the most certain scenarios [31], [32].

Designs like amphibious buildings must be defined as hard, since the entire structural design is dedicated to the adaptation strategy. Houses designed around complex passive heating and cooling systems will likewise be working in the hard adaptation tier, if they employ elements like heat mazes, integrated thermal mass and structural elements etcetera.

5.2 Soft

Soft adaptations are soft in the way that they allow inhabitants to change the buildings easily and with minimal costs. What can be considered as soft as opposed to hard adaptations is dependent on the building structure [11].

This level of adaptations may provide most benefit if they can enhance the base adaptations provided by the hard adaptations. They may also be employed on their own with only human adaptation as a further layer.

Soft adaptations can be present in architectural design through the original construction or as a possibility for adaptation when the need arises. Therefore, soft adaptations demands less resources and energy be committed to increasing the resilience of the building from the beginning of the design.

It is important to note that soft adaptations bridges the gap between hard adaptations and pure human adaptations. Most soft adaptation requires the interference of humans to function; it could be flood protections that can be mounted and dismounted or solar shading actively controlled by the inhabitant.

Hard adaptations, like flexible construction systems and modular design, functions by essentially softening the design and open up for continuous adaptations, which are implemented as needed over the buildings lifetime [14], [33].

Soft adaptations often require active use and interference from the residences. Implementation should therefore be done with considerations to t normal cultural practices in the everyday life of residents [34]. Solutions that are efficient on paper should match what the typical resident will be able to cope with as an adaptive measure. This could mean that solutions that require continuous involvement of the inhabitant without tangible gains might be abandoned, while larger singular time-consuming changes to houses might seem insurmountable [35]. Therefore, soft adaptations need to strike a balance between efficiency, physical implementation and usability for inhabitants.

5.3 Human

The user, their practices and physiology is essential as a final acting layer of adaptation. The success of humankind as a species stems from our capability to adapt under different circumstances and environments.

To utilize humane adaptation to climate change is not only to implement human ergonomics into the architectural design, rather to understand the homeostasis of the body and incorporate this in architecture, designing architectural form not only as something to encapsulate the inhabitant, rather as an extension of the body. It is important that the adaptive design accommodate the psychological complications when creating designs for climate change. Unless people experience extreme events they tend to find them unlikely and will only bother with minimal changes[36].

Human adaptations relies on behavior and biology, allowing interior temperatures to swing with the exterior, since human tolerance of temperatures will adapt naturally. Therefore, perfectly conditioned buildings will make the hotter climate of the future become less tolerable for their inhabitants. Which could lead to reliance on powered cooling in the general building stock [11], [37], [38].

5.4 Summary

- **Hard:** Adaptive designs that are hard/expensive to change during the buildings lifetime, often embedded in or deeply connected with the structural design of the building.
- **Soft:** Strategies that are easy/cheap to implement or change during the buildings lifetime. The residents can ideally manage it.
- **Human:** The functional and biological adaptive capacity of the inhabitants, it can be enhanced through thoughtful design of space and indoor environment.

6 Discussion

This paper has mostly served to define overarching strategies for adapting especially residential architecture to climate change. Defining diverse architectural adaptation measures as overall strategies could help understanding how buildings could behave and adapt to certain regional peculiarities and site features. Understanding how the adaptive measures and systems interact in an overall strategy might allow designers to focus on designing buildings remaining being sustainable as well as setting long-term goals for the building performance as a part of the strategy [33].

The understanding that a building might benefit greatly from natural features by taking an embedded approach in the early design phase, could prevent over complicated or even maladapted final designs.

Architectural climate change adaptation will always be a difficult subject by the fact that the problems addressed reaches far beyond the classic delivery of a finished building handed over to owners, even beyond the scope of most post occupancy evaluations and adjustments. To design fully adapted and beneficial buildings for an uncertain future, strategies for the long-term development of the buildings must be lay out. Whether it is by well-dimensioned defensive strategies, a developing reactive process or an embedded building benefitting further as more buildings join the embedded network over time, the designer must see the full perspective of the building's lifetime and its development in several possible future scenarios.

Adaptation to climate change within the field of architecture has until present day been rather unstructured, relying on building engineering to supply solutions applied to the finished design. There are plenty of solutions, which can increase the resilience of buildings, either by themselves or in unison. Most adaptation in architectural design seems to be focused on either solving overheating or flooding, with very little in the way of holistic adaptations. Climate change is happening at full range and the architecture of the future must be able to respond to all challenges [10].

While establishing strategic overviews of climate change adaptations may seem like an exercise in semantics, it helps gain an understanding of architectural adaptation and serve as a starting goal for the architect tasked with designing buildings that will have to last well into the future. Upon assessment of site and context, a consideration choosing the overall strategy for resilience and adaptation could be within the realm of the architectural designer, just as energy efficiency has become a more important part of architecture during the last decades [19].

7 Conclusion

The strategies as described here primarily concerns towards residential architecture, but most of the strategies does carry over into commercial buildings. However, the user focus is less necessary in commercial buildings, since the users inhabit them for more manageable time spans. The major impact of climate change in commercial buildings are economic, for example damages, lower efficiency and energy use. While there is a larger human aspect present when considering residential architectural design, in that people are bound to their homes and possessions.

The outlines of the strategies might be interpreted differently, but they seem to encompass three major flows within the literature of adaptive architecture. A damage-minimizing passive and low-tech road characterized as defensive strategies. A technology-optimistic perspective that uses dynamic approaches to mitigate impacts characterized as reactive strategies. Finally, a large group of literature that has a larger focus on the role of nature in climate change and how manmade impacts on natural factor is exaggerated by climate change, these views fitted well within the embedded category.

There need to be further studies to refine and exemplify the strategies in use. The study shows that there is a need for comprehensive and holistic approaches to climate adaptation in buildings, which the strategic adaptation method could offer if refined. Simulation and experimentation of example buildings could help the refinement of the study, and help create a comprehensive method for implementing climate change adaptation in future buildings.

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Challenges of the Nigerian Construction Industry: A Systematic Review

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Abstract

The fragmented nature of construction industry around the world allows for many active players which contributes to the enormous challenges faced today. These challenges vary across nations but some are more specific to developing nations. In Nigeria, the challenges of the construction industry are enormous and may be responsible for the slow adoption of sustainable construction. This paper attempts to identify these challenges with a view to providing specific solutions in the Nigerian context. A qualitative exploratory research design where data derived from systematic review of literature was adopted. The study identified challenges such as lack of synergy, material shortage, unethical practices, unstable price of materials, project delays, and poor management. These challenges are categorised into industry, firms, project, and government-based. Practical solutions including compulsory continuing professional development (CCPD), incentives, and establishment of construction material price monitoring units were proposed.

Keywords: *challenges, construction, Nigeria, sustainable construction, systematic review*

1 Background

Over the years, the construction industry has been recognised as one of the major contributors to economic development of a country owing to its ability to create employment, wealth, and infrastructure. Through its activities encompassing design, construction, and operation; resources are transformed into structures or facilities [32] which could be argued as one of many reasons why the industry is significant. As a socio-economic hub, the industry is responsible for providing shelter, a basic human need in the form of residential and non-residential buildings. Likewise, the contribution of the industry to GDP growth is worthy of note especially in developing countries as emphasized by Ref. [33] and [39]. The situation in the Nigerian construction industry is not different from other developing countries. For instance, the National Bureau of Statistics [40] reported that the industry grew in nominal terms by 44.09% which represents 5.47% of the country's GDP during the second quarter of 2018. Aside contributing to the GDP growth, there are several other opportunities for the industry to grow the economy. Nigeria has now attained self-sufficiency in cement production [52] and according to the Federal Mortgage Bank of Nigeria, the demand for housing units is estimated to be around 17 million units aside other types of construction such as roads, offices, and bridges. Despite the growth and various opportunities, the industry is faced with enormous challenges which span across major stakeholders, method of construction, and regulatory framework.

These challenges have been viewed from different perspective in the literature. Some authors have addressed the issue by focusing on specific sections of the industry. For example, Ref. [57] reviewed barriers to the adoption of offsite manufacturing while Ref. [5] identified causative factors for construction delay. Similarly, Ref. [55] identified factors responsible for rework in the Nigerian construction industry, Ref. [61] evaluated effects of communication in construction project delivery while several other studies [4, 16, 21, 49] have identified time and cost effects on construction projects in Nigeria. Apart from these studies that addressed specific sections, few studies have provided a broad overview of the industry. For instance, Ref. [18] provided a general overview of the Nigerian construction industry while Ref. [32] reviewed the contributions of the industry to sustainable development. From all aforementioned studies, it is clear that little or no studies have specifically identified the challenges of the industry. The question now is: what are the challenges of the Nigerian construction industry and how can they be resolved. Therefore, the aim of this study is to identify these challenges and proffer possible solutions while the objectives are to: list all challenges and categorise them; describe all challenges based on the categories; and offer possible solutions.

2 Research Methodology

This paper adopts a systematic review of literature to identify challenges of the Nigerian construction industry. There are several definitions of systematic literature review but the common keywords are transparency, clarity, integration, focus, equality, accessibility, and coverage [56]. The ability to assess, review, and discuss findings [29] justifies the adoption of a systematic review for this study. Likewise, it has been adopted by several authors [12, 22, 59, 38, 36] in their studies. For the purpose of this study, the five-stage process as adopted in previous studies [12, 28, 38, 34] were followed and are described in Table 1.

Tab. 1 *Systematic review process*

Process	Description
Propose a research question	A research question encompassing the topic and scope of the study as suggested by Ref. [20] and highlighted in section 1.
Collect data	Data here refers to materials which previous studies related to the topic.
Evaluate data	Descriptive analysis to identify quality and relevant published studies.
Provide a summary	Summary of all studies previously identified.
Interpret results	Discussion about the major findings of the review in clear terms.

Data for the study were collected via literature search in web of science (WoS), Scopus, and Google Scholar. These databases were adopted based on recommendations from authors [3, 25, 30, 60] that have used them and identified their strengths to include comprehensive peer-reviewed and non-peer reviewed materials and organised bibliometric studies. The search criteria was the same for all databases abd keywords such as "*challenges*", "*construction industry*", and "*Nigeria*" were used to identify relevant published materials between 1997 and 2018. The search in both WoS and Scopus returned 14 and 48 papers respectively. To identify a wide range of studies, patents and citations were excluded in the search in Google Scholar and 7520 papers were returned including non-peer reviewed papers which brings the total number to 7582. All papers were first screened based on relevance to the topic by identifying those with the study's keywords in their titles and abstracts (see Table 2) while duplicates were removed. The second screening was to determine relevance with the research question by reading the abstracts of articles that were selected in the first screening. Thereafter, all articles were read in full and a total of 53 articles were reviewed. The results are presented and discussed in section 3 and 4 respectively.

Tab. 2 *Study selection*

Screening	WoS	Scopus	Google Scholar	Duplicates	Total
Initial search	14	48	7520	-	7582
First screening (keywords in titles and abstracts)	8	24	3061	26	3067
Second screening (abstract reading)	8	21	1104	-	1133
Third screening (full text reading)	2	8	43	-	53

3 Findings

Following the procedure described in section 2, a total of 25 challenges were identified and categorised into four main sections with two sub sections as presented in Table 3. The relationship between the categories are also presented in Figure 1 for ease of understanding.

Tab. 3 *Challenges of the Nigerian construction industry*

Category	Challenges	Sources
Industry-related	Lack of Synergy	[5], [63]
	Poor management	[5], [44], [4], [27]
	Lack of modern building methods and equipment	[24]
	Lack of reliable data	[17]
	Absence of national agency	[5]
	Lack of skilled manpower	[31], [24], [11], [23], [2], [63]
	Building collapse	[47], [41], [64]
Client-related	Insufficient finance	[24], [44], [5], [27]
	Lack of confidence in the industry	[6], [46]
	Racial discrimination	[24]
Professionals-related	Unethical practices	[7], [8], [14], [54]
	Resistance to change and unwillingness to innovate	[11]
	Inadequate technical know-how	[44], [27]
Government-related	Epileptic power supply	[18]
	Poor implementation of policies and programmes	[17], [19], [50], [26], [13], [15]
	High and unstable price of materials	[18], [62], [53]
	Undeveloped ancillary industries	[24]
	Political and social unrest	[18]
	Dominance of foreign players	[52]
Construction firms-related	Insufficient finance	[24], [44], [5], [27]
	Incompetent companies winning bids	[18], [50], [1], [45]
Project-related	Materials shortage	[44], [5], [18]
	Changes in site conditions	[5]
	Project delays	[42], [4], [43], [48], [62], [27], [64]
	Project abandonment	[51], [62], [64]
	Time performance	[27], [9], [21]

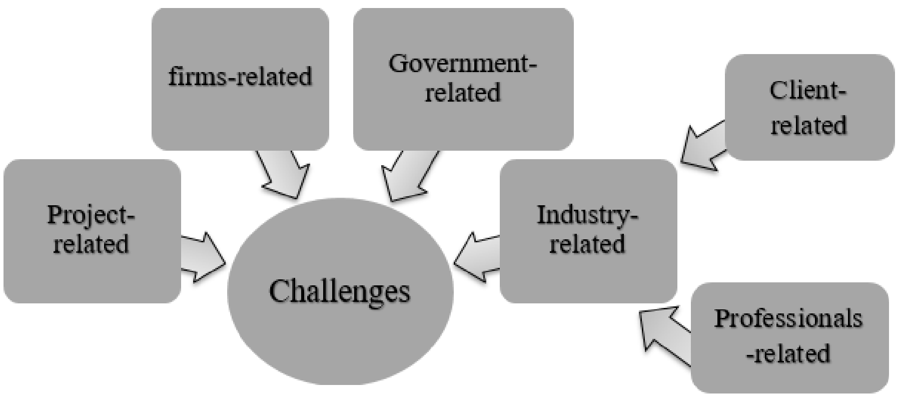

Fig. 1 *Categories of challenges in the Nigerian construction industry*

4 Discussions

This section discusses findings of the literature search. It is worthy of mention that some of the challenges identified and categorised in this study are interwoven cutting across different categories. However, they have been discussed under the appropriate category as determined by the authors and practical solutions have been provided as well. The findings of this study forms a section of an on-going PhD research.

4.1 Industry-related challenges

The challenges of the Nigerian construction industry are a function of the industry itself as revealed in this study. According to Ref. [5] and [63], the industry lacks coordination of all associations including professional bodies and trade unions. Although, these bodies are present but the lack of synergy between them exposes the industry to risks including influx of quacks which could be devastating to the industry in the long run. Likewise, there is no national agency that coordinates activities of the industry [5] which in itself is a disaster to the industry. An organisation without coordination is prone to chaos, disorder, and negligence as experienced in the Nigerian construction industry. Therefore, it is imperative that different professional organisations come under a national body that will coordinate activities within the industry and ensure its smooth running. Management, an effective business tool is essential for the success of any organisation and as for the construction industry, it encompasses the workforce, projects, and contracts. Unfortunately, the industry is engrossed in poor management which Ref. [5] and [4] attributed to lack of training and absence of specialisation. Effective management of the industry is however essential to ensure smooth operation and effective output. Management at all levels within the industry should be the responsibility of all professionals and as such, series of trainings should be organised to provide professionals with required skills.

Another challenge of the industry is its lack of modern building methods and equipment which Ref. [24] blamed on the lackadaisical attitudes of professionals whom he reckoned do not have time for seminars and workshops to improve their knowledge base. Although, time is an important factor in the industry however, personal development and growth should be highly encouraged especially with modern methods of construction which offers better time management when compared to the common traditional methods. The compulsory continuous professional development (CCPD) programme should be encouraged among professionals in order to improve their overall managerial skills. The industry's lack of reliable data as reported by Ref. [17] may be due to low priority and level of support given to research and development which is not specific to the industry but to the country at large. The industry require reliable data in order to map out effective strategies that may resolve majority of the challenges identified in this study. It is recommended that the industry look into collaboration with research institutions to provide reliable data and tailor-made solutions.

Several authors [2, 11, 23, 24, 31] identified lack of skilled manpower as a major challenge ravaging the industry. Skilled workers such as contract administrators, site supervisors, estimators, foremen, carpenters, and steel fixers are generally required on construction projects and without them, it may be extremely difficult to achieve success. The industry should invest in providing specialised training in those trades lacking skilled manpower to those interested in the industry especially young school leavers. It will be a win-win situation for both parties because the industry will be able to fill the skills gap while providing employment for the young school leavers. The last factor in this category is building collapse which is a serious challenge impacting the growth of the industry [47, 62, 64] and of concern to the nation due to its catastrophic nature. Building collapse has become a common occurrence in the country with at least minimum of two collapses each year. Figures released by the Federal Ministry of Power, Works, and Housing indicates that a total of 54 buildings collapsed in Nigeria between 2012 and 2016. In August 2018, a building under construction collapsed in Jabi district of Abuja, killing three people. Three months after, another building on Woji Road, Port Harcourt, River State, collapsed killing 17 people. These incidents portray the industry in a bad light while the infiltration of quacks (unregistered professionals) may be blamed for incessant collapses. To eradicate collapses, it is recommended that the industry look inward to identify quacks and ensure prompt compliance to building codes and standards. Each professional body in the industry should set up enforcement committee with support from the government to go around all construction projects to enforce compliance of all aspects of works relating to their respective professions.

4.1.1 Client-related challenges

These are challenges posed by the clients recognised as all levels of government (Local, State, and Federal), private individuals, and organisations (indigenous and foreign). Lack of funding for projects has been identified as one of the challenges facing the industry [5, 24, 27]. A project devoid of funds could be abandoned, delayed, and may be of low quality which negatively affects the image of the industry. Generally, clients provide funding and are expected to pay all consultancy fees or professional costs depending on the procurement type. However, some clients may delay payment while some may default. Ezeifedi [24] cited the example of the government not paying on time for completed works. This action may impact the industry negatively and could affect professionals' morale and commitment. Therefore, clients should be advised of the effects of insufficient funding and legal agreement for prompt payments may be reached at the commencement of the project. As a result of several challenges and other salient issues such as heavy presence of foreign firms and negative perceptions about the industry, clients especially government and other international organisations lack confidence in the industry [46, 6]. Most foreign firms are believed to be efficient, technical, and are able to provide high quality construction projects. Therefore, they are preferred to indigenous firms by most clients which Ref. [24] described as racial discrimination. The government should provide incentives in the form of tax exemption to indigenous firms in order to make them more competitive with their foreign counterparts. More so, policies that will relinquish all public buildings to indigenous firm should be formulated.

4.1.2 Professionals-related challenges

Several authors [7, 8, 14, 54] have identified unethical practices as one of the main problems of the industry. Corruption tops the list of unethical practices being a general problem in Nigeria which has crept into the industry in different forms. Corruption as practiced in the industry cut across all stakeholders including clients and regulation agencies. Alutu [7] described different types of corruption in the industry to include bribes, kickback in tenders, multiple subcontracting, and other sharp practices. Corruption in whatever form it may be kills a system and should be utterly discouraged in the industry. Severe penalty like jail sentences, license withdrawal, and heavy fines should be proposed for any professional or individuals found guilty of corrupt practices in the industry.

Another issue with the industry is resistance to change practice which Ref. [11] rated to be strong among construction professionals. Those who have been in the industry for years may be resistant to new innovations and methods for fear of unknown. For example, a contractor that is conversant with the traditional method of construction may find it difficult to adopt modern methods of construction for the fear of not doing it right. However, with adequate training, appropriate mentoring, and critical thinking, professionals may be innovative. They should be encouraged to invest in self-development by staying up to date with advanced developments in the industry in other to remain relevant. In another related development, Ref. [27] and [44] identified inadequate technical know-how as a big challenge responsible for the industry's slow growth. The required knowledge for some special construction processes like plastering are lacking hence the invasion of expatriates from developed countries and from neighbouring countries like Benin Republic. The ineffectiveness of technical schools in Nigeria may be responsible for lapses in technical education. Therefore, the construction industry should establish technical institutions that will train would-be tradesmen in the different technical skills required for the industry to expand while appealing to the government to revamp technical schools.

4.2 Government-related challenges

Dantata [18] identified epileptic power supply as a major challenge in the industry. Most construction equipment require electricity to function and in the absence of power supply, construction firms will have to provide alternatives in the form of generator which is at extra cost to the project. The issue of power supply transcend beyond the industry because it is a national calamity affecting all other industries in the country. As a matter of fact, there seems to be no industry or trade that does not rely on electricity. Therefore, constant and regular supply of electricity if provided could improve activities of the construction industry. It is recommended that the government invest in other sources of power generation such as renewable energy, fossil fuel, and solar systems. As reported by Ref. [24], ancillary industries such as the steel and mining industries to support activities of the construction industry are not well developed which is affecting its growth because the industry cannot survive in isolation. Hence, the government should invest more in building ancillary facilities that will not only serve the construction industry but other industries as well. Another noticeable challenge in the industry is poor implementation of policies and programmes [17, 19, 50, 26, 13, 15]. The government has good intentions for the industry by providing policies and programmes to guide its activities. Unfortunately, some of the policies are lacking effective implementation while others lack enforcement [50]. Dania [17] observed that lack of political will to enforce policies is one of the factors affecting enforcement and therefore concluded that enforcement generally in Nigeria is weak. Lack of enforcement especially for building codes and standards may be responsible for building collapses, substandard materials, and corruption in the industry. The government should establish enforcement agencies specifically for the construction industry to monitor and ensure full compliance to codes and standards. Through appropriate policies, the government can balance the ratio of foreign firms and indigenous firms thereby eradicating dominance of foreign players which Ref. [52] described as one of the major challenges affecting the industry. For instance, the oil sector local content act may be replicated in the construction industry to regulate the activities of foreign players.

Owing to lack of regulations and other factors such as high import rate, and clients' taste and fashion, prices of construction materials are high and unstable [18, 62, 53]. Since some materials are not produced locally and due to the nation's unstable economy, prices of materials are not stable (Dantata, 2007). Commonly imported materials including wooden formwork, ceramic tiles, lighting, and fittings are increasingly been used based on the perception that locally produced materials are of less quality hence, the high cost of construction [62]. The government in conjunction with the industry should establish material price monitoring units in order to ensure standardized prices. The social and political unrest in the country is another factor affecting the construction industry [18]. For instance, construction activities have been suspended in the North Eastern part of the country especially in Borno State due to heightened operations of the "*Boko Haram*" insurgent group. Similarly, construction has been on hold in some parts of Benue State due to incessant attacks by the "*Fulani herdsmen*". It is no gain saying that construction thrives in a safe and peaceful environment. Therefore, the government has to do more in providing a safe environment for its citizens to live and work.

4.3 Construction firms-related challenges

Some of the challenges are caused by construction firms as identified in this study. Some companies are financially incapacitated to embark on construction projects [44, 5, 27] even when they are provided with a certain percentage of the contract fee upfront [24]. They tend to struggle because construction projects are capital intensive and when they cannot meet up with the financial demands, they may abandon the project. The question now is – how did such companies get the projects in the first instance? The answer to the question is another challenge that the industry is faced with. Some incompetent companies are winning bids [18, 50, 1, 45] through corruption and lobbying which is common in the industry. For example, companies that have not handled a massive construction project may create a fake portfolio and bribe their way through the tendering process. In the long run, they will abandon the project or produce low quality structures due to their lack of experience and capacity to handle such projects. Therefore, it becomes imperative that the industry increase efforts to tame corruption before it kills the industry.

4.4 Project-related challenges

Although the industry consumes a lot of material, it has been established by Ref. [5] and [18] that material shortage affects the industry. Due to logistics and procurement problems [18], the industry may experience material shortage leading to project abandonment, delays, and cost overrun. The causes of material shortage may vary from one project to another depending on the size, location, value, and client's requirements. For example, a study by Ref. [58] identified possible causes of material shortage in Brunei to include: origin and availability of materials, poor estimation of materials quantity, poor workmanship, quality of material, inconsistent demand, and special materials. These causes are not entirely different from the situation in Nigeria. Similarly, several authors [51, 62, 64] identified project abandonment as another major challenge. These authors noted that factors such as those discussed in this study including the project itself may be responsible for delays. In addition, previous studies [42, 4, 43, 48, 62, 27, 64] identified project delays which refers to interruptions resulting in the extension of project completion date. For example, Ref. [27] categorised factors relating to client, consultant, contractor, project and extra contractual factors as causes of construction delay in Nigeria. To overcome delays, adequate planning at inception is highly recommended.

Closely related to project delay is time performance or time overrun which has been identified as a significant factor affecting the industry [27, 9, 21]. It implies inability to complete specific tasks or the entire construction project within the time frame specified in the contract or agreed upon [10]. Construction projects in developing countries have been reported to exceed estimated time period [37, 35] which is a critical problem for the industry. Therefore, Ref. [27] emphasised the need to improve time performance of projects in order to build clients' trust and confidence. Changes in site conditions is a project-specific issue facing the industry as observed by Ref. [5]. It implies changes in the physical conditions on site different from those anticipated by construction professionals or technicians which may cause cost overrun. The effect of these changes may be linked to professional's inadequate technical know-how [5] to conduct proper feasibility studies despite the array of modern technologies available for testing site conditions. Likewise, professionals' resistance to change may be responsible as well. Therefore, professionals and technicians should be encouraged to attend trainings and seminars to understand technicalities involved in testing site conditions and to further develop their technical-know how.

The Nigerian construction industry faces challenges related to industry, government, firms, and projects. Until these challenges are minimised, the industry will continue to impact the environment negatively while time and cost overrun will linger.

5 Conclusion

This paper has provided answers to the question – what are the challenges of the Nigerian construction industry? Through systematic review of 53 published articles retrieved from Google Scholar, Web of Science, and Scopus, the challenges were identified, categorised, and discussed appropriately. Overall, 25 challenges were identified and categorised into four major groups with two sub groups. At least, seven factors were grouped under industry-related challenges, while the two sub groups, client-related and professionals-related challenges had three factors each. Government-related challenges had six factors, construction firms-related challenges had two factors, one of which was shared with client-related factors while five factors were grouped under project-related challenges. Findings of this study highlight challenges of the industry as all-encompassing and provide useful insights into the effects of the challenges on the industry. It also provides better understanding of current issues and recommends practical solutions to ease the challenges including trainings, CCPD, incentives, adequate planning, establishment of enforcement and monitoring committees or agencies, and investment in alternative power generation. Future studies may seek industry stakeholders' opinion about these challenges using quantitative, qualitative or mixed methods approach.

Acknowledgement

This paper is based on a research supported by the University of Newcastle International Postgraduate Research Scholarship and University of Newcastle Research Scholarship Central and Faculty (UNRSC50:50).

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Relationship between Political Borders and Ecosystem Edges. Case study The City of Prague

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Abstract

Humanity is increasingly urban but continues to depend on Nature for its survival. Political jurisdictional borders are an inevitable part of a human-dominated world. Rarely coincident with ecological boundaries, they nevertheless impose substantial costs on natural resources by ownership, governance, and management. Where boundaries are in place, study correlation between political borders as the reflection of urban development and ecosystems in the city reflects the ability to create and manage green infrastructure, according to the increasing scientific evidence of the positive impacts that urban green infrastructure (UGI) is having on the urban sustainable development. [1].

The city of Prague has grown and evolved, political jurisdictional borders have divided the urban figure into districts with their needs, and it is considered as the words greenest city in the world. Creating a methodology to discover the relation between political districts and ecosystems, using new GIS data to reach recommendations to be the sustainable city.

Keywords: *City Districts, Ecosystems, Watersheds, ÚSES, GIS.*

1 Introduction

Cities are place where people live and do their activities by urban development which affects the ecosystems through the time. Studying the relation between urban development areas and ecosystems will help to understand the nature and strength of this relation for the future development of the city to create green sustainable place to live. Looking for the historical development of the city will help to understand through the time how did the planners create the city, and the role of the ecosystems in this development in the present and future.

City District Borders are the reflection of urban areas development and changes in this lines through the history shows how the planners take in consideration the landscape characteristics and ecosystems. [2].

The aim of the study is finding a methodology could be used for any case study has development urban areas affect ecosystems and realize the nature and strength of the relation to create green infrastructure as a step to have sustainable city.

For this study the City of Prague has been selected a case study as the most developing area in whole Czech Republic with higher levels of living than before. Prague is ranked 24th overall in the European Green City Index, with a score of 57 out of 100 of the green area. The city government making large efforts to be sustainable with higher standard quality of life, the importance to study the relation and interaction of political borders as reflection of the urban development and ecosystem capacity to create green infrastructure application as a step for sustainability. [3]. [4].

1.1 Political Borders and Ecosystem Edges

An ecosystem edge is a physical boundary such as a river; mountain or ocean; don't change often, while a political border is where countries, states or cities are separated; they can be changed for political reasons or if areas of land are taken over and they are different in scales. [4]. [5].The best way to determine it is to look at a map; it is made by governments according to ownerships and often not responded to the ecological edges most of the time, studying interaction between them is important for the development and conservation of natural resources. **(Fig. 1), (Fig. 2) & (Fig. 3).**

Most Ecosystem edges are curvilinear, complex and soft, whereas humans tend to make straight, simple and hard borders. Edge usually has width; (which is different around a patch) as a buffer zone around the natural resources to protect it from surroundings on the ecosystems. **(Fig. 4)**. [2].

Simple diagram show the difference between the concept of a political borders (usually straight) and ecosystem edges (usually curved) as lines and as an interaction zone area. [6].

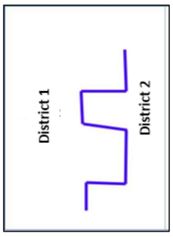


Fig. 1 *Political liner borders and ecosystem edges (Authors).*

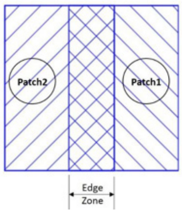


Fig. 2 *Edges as an interaction zone area (Authors).*

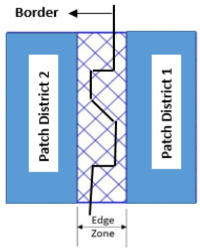
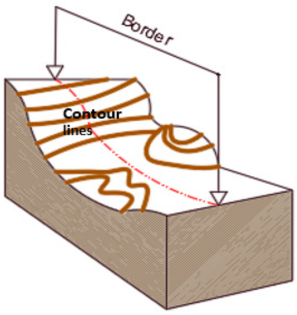
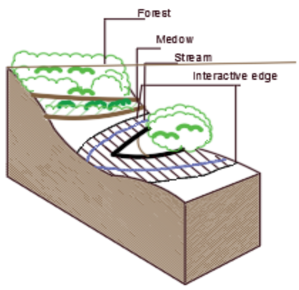


Fig. 3 *Edge zones as place for interaction (Authors).*



Border: as superimposed plan metric division.



Edge: as an interactive area between patches.

Fig. 4 *Borders and Edges (Authors). [2].*

1.2 Case Study

The city of Prague, is the capital city in Czech Republic located on the centre of the Bohemian Basin, with a population of 1,297,000 inhabitants, ranking the 14th largest city in the European Union and included in the UNESCO list of World Heritage Sites complete with a rich history. The city has a ring of mountainous surroundings, natural water resources have played a vital role in the city's early development, the Vltava River runs through the city influencing a breath taking landscape: natural parks. Residual green areas within the historic fabric primarily include chateau gardens, urban parks and cemeteries.

The city was founded in the 6th century and starting from the historic core straddling the Vltava River Prague has expanded East and West along stream corridors and over the hillsides that separate the stream valleys with higher preference for South facing slopes, the development of city borders by the time; the national government in Prague holds all control over administration of border issues, The city also consists of 22 administrative districts with the city waterbodies as an ecosystem reflects water and topography of the city (**Fig. 5**).

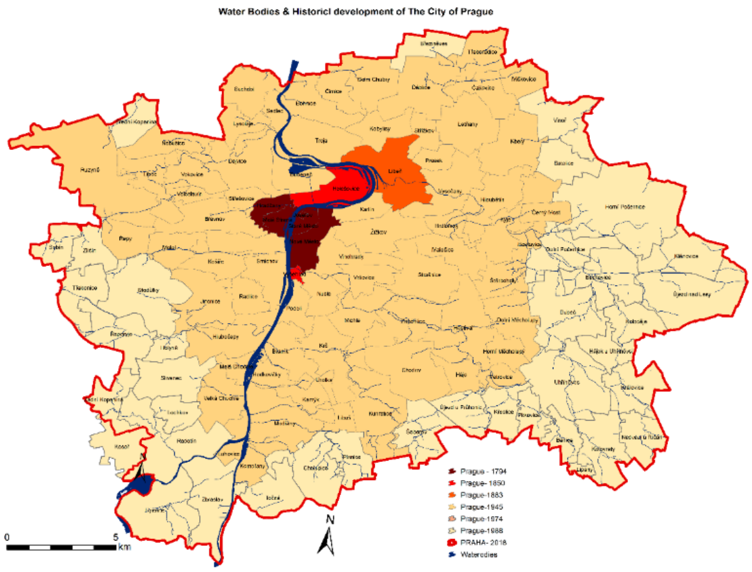


Fig. 5 *Historical development of the city of Prague [12] & (Authors).*

2 Methodology

The aim of our work is to develop a methodology to identify and describe the relationship between political borders and ecosystem edges.

2.1 Study topics

We use the following topics for our study:

- City District Border (CDB)**:**an area of a country, state, or city that has been given fixed borders for official purposes, or one having a particular feature that makes it different from surrounding areas, including the general city border and the 22 districts inside the city .[12].
- ÚSES (Ú): Uzemní Systém Ekologické Stability is the same word in English "TSES" based on landscape ecological knowledge and landscape planning, to keep the ecosystems protected, Czech Republic government developed the concept of (ÚSES) and it procedures to create G.I. functions consists of all existing and proposed landscape segments of ecological significance that can contribute to the conservation of landscape and promoting biodiversity. The ÚSES concept is used for small areas of natural communities with favorable conditions in the cultural landscape and development areas and subdivided into ÚSES Functional (ÚF) which are existed and can be found on land and maps while ÚSES Non-Functional (ÚNF) bio corridors, recognized as critical components of the bio corridor network that should be transformed into functional bio corridors; it means they are not existed yet but considered in the future development master plan as green areas with a great role in creating green infrastructure . [13] [14].
- Watersheds Edges (WE): The land area upon which precipitation (rain and snow) falls and flows to a common open flow channels such as creeks, streams, and rivers, and eventually to outflow points such as reservoirs, bays, and the ocean, and different in scale; A watershed can be small, such as a modest inland lake or a single county.[15].
- Rivers (W3) & Streams (W4): using the main rivers and streams in the city as ecosystems to study the relationship with the previous topics.

2.2 Study steps

Steps of methodology are shown in (**Fig. 6**)**,** techniques of Geographic Information System are used in the process:

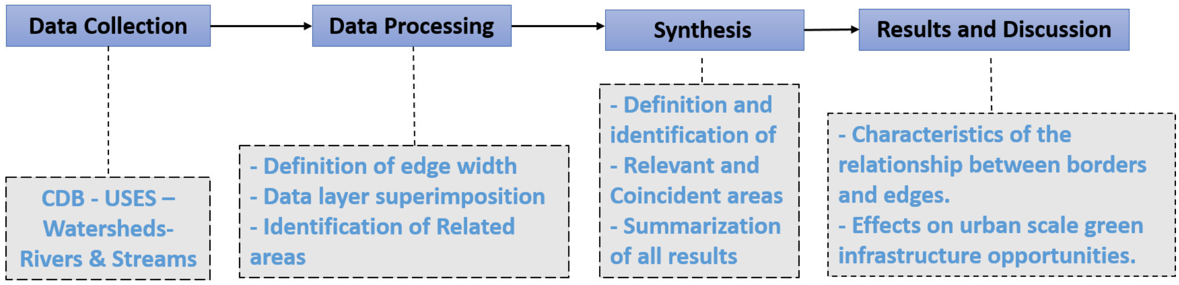


Fig. 6 Methodology *steps (Authors).*

2.2.1 Data collection

Collecting the needed data from different resources: CDB, USES were uploaded from study made on 2015 by .Iprpraha.cz.Watersheds in the city of Prague is made based on the elevation and geology of the city by (Hydrologicky Ustav-2013 & corporation with DIBAVO) in two levels A08 is level 4 of watersheds detailed for the city of Prague. Rivers & Streams were uploaded from Ipr-Praha in correlation with DIBAVO, to correct and check data. [16], [17]. [18]. [19].

Note: Correcting and dissolving for data are used because of mistakes from the source; like deleting double lines and connect cut once.

2.2.2 Data Processing

Edge Zone: as an important parameter; differs from case study to other. Defined as width from the centreline to the both sides of the ecosystem, we tested 10m, 25m, but the results were so small and no meaning. Recognizing the nature of landscape of Prague and watershed edges are based on topographic data with an interval of 5m, it was clear that we needed to expand the width of the edge area so that the variations within this contour interval would be inclusive.

Therefore, we choose and worked with a 50 m edge zone (100m total width) for all ecosystem edges, then identify related connected parts.

2.2.3 Synthesis

Studying and clarify the related parts to give the relationship meaning by using the concept of noise to find a value that before it the length of the related parts has no meaning and after it, the parts are meaningful and the amount of the parts with this length gives strength of the relation described in **(Fig. 7)** as an example related parts in between CDB & WE buffer zone 50m, with histogram reflect the Coincidental (Noise) & Relevant (Not noise) parts. [20]. [21].

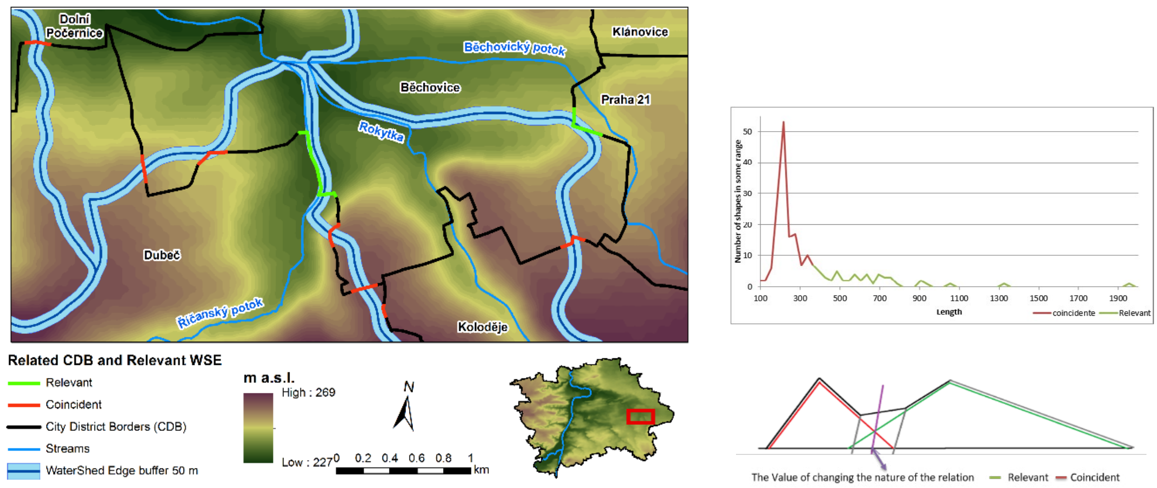


Fig. 7 *Map and* Histogram *as an Example of Noise (Authors) & [16]. [19]. [20].*

3 Results & Discussion

In accordance with previous steps of methodology maps and summary diagram were obtained. The summary diagram **(Fig. 8)** with numbers and percentage for the relevant parts of relationships, the total width including white, blue and red is the total potential relevant relationship. Green represents the Functional relationships and the Red represents the Non Functional relationships. Therefore, the graphic relationship is relative to the total width of all lines; red, green and blue.

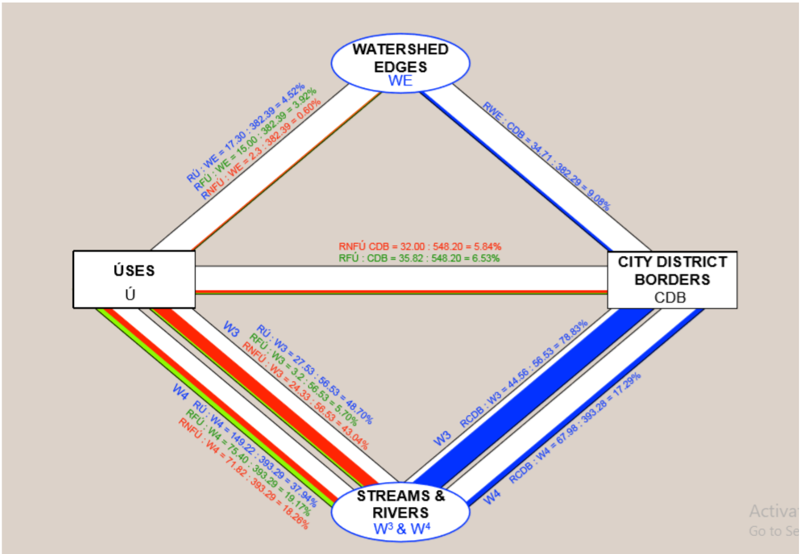


Fig. 8 *The Summary Diagram (*Author)

The top level maps as follows:

Watershed Edges (WE) and City District Borders (CDB): Using an edge zone of 50m buffer around the lines of WE, RWE: 9.08%. **(Fig. 9).**

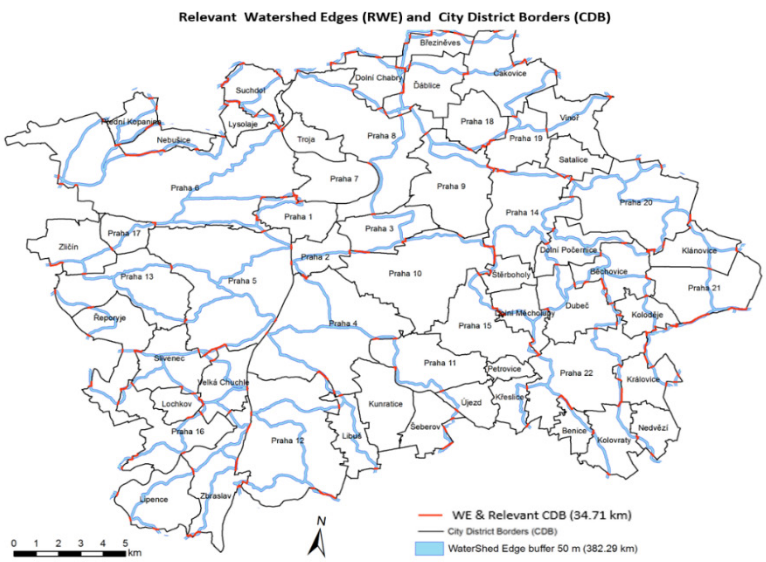


Fig. 9 *Watershed Edges and Related City District Borders (Authors). [16].[19]*

<u>WE: CDB</u>

Based on the analysis we see that approximately 9% of the watershed edges have some relevant relationship with City district borders. As can be clearly see on the map, the locations of relevant relationship are greatly dispersed throughout the City, there are no significant lengths that indicate watershed edges are not a primary influencing factors in the identification of City districts.

Ecosystem function is not an important consideration in the definition of jurisdictional areas. Furthermore, jurisdictional areas in the City of Prague dissect watershed areas such that every watershed in Prague has multiple jurisdictions.

Watershed Edges (WE) and ÚSES (Ú): 4.52% (**Fig. 10**).

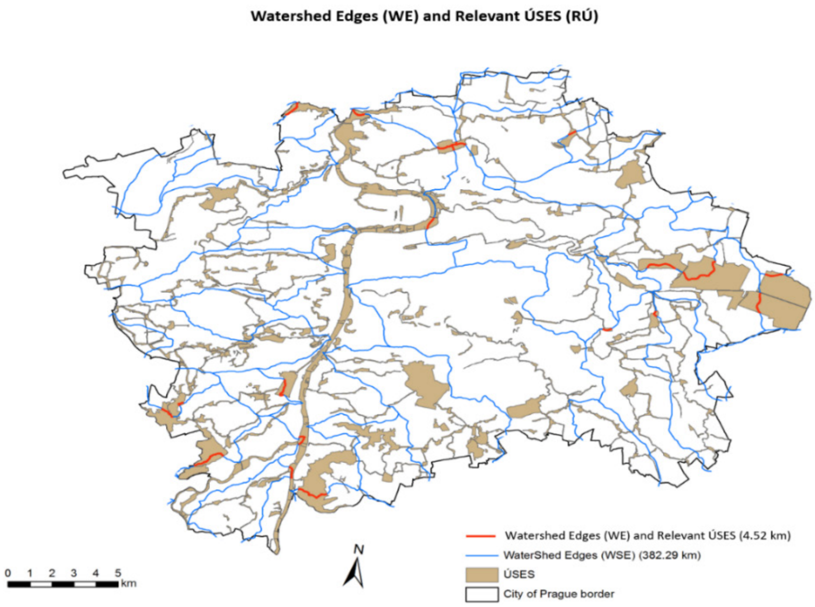


Fig. 10 *Watershed Edges and Related ÚSES (Authors). [16].[19].*

ÚSES (Ú) and City District Borders (CDB): (Fig. 11) the result is (RÚ = 12.37%) . maps for Function ÚSES (RFÚ): 6.53% & Non Function ÚSES (RNFÚ): 5.84%.

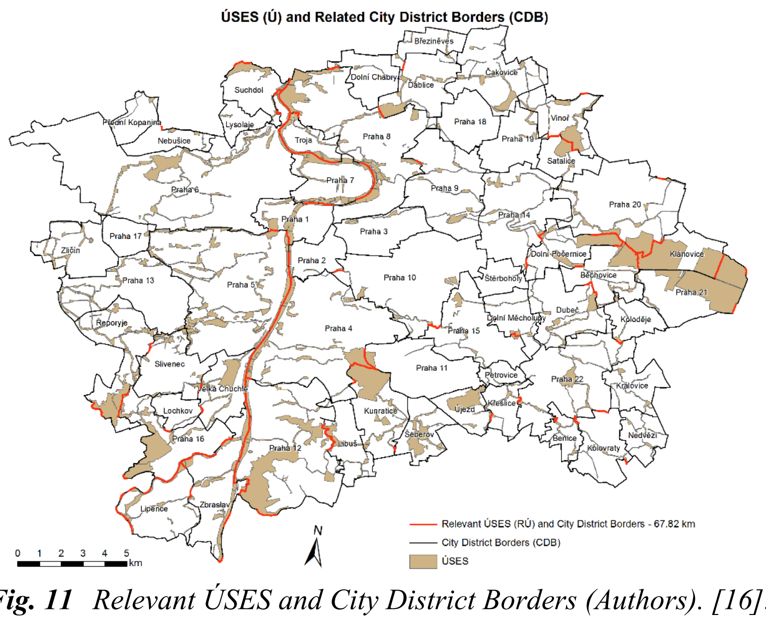


Fig. 11 *Relevant ÚSES and City District Borders (Authors). [16].*

Ú: CDB

As neither ÚSES nor City District Borders have an edge effect, an edge effect area was not applied in the analysis; therefore, the analysis identifies relevant correlations based on the specific geometries of the two layers. It can be seen in the analysis mapping that there are numerous areas where ÚSES designed areas follow very close to borders. The absence of correlation comes from the definition of the ÚSES corridor within a single City District rather than a designation that overlaps multiple CDB's. The most significant correlations is the rivers Vltava and Berounka.

City District Borders with Rivers W3, Streams W4: RCDB & W3: 78.83% (**Fig. 12**). RCDB & W4: 17.29%

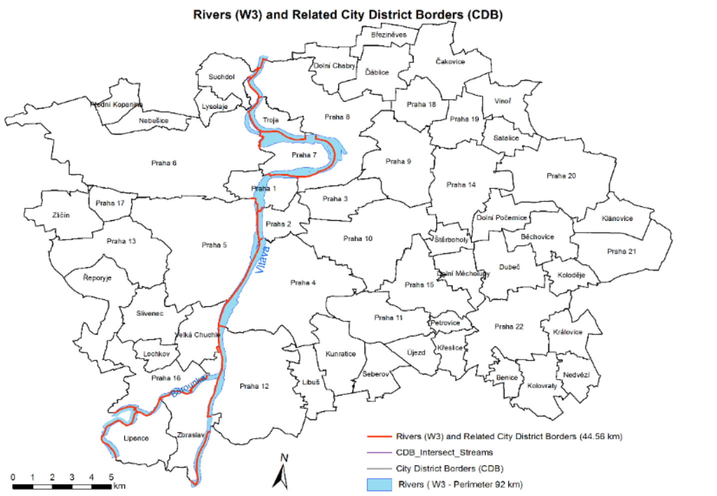


Fig. 12 *Relevant City District Borders and Rivers (Authors). [16].*

ÚSES and Rivers (W3), Streams (W4): RÚ& W3: 48, 70% (**Fig.13**) – RÚ & W4: 37, 94%.

CDB: W3 and W4

The Vltava and Berounka Rivers are primary landscape features that have significantly influenced the establishment and development of Prague. It is not surprising that these rivers have a strong correlation with CDB's with virtually the entire length of these rivers having a direct correlation. The primary exception is Prague 1 which is similar to the medieval city definition.

Approximately 17% of the streams throughout the urban landscape of Prague have a correlation with the CDB's and are generally in the newer, less densely developed areas of the City, particularly in the South East quadrant. Although the relationship between the Vltava River and Prague has changed substantially over the centuries, it remains a critical part of the urban structure. The ÚSES designation of the entire length of the River through the City is one of the significant intended roles for the River.

Ú: W3 and W4

As primary landscape features and it is reasonable to expect them to a significant correlation with at least the intent of Ú. The total correlated area of approximately 49%. The vast majority of the Ú along the rivers is designated as non-functional; therefore, not serving the intent of Ú.

Apparently, the jurisdictional divisions of the City into districts is without regard for either watersheds with correlations largely fragmented. Based on the results of this case study, the border based definition, differentiation and division of land largely ignores and conflicts with the edge based hydrological systems of landscape. If integration of natural systems into urbanism is a valued pursuit, then is an edge based view of these systems more appropriate that the delineated? Are the anthropocentric border system and the edge based natural systems mutually exclusive or can they coexist, and if so, how?

As a conclusion: In the City of Prague ecosystems have a great role affecting the development of the city through the history of the city till now, and in the future will affect more because of the nature of the relation between city district borders and ecosystem edges as we have seen. That gives the city ability to have more connected green areas and open spaces well related to urban residential areas, it means more sustainable.

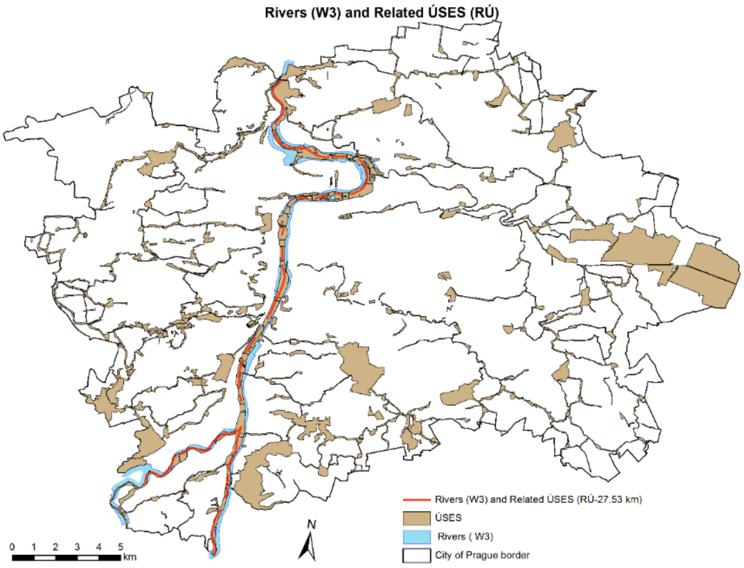


Fig. 13 *Relevant ÚSES and Rivers (Authors). [16]*

4 Conclusion

In this paper we describe a process for studying the relationship between political borders and ecosystem edges. During it was clear that some of the ecosystems are fundamental and have a great role in the development of the city through the time. Dealing with political borders as lines and with natural ecosystems as an edge buffer zone and using noise concept; for further study it will be good to count the relation for more ecosystems to clarify better vision for future plans.

The existence of the relation is related to the noise concept, and the nature of this relation related to the amount of not noise values. Having weak relation with political borders gives the ability to protect ecosystems and save valuable natural resources from the negative affect from urban areas. While strong relation gives opportunity to create connection between urban and green areas, with better management.

However, using the methodology is possible for development cities gives the ability to realise values of natural resources and best places for urban development area with ability of connection with ecosystems using green networks and green ways as application of green infrastructure instead of gray infrastructure special landscape characteristics.

The importance of this study comes from giving planners the guidelines to create urban areas and ability to connect them with green areas and raise the value of life, as a step for sustainability.

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The Principles of Sustainability in Cairo Built Environment

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Abstract

Sustainability can be characterized as the ability to meet the needs of the present without compromising the ability of future generations to address their own needs. It is a compulsory prerequisite, particularly with all needs in the Egyptian context as Cairo is considered one of the fundamental developing cities in the Arab world today. Unfortunately, Architecture in Egypt missed numerous environmental solutions and influenced negatively on the environment.

In addition, conventional planning has failed to coordinate that development towards creating sustainable urban environments. Thus, the paper aims to push towards the outlining sustainable environment that will give individuals a chance to interact with it for the subsequent generations.

Furthermore, it features the sustainability principles from various perspectives as environmental, social and economic. It investigates those principles concerning diverse methodologies for accomplishing the built environment's transformations within Cairo's context. The paper contributes to improve the quality of life for Cairo's residents and promote the built environment through diverse pillars to achieve the proposed vision.

Keywords: *Principles of Sustainability, built environment, quality of life, Cairo*

1 Introduction

Countries are presently mindful of the environmental challenges where the beginning of this awareness was in a conference provided by World Commission on Environment and Development, likewise recognized as the Brundtland Commission, which established the concept of sustainability (Nations, 1987).

Sustainability is a characteristic of a procedure that can be maintained at a certain level indefinitely. The term, in its environmental usage, alludes to the potential longevity of indispensable human ecological supportive systems, generally human communities, and the various frameworks on which they depend (ISC, 2009). On the other hand, sustainability is most known as the maintenance of the health of the biosphere and the husbanding of key resources of air, water, land and minerals (Barton, 1995). It is a condition in which economic, social and environmental factors are streamlined, considering indirect and long-term impacts. The concept of sustainability is the management of natural resources in a way that is reliable with the preservation of the regenerative capacity (Litman, 2011).

The paper begins by introducing various definitions and background concerning sustainability. Therefore, the built environment is distinguished and its relation towards sustainability is explored. Finally, the paper contributes to the vision of enhancing the quality of life in Cairo and highlights its primary proposed pillars.

2 Research aims and objectives

The paper aims to promote a sustainable environment that will give people several chances for interaction and especially for the coming generations. It adds to enhance the quality of life for Cairo's occupants and boosts the built environment through different pillars to accomplish the proposed vision.

It proposes a vision that aims at controlling rates of population growth and urban growth in Cairo, and restructuring it in a way that improves the ability to efficiently address Cairo's problems and helps to achieve that vision. It also aims at raising the standard of living of all Cairo's residents in a manner that achieves social peace and justice, become a global beacon of culture and civilization, and a global highly competitive center of business and communications.

The paper endeavours to make a typical and combined comprehension concerning sustainability and its principles for improving the quality of life for Cairo's residents. It supplies different techniques and expertise from various perspectives such as environmental, social and economic. Moreover, it investigates the principles of sustainability concerning various approaches and provides some guidelines for creating a better environment to improve the quality of live in Cairo.

Thus, the quality of life means the quality of urban, economic, social and environmental condition. It also denotes the quality of health, educational and cultural services for all groups of the society as well as the quality of transportation and the availability of public spaces and green areas.

3 Research methodology

The paper attempts to discuss the topic of how the sustainability's principles can be promoted and integrated for improving the quality of life in Cairo's built environment. It focuses on the different interactions between environmental, economic, and social principles which represent the hypothesis of the major sustainability's approach.

The main objective of the methodology is to create an urban development vision that is based on the participation of the concerned parties and development partners, taking into consideration all opinions, inputs and views during the stages of preparing this strategy. Consequently, the survey is conducted to recognize the needs of Cairo's residents and identify their daily problems they face and their priorities to solve such problems. To ensure the participation of a broad sector of the society, various surveys were conducted in different areas of Cairo.

The paper assorted sustainability into two essential themes, behavioural and technical sustainability. It represents a vision to develop Cairo for being a sustainable city. Its conclusive goal is boosting the quality of life for Cairo's inhabitants and enhancing its environment.

4 Sustainability and built environment

Sustainability has two distinct types that are termed technical and behavioural sustainability as appeared in Figure 1 (Williams et al., 2010). Technical sustainability implies that the technologies, materials or design features utilized as a part of the development perform efficiently and add to sustainability in their right.

Behavioural sustainability contrasts with technical sustainability in that it alludes to the sustainable activities of those living, working and enjoying their leisure time in an improvement (Jenks & Dempsey, 2007). It is contended that several components of the built environment can empower or bolster behavioural sustainability such as; providing cycle paths, pedestrian routes, and neighbourhood recycling facilities. These features are sustainable behaviours that are not dependent on the physical environment and can be implemented in any environment (Williams et al., 2010).

The built environment, including the outside streets and their regional neighbourhood, is experienced by individuals every day. What's more, the quality of the built environment is consequently contended to make an immediate commitment to their everyday lives (Blackman et al., 2004; Carmona et al., 2004; Gehl, 2001). The primary target behind the creation of high quality built environments is contended to be the design and maintenance of places for individuals (DETR, 2000; Davies, 2000; Urban Task Force, 1999).

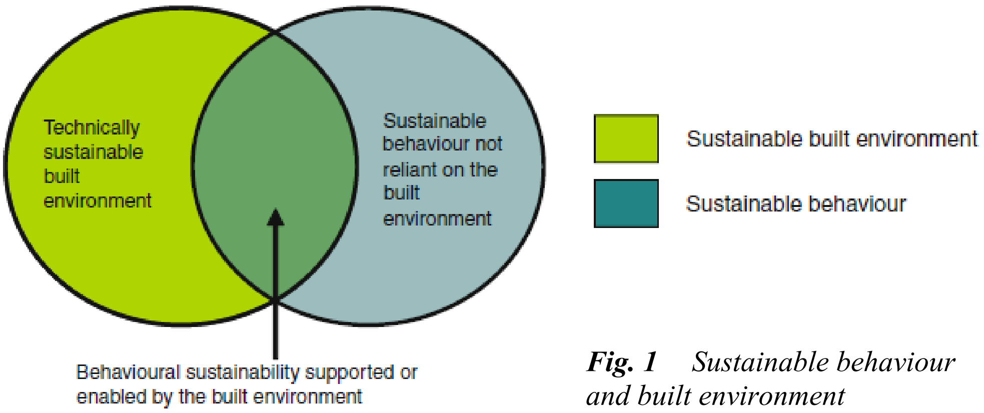

Fig. 1 *Sustainable behaviour and built environment*

There are various trials have been made to identify the particular characteristics of high-quality urban places (Bentley et al., 1985; Lynch, 1960; Jacobs & Appleyard, 1987). Some of these approaches concentrate on the visual quality of the built environment (Cullen, 1961; Lynch, 1960; Nasar, 1998), while others focus on the significance of implying the built environment holds for occupants and different users (Rapoport, 1982; Relph, 1976). In addition, there is a focus on enhancing the quality of the built environment which frequently rises because of a claimed need to upgrade the existing environment (Jenks & Dempsey, 2007). The built environment ought to be responsive and provide its users with an essentially democratic setting (Bentley et al., 1985).

The cleanliness and maintenance of the built environment and how inviting it is likewise been referred as major features of high quality by other literature reviews (Carmona et al., 2004; CABE, 2002; DETR, 2000; Blackman et al., 2003; Friedman and Rosenbaum, 2006). Unmistakably, there is no agreement on which features of the built environment add to its high quality or on which features may be more imperative than others (Jenks & Dempsey, 2007).

The principles of sustainability are classified into three main categories which are environmental, social and economic. Environmental principles would help in enhancing the environment by; providing good air quality, advancing utilizations of recycled water, and improving better local climate (Sherer, 2003). Social principles are the hardest to quantify as they are tools for the community development that help in improving the quality of social life for public by considering some aspects.

These aspects are; generating community cohesion, supplying walkways and sidewalks, promoting community cohesion and social inclusion, education, providing important settings for recreation, ensuring privacy and secure (Tibbatts, 2002). Moreover, there are some additional aspects such as upgrading individual and social communication skills, providing pleasure whether by feelings of relaxation or connection to nature, and enhancing physical and mental health (Baines, 2005).

Economic principles have two types of implications. The first is an economic activity which promotes commercial and income-generating outcomes. While, the other type of implication is an economic efficiency effect that appears an increase in net social aid, typically in the form of reduced costs to society. Economic principles could be accomplished by; material and waste recycling, and utilizing renewable energy (USGBC, 2009).

5 Cairo case study

Over the past few years, different studies have been conducted on a wide scope of issues. Besides, various institutional conferences and clerical dialogs were held with the goal of gathering all ideas and proposals for the future of Cairo and concurring on the basic needs. Most of populace expressed their longing to live in a cleaner, more attractive and less crowded Cairo by 2032 (MHUC, 2012).

The cleanliness issue came as the principal need in the conclusions of roughly half the number of participants, while the issue of developing facilities and decreasing traffic jams came as the second need. Cairo's occupants focused on the need of getting an adequate load of the new housing alternatives in the future that better addresses their needs which was considered the main demand in certain areas (MHUC, 2012).

An obvious vision of Cairo city has been developed with the definitive objective of improving the quality of life for inhabitants and upgrading the standards of living. Additionally, the vision considers several techniques to determine time-phased steps to enhance and strengthen the sustainability principles. There are three concepts that can splendidly condense that vision; social justice, economic competitiveness, and environmental friendliness (MHUC, 2012).

Detailing this vision and characterizing strategic directions is just the initial step towards accomplishing the exhaustive improvement. Achieving this vision on the ground requires all advancement accomplices to consolidate and adjust among aspiration and the genuine circumstance on the ground. To move from the phase of vision plan to the real situation and so as coordinating the decision-making process amid the execution stage, the vision contains three primary pillars and five complementary ones. Therefore, each of the eight pillars structure the fundamental framework of all strategies that aim for Cairo’s development.

The main pillars make up the general framework of the vision and represent the main issues upon which the strategic vision was built; this group includes the following pillars; enhancing residents’ living conditions and quality of life; creating a competitive environment for knowledge-based economy; improving environmental conditions and achieving sustainability.

While the complementary ones achieve the objectives of the three main pillars altogether, and they are; upgrading transportation network infrastructure; developing new urban communities; creating suitable environment for tourism prosperity and conserving historical and archaeological territories; reviving Cairo’s focal area; providing an effective governance framework for managing the development projects (MHUC, 2012).

The vision of Cairo comprises of those required eight moves to transform into reality, and to guide the decision-making process into the implementation period (Nassar, 2013) as shown in Figure 2. Finally, Cairo needs to keep up its unique identity, cultural value, memory, diversity and authentic character.

Fig. 2 *Pillars and moves of Cairo’s vision*

6 Conclusion

The paper presented the sustainability approach which is contained by various interactions between social, environmental, and economic principles which are the three poles of sustainability. Besides, it classified sustainability into two particular sorts, technical and behavioural sustainability. The fundamental objective is considered as the design and conservation of places for individuals behind the creation of sustainable built environments for ameliorating its quality.

The urban improvement vision characterizes a clear path for developing Cairo to determine its urgent problems and control the aggravation of several issues such as housing, facilities and services, in order to restore Cairo's international, regional and local standing. The paper aimed to reach an agreed upon vision through the participation of all concerned authorities and development partners. This vision addresses all inhabitants to make their contributions on it through the positive communication for making Cairo a sustainable city that accomplishes social, economic and environmental objectives.

The definitive goal of this vision is to enhance the quality of life for Cairo's residents. Besides, ambitious plans were determined for improving the environment so as contributing to the accomplishment of the main goal.

The proposed vision aims for developing Cairo in a manner of befitting its position as a capital that combines the constituents of global cities, the completeness of services and utilities as well as the sustainability of assets. Meanwhile, this vision aims to upgrade Cairo to probably address the needs and wishes of various categories of citizens. These objectives can be accomplished by making an interpretation of this vision into explicit needs that will coordinate the strategies and decisions amid the implementation arrange.

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An autonomous and self-sufficient buildings in The Czech Republic and Europe

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Abstract

Sustainable construction is an integral part of sustainable social development and, above all, an effort to minimize the impact on the environment. New trend in the field of the sustainable construction includes constructions referred to as autonomous buildings. These buildings are designed to be self-sufficient and, under certain other conditions, may even be energy plus. This can be achieved by increasing the surface of photovoltaic panels than is necessary for house needs or solar gains, etc. Surplus energy can be used in other ways, for example for growing crops, where excess heat is used to heat greenhouses and thereby achieve a higher degree of self-sufficiency. The trend of autonomous buildings could form satellite towns in the future. The aim of the paper is to compare the current trend in the construction of autonomous houses in the Czech Republic with the Member States of the European Union and to define the basic criteria for the self-sufficiency source of residential houses pursuant to EPBD II and EPBD III. Defined criteria may eventually lead to introducing a certain standardisation in the field of thermal engineering and energy in sustainable house also known as autonomous buildings.

Keywords: *self-sufficient, autonomous, sustainability, off-grid*

1 Introduction

1.1 The Current State of Construction of Autonomous Houses in the Czech Republic and Europe

In the Czech Republic, there is no central register of family houses constructed to higher energy efficiency standards. A separate group of low-energy houses is off-grid (or autonomous building). As mentioned by the authors [Hioraki, N., or Lennar, S., 2017], construction of family houses in the style of “off-gird” should not be seen as summarised requirements of the current building legislation but as a philosophical idea of the way of living in relation to the environment and sustainability, converging with a holistic view of construction. The foreign concept goes further towards "autonomous cities" [1].

Currently, data on family houses constructed to higher energy efficiency standards are available only from the State Environmental Fund of the Czech Republic, which on behalf of the Ministry of Environment administers the “New Green Savings Programme”[2]. According to the information available from this source [3] not a single autonomous house has been built under this energy intensity reduction programme and if a self-sustaining family house was built outside of the programme it is not registered anywhere. As of November 2018, only four family houses are built as an autonomous houses, which are not connected on any public site [4], [5]. However, currently a construction of two smaller family houses is under way within the Czech Autonomous House contest [6], organized by a company of the same name. The construction of autonomous houses is still more an exceptional matter not only in Europe but also in the world. Among the ground-breaking and interesting project as is a block of

9 flats in the Swiss city of Brütten [7] (Fig.1). This building was built in 2016. The house uses contemporary the best technology, such as the conversion of excess energy into hydrogen, which can then be converted back to electricity or heat [8] also using geothermal pumps for heating and hot water.

One of the first autonomous house in Europe was built in 1992 in Freiburg in Germany [9]. The house has U value [W/(m²·K)] which are on the borderline of today's passive house requirements. The house also uses hydrogen storage of surplus energy produced by the photovoltaics installed on the roof of the house. The first autonomous house in the UK has been built in Southwell in Nottinghamshire [10]. Here "The Composting Toilet System" has been used to minimize the need for water by composting human excreta without flushing. In 1997 there were 5 further houses built in the same city using also wind energy.

From the examples above, it is clear that the basic technologies of autonomous houses and their hallmark are the application of big number photovoltaic panels a solar collectors on the roof of building also the storage of surplus energies into the battery or different storage of surplus energies. With regard to the issue, it is necessary to distinguish whether it is actually an "autonomous house" or a "self sufficient house". These concepts are found in the specialized literature on low-energy houses and in expert discussions. In essence, every autonomous house must be self-sufficient otherwise it could not work without connecting to public networks. The autonomous house is therefore a construction that can make all its energy for its use on its own. It has a storage place to store surplus energy and possibly another alternative source of energy to be used in the winter season. A self-sufficient house is a construction that can produce all the energy for its consumption on its own. Such house can be connected to a public network, and surpluses obtained from photovoltaics can be transmitted/sold to the network where the energy received will be used in a different way. In the winter, this energy is drawn/bought back to the house. From the economic point of view such house is self-sufficient but it is no longer the autonomous house because it is connected to the public energy network and is unable to cover its energy consumption in the winter from its own resources.

Fig. 1 *The world's first self-sufficient multi-family house in Brüten, Switzerland [7]*

1.2 Construction of Autonomous Houses Outlook

It may appear that construction of autonomous houses on a larger scale is still a question of a distant future. But the tightening of European standards and the new Development Agenda titled "Transforming our world: the 2030 Agenda for Sustainable Development" adopted by the UN General Assembly in September 2015 [11] will put a great deal of pressure to build, if not autonomous houses then at least self-sufficient houses, as soon as possible. The share of emissions from building operations is estimated at 36% of all emissions produced in the EU. The pressure of the whole society to reduce greenhouse gas production as a result of global warming will be increasing and The pressure of the whole society to reduce greenhouse gas production as a result of global warming will be increasing and self-sufficiency or off-grid homes can be taken as a standard according to the principles of sustainable construction. According to the Agenda 2030 programming document already mentioned above, off gird-construction can meet selected objectives of agenda, including:

- Significant increase in the share of renewable energy in the global energy mix.
- Improving energy efficiency and enhancing international cooperation to facilitate more open access to clean energy technology and more investment in clean energy infrastructure.
- Developing a high-quality, reliable, sustainable and resilient infrastructure, including regional and cross-border infrastructure, to support economic development and improved quality of life, with a focus on affordable and equal access for all.
- Modernising infrastructure and improving the equipment of industrial enterprises so that they are sustainable including more efficient use of resources.
- Using cleaner and more environmentally friendly technologies and production processes; involving all countries within their means.
- Strengthening inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable planning and management of cities and towns in all countries.
- Great reduction of waste production by prevention, reduction, recycling and re-use.

2 Material

To compare the current trend in the construction of autonomous buildings in the Czech Republic with the Member States of the European Union and to define the basic criteria that lead to self-sufficiency of family houses in accordance with EPBD II and EPBD III for Czech conditions, the following were used:

a) The CZ and EU energy and heat technology criteria [17].
b) Criteria according to EPBD II EPBD III [12], [14].
c) Selected houses for comparison with descriptive characteristic [4], [5], [6], [18], [20].

3 Methology

A comparison and description of selected houses was used to compare the current situation. Description of selected houses selected technological and technical solutions that predict the house to the "autonomous" type.

3.1 The Thermal-Technical Part of the Assessment of Buildings in the Czech Republic and Europe

The most basic requirement for building resistance from the point of view of thermal engineering is the assessment based on the heat transfer coefficient of individual constructions. These values are implemented according to the European Directives EPBD II and EPBD III into the national standards of European countries at the discretion of each state. For this reason, a differentiated requirement for U [W/(m^2.K)] values arises. For EU-wide readability, Table 1 is selected.

Tab. 1 *House evaluation according to the type of construction and U [W/(m^2.K)] requirement in selected EU countries [19].*

State / Construction	CZ	NL	UK	LT	PL	B	D	I	A	SK	SWE
Floor [W/(m^2.K)]	**0,45**	0,20	0,25	0,25	0,25	0,30	0,35	0,37	0,40	0,40	0,15
Wall [W/(m^2.K)]	**0,30**	0,20	0,30	0,20	0,25	0,24	0,28	0,37	0,35	0,32	0,18
Ceiling [W/(m^2.K)]	**0,24**	0,20	0,20	0,16	0,20	0,24	0,20	0,33	0,20	0,20	0,13
Windows [W/(m^2.K)]	**1,50**	1,65	2	1,60	1,30	1,8	1,30	2,37	1,40	4,40	1,30

3.2 House Evaluation Based on Individual criteria

3.2.1 Building Evaluation Methodology:

Buildings were rated from 5 basic criteria. Each criterion has a certain importance in the overall share of the building evaluation. The importance of each criterion is shown in Fig. 2. The importance of the individual criteria was chosen on the basis of its own survey in 2018, in order to best describe the problems of self-sufficient houses and at the same time to comply with the technical requirements and energy concept of the Czech Republic and the EU by 2030.

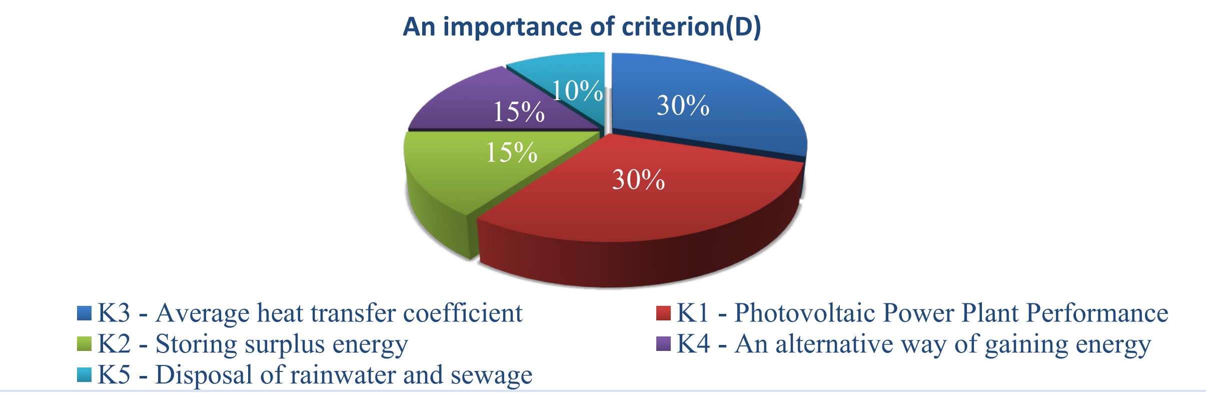

Fig. 2 *An importance of criterion in %.*

The evaluation was carried out according to the relations (1), (2):

$$K = D \cdot H \quad (1)$$

where K is a criterion.
where D is an importance of criterion.
where H is point marking of each criterion

$$A = K_1 + K_2 + K_3 + K_4 + K_5 = D_1.H_1 + D_2.H_2 + D_3.H_3 + D_4.H_4 + D_5.H_5 \quad (2)$$

where A is a final score

3.2.2 Assessment of Criterion

The houses were rated according to the criteria below, where the direction is drawn from 1 to 5. The best is five and one is the worst. The individual score of each criterion is shown in Table 2.

K 1 Photovoltaic Power plant performance [kWp]

- It is necessary to ensure sufficient production and storage of electricity to ensure self sufficiency of the house.
- In the Czech Republic, where wind, water or geothermal resources are not very efficient, the photovoltaic panels are virtually always used as the main source of electricity.
- The disadvantage of this system is its unstable production of the power supply, which means a lot of electricity produced during the day and zero or near zero electricity production in very cloudy days or at night.

K 2 Storing surplus energy

K 2.1 Storage in batteries [kWh]

- In this area, a notable performance improvement has been due and keenly awaited for sometimes currently lithium batteries are used most often. Problem with batteries is their acquisition cost and limited lifetime resulting in the necessity of their replacement after a certain number of cycles when their capacity drops below specified level.

K 2.2 Storing into water [hl]

K 2.3 Conversion to hydrogen [kg]

- Another option to convert electricity produced by photovoltaic panels to hydrogen through an electrolyser and then store it in a hydrogen tank.
- Results of research in this area show about 30% efficiency when converting energy from hydrogen back to electricity, which no other system can currently achieve in terms of long-term energy storage. For comparison purposes imagine a tank that can store an equivalent of 150 kWh of usable energy, which corresponds to about 10 kg of hydrogen, then the storage of this amount of energy in lead batteries would require about 200 pieces with a total weight of 5 tons.

K 3 Average heat transfer coefficient [W/(m^2.K)]

K 4 – An alternative way of gaining energy [yes/no]

K 4.1 Stirling engine

- Due to the small amount of energy available from the photovoltaic panels in the winter, the property must be supplemented by an additional energy source. For example wood pellets fired boilers are used for these purposes. Such boiler can be fitted with a Stirling engine, which can produce electrical energy from the heat generated by the pellet boiler.

K 4.2 Power plant for petrol

- Another additional source of energy for the winter months can be a power plant. The power plant should always be used as a backup power source if the property is a fully fledged autonomous house not connected to the electricity grid.

K 4.3 Boiler for wood or biomass
K 4.4 Boiler for wood pellets
K 4.5 Solar collectors

K 5 – Disposal of rainwater and sewage [yes/no]

K 5.1 Cesspit
K 5.2 Rainwater accumulation tank using water in the garden
K 5.3 Rainwater accumulation tank using water in the garden, toilet and for washing
K 5.4 Domestic sewage disposal plant
K 5.5 Domestic sewage disposal plant with another using water

Tab. 2 *Point rating of criterions*

<table>
<tr><th colspan="16">Criterion</th></tr>
<tr><th rowspan="2">Point</th><th rowspan="2">1</th><th colspan="3">2</th><th rowspan="2">3</th><th colspan="5">4</th><th colspan="5">5</th></tr>
<tr><th>2.1</th><th>2.2</th><th>2.3</th><th>4.1</th><th>4.2</th><th>4.3</th><th>4.4</th><th>4.5</th><th>5.1</th><th>5.2</th><th>5.3</th><th>5.4</th><th>5.5</th></tr>
<tr><td>1 p</td><td>0-0.99</td><td>0-2.99</td><td>< 5</td><td>0-0.19</td><td>0.3-0.26</td><td>N</td><td>Y</td><td>N</td><td>N</td><td>Y</td><td>Y</td><td>Y</td><td>N</td><td>N</td><td rowspan="2">N</td></tr>
<tr><td>2 p</td><td>1-1.99</td><td>3-4.99</td><td>5-14.9</td><td>0.2-0.39</td><td>0.25-0.21</td><td>Y</td><td rowspan="4">N</td><td>Y</td><td>Y</td><td rowspan="4">N</td><td rowspan="4">N</td><td rowspan="4">N</td><td>Y</td><td>Y</td></tr>
<tr><td>3 p</td><td>2-2.99</td><td>5-7.99</td><td>15-29.9</td><td>0.4-0.59</td><td>0.2-0.19</td><td rowspan="3">N</td><td rowspan="3">N</td><td rowspan="3">N</td><td rowspan="3">N</td><td rowspan="3">N</td><td>Y</td></tr>
<tr><td>4 p</td><td>3-3.99</td><td>8-10</td><td>30-50</td><td>0.6-0.8</td><td>0.18-0.15</td><td rowspan="2">N</td></tr>
<tr><td>5 p</td><td>4-5</td><td>> 10</td><td>> 50</td><td>>0.8</td><td>< 0,15</td></tr>
</table>

3.2.3 Appraised Houses

In Table 3 we can see the comparison of individual island houses built in the Czech Republic, Switzerland, Austria and Germany. Houses were compared based on the criteria described in Chapter 3.2.2. It is important to note that the houses in Vyšší Brod fig. 5 [6] and German Freiburg fig. 8 [9] (House CZ 3 and House D) are primarily experimental houses, unlike houses in Prague fig.3 [House CZ 1], Chocni fig. 4 [5] (House CZ 2), Buttisholz in Switzerland fig. 7 (House CH) and Austrian Gaspoltshofen [6] fig. 6 (House A), which are already in use for permanent living.

Fig. 3 *House CZ 1 in Prague [4]*

Fig. 4 *House CZ 2 in Chocen [5]*

Fig. 5 *House 3 CZ in Vyšší Brod [6]*

Fig. 6 *House A in Gaspoltshofen [18]*

Fig. 7 *House CH in Buttisholz [18]*

Fig. 8 *House D in Freiburg [20]*

Tab. 3 Values of individual criteria for selected houses

House	Criterion 1	2			3	4					5				
		2.1	2.2	2.3		4.1	4.2	4.3	4.4	4.5	5.1	5.2	5.3	5.4	5.5
House CZ 1	2.5	2	45	-	0.22	N	Y	Y	N	Y	Y	N	N	N	N
House CZ 2	3.5	2.7	7	-	0.18	N	N	Y	N	N	N	N	Y	Y	N
House CZ 3	5	10	-	-	0.13	Y	N	N	Y	N	N	N	Y	Y	N
House CH	1	?	4	-	0.13	N	Y	Y	N	Y	Y	N	Y	N	N
House A	2.8	?	20	-	0.32	N	N	Y	N	Y	?	?	?	?	?
House D	4.2	20.8	10	1.33	0.25	N	N	N	N	Y	?	?	?	?	?

3.2.4 Additional Information About Czech Houses

House CZ 1

Floors, ceilings, reinforced concrete, walls from formwork embedded in concrete. The roof is flat covered with about 30 cm of soil. Foundation on 10 cm layer of polystyrene, walls 20 cm polystyrene, roof 20 cm polystyrene + approx. 30 cm of soil. Recuperation unit for ventilation. Wood fired boiler with storage tank (34 kWh + fireplace insert + solar collectors). Back-up power generator, storage tank 4 500 l, gas cooker.

House CZ 2

Wooden house. Coarse earthen floors, internal partitions and plasters of clay. Electric boiler, wood stove with tap water exchanger, heavy accumulator stove, storage tank. Storage of food without a fridge. Insulation from blown cellulose. Using ground heat exchanger.

House CZ 3

Steico wooden timber construction. Boiler for wood pellets (8kW) with built in Stirling engine. 8 m^3 storage tank, recovery for flushing and showering, laundry (non-compliance with Czech standards), surplus to site seepage. Recuperation unit, whole technology system controlled by one software.

3.2.5 Evaluation Of Selected Houses Based on Table 2

Table 4 shows the house rating for the individual criteria. Figure 9 can be seen the total score of individual houses.

Tab. 4 Total points for each house

CZ / EU		CZ			EU		
Criterion		House 1 (2002) [4] Picture 2	House 2 (2015) [5] Picture 3	House 3 (2019) [6] Picture 4	House CH [18] Picture 5	House A [18] Picture 6	House D [9] Picture 7
K 1		3	4	5	1	3	5
K 2	2.1	1	1	5	?	?	5
	2.2	4	2	0	1	2	2
	2.3	0	0	0	0	0	5
K 3		2	3	5	5	5	1
K 4	4.1	0	0	2	0	0	0
	4.2	1	0	0	1	0	0
	4.3	2	2	0	2	2	0
	4.4	0	0	2	0	0	0
	4.5	1	0	0	1	1	1
K 5	5.1	1	0	0	1	?	?
	5.2	0	0	0	1	?	?
	5.3	0	2	2	2	?	?
	5.4	0	2	2	0	?	?
	5.5	0	0	0	0	?	?

Values with ? are not available

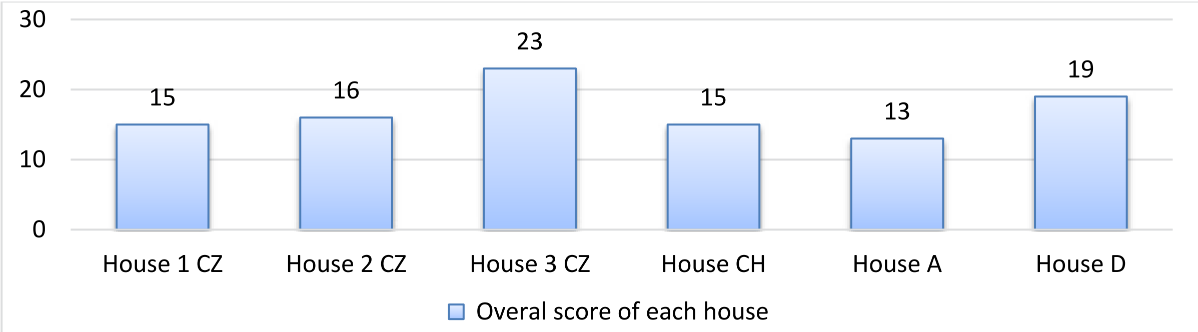

Fig. 9 *Overall score of each house*

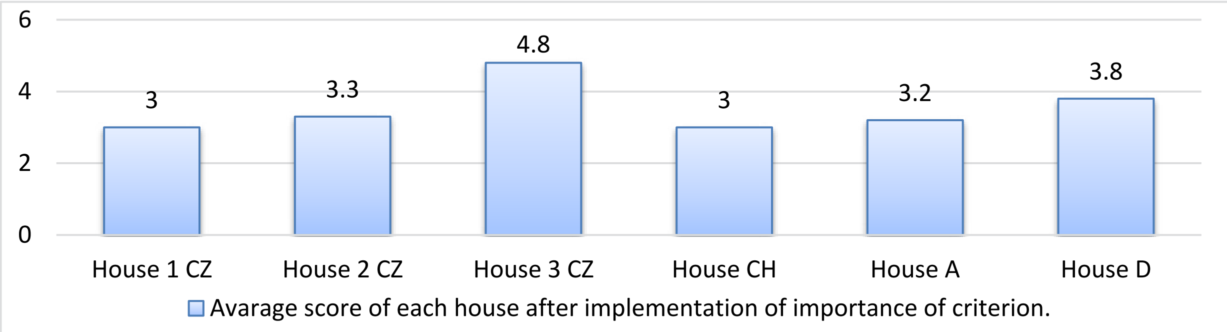

Fig. 10 *Average score of each house after implementation of importance of criterion*

Evaluation

Figure 9 shows that House 3 CZ house in Vyšší Brod get the highest self-sufficiency rating. However, it is necessary to note that House D, which has no point in the K5 criterion due to the unreliability of the information, achieved the second best rating.

In Figure 10, after the importance of each criterion has been established, there is, for example, a change of order when House CH (15 p) and House A (13 p) have House CH mark 3 and House A mark 3.2. This implies that House A has the main criteria with a higher score.

4 Conclusion and Discussion

Nowadays we can state, that houses functioning entirely as autonomous houses are likely to always be a kind of an extreme, or a certain way of living. Pure autonomous houses will have their justification in isolated areas such as the Australian bush, Siberia or Canadian plains, or where public infrastructure connections are very remote, limited or impossible. The self-sufficiency of new construction is a positive step towards further reduction of greenhouse gas production and, above all, as a set direction for sustainable development, with an impact on the sustainable construction segment. The growing legislative pressures to build the self-sufficient homes will increase the pressure on the competitive environment of companies, and soon these houses will be as affordable as those of today's standard. Currently the biggest problem for autonomous houses is the conservation of surplus energy from solar power plants, from the summer months as well as the lack of solar energy in the winter months, thus designing alternative heat and energy technology in this period. An interesting alternative for this period is Stirling's engine or hydrogen conversion. Furthermore hydrogen conversion has the best parameter of take back energy conversion to electricity. A big progress in U-value [W/(m^2.K)] improvement can be achieved by using vacuum. For example, a facade panel with a vacuum layer and a window where the space between glasses will also be a vacuum. In the area of certain typing of self-sufficient houses, it is necessary to develop the direction of multi-criteria optimization based on sources and data. To do this, it would be useful to introduce a database that would contribute not only to education but also to the monitoring of selected variables, which are crucial for self-sufficiency. Criteria such as the average heat transfer coefficient, the amount of energy gain in the form of electricity or heat, and the method of storing surplus energy.

Acknowledgement

This article was created with the financial support 1101 of the Department of Civil Engineering FAST – VSB-Technical University of Ostrava for year 2019, Ministry of Education, Youth and Sports of the Czech Republic.

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Sustainable Retrofitting of Existing Buildings

A Review of Thermal and Hygrothermal Requirements in Historic Churches

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Abstract

Upgrading the building fabric of historic churches is challenging due, in part, to decorative finishes, important religious artefacts and the desire to preserve cultural heritage. This paper reviews current literature, aiming to establish the thermal and hygrothermal requirements of historic churches. Main observations from the literature are that many limits exist when trying to improve the energy performance of historic building fabric. Natural control of external temperature and humidity cycles is exhibited by the building fabric, resulting in some retrofit technologies causing an increase in moisture accumulation. However, some novel technologies may help to improve fabric performance without the loss of historic value. Historic fabric energy performance may be better than expected due to lack of knowledge of historic materials. Artefacts contained within the building often dictate the range of acceptable temperature and relative humidity fluctuations. Ventilation and installed heating systems can assist in maintaining the correct internal environment.

Keywords: *historic, churches, environmental, hygrothermal*

1 Introduction and motivation

Churches vary greatly in design and character across Europe. Depending on age, location and the denomination, interior and exterior decorations range from the simple to the lavish. Built to serve the local community, churches play a pivotal role in gathering people together. Operation of historic buildings present many challenges. Alterations to the building fabric are often highly regulated through legislation and historical listing systems, which prevent loss of heritage value. Retrofitting of newer technologies, such as internal insulation could damage the fabric of the building and the valuable finishes found internally. It is therefore challenging to find methods to improve the energy performance of the structure and the windows, leading to compromise on how to address the various criteria [1]. Historic buildings have been exempt from energy efficiency targets because they are often constructed using methods which do not meet energy performance benchmarks [2]. Energy savings, conservation and thermal improvement are possible through detailed knowledge of hygrothermal response [3]. Churches in particular are often relatively complicated in design, compared to modern equivalents, with buildings lacking insulation and vapour barriers [4, 5].

When human comfort demands are considered alongside the conservation of heritage, there is often a conflict. Operating the church in a sustainable manner requires a conditioning system which can reduce energy demand and environmental impact. Recognising the unique environment presented by historic places of worship British Standard EN 15759-1: *Heating churches, chapels and other places of worship* provides specific guidelines for preserving the building fabric alongside heritage items. Climate change is expected to influence many aspects of building performance. Historic buildings are considered to be the most vulnerable to this adverse climatic impact, via moisture induced deterioration and resulting strength decay in their construction materials [6]. With UK weather patterns changing to more significant weather events and warmer wetter winters, the outlook for historic buildings appears challenging [7]. Preserving historic churches requires greater understanding of adaptations that are now necessary to facilitate continued use. The aim of this study is to critically review current literature and thinking on the subject. The thermal and hygrothermal criteria of historic churches are identified to draw conclusions on the best approach in relation to environmental sustainability and retrofitting opportunities.

2 Research methodology

This research contains a range of source material composed of case studies, conference proceedings, scientific journal papers, defined standards and techniques for cultural heritage preservation. A number of scientific studies from churches across Europe feature in the available literature. Three sections have been created to review thermal, hygrothermal and artefacts. Observations from authors have been tabulated. A discussion of the findings brings together the relevant criteria. The review will aid research into the criteria heating systems should aim to achieve. Computer software will be used to model suitable technologies in historic churches during future research.

3 Literature review

This section summarises contributions to establish the thermal and hygrothermal characteristics. The research touches on the effect space heating has on the structure of the building, however, the main aim is to establish thermal and hygrothermal criteria for a class of important historic buildings which may also be filled with items of cultural significance.

3.1 Thermal characteristics

Historic buildings were often designed without a space heating system, therefore the construction used high thermal mass materials which could retain any heat for longer [6]. Although historic churches follow the same design principles as other historic buildings, they are different in having a large open area for worship services rather than separate rooms. Usage patterns also differ from other public buildings as church services may be planned sporadically throughout the week. In rural locations churches may only be in use once per week. Traditionally constructed buildings exhibit a pattern of heat loss described by The Prince's Regeneration Trust [8] where approximately half the thermal energy is lost through the uninsulated roof and walls. Infiltration is also a key contributor to energy loss within historic buildings. The prevailing natural internal environment of a historic church does not match modern human comfort expectations all year round. Sitting in a cold and sometimes damp building contrasts sharply with most centrally heated dwellings. Space heating systems have been retrofitted in many historic churches, mainly to meet comfort demands. Although the energy output is capable of heating the building fabric and the volume of air, the design of historic churches often leads to human discomfort as large vertical temperature gradients exist and inadequate mean radiant and operative temperatures are experienced [9]. Tab. 1 presents a summary of findings related to thermal performance.

Determining fabric performance can be challenging due to lack of data for known materials and varying construction methods employed during the lifetime of the building. Construction material may not be uniform across the whole structure, leading to different microclimates within the building [16]. Building technology and the material utilised to construct historic churches varies considerably with construction date and locality [17].

Tab. 1 *Summary of findings related to thermal performance*

Author	Thermal: Main observations
Silva and Henriques [10]	Lack of heating does not mean damage is occurring to the church
D'Ayala and Aktas [6]	Solid wall construction exhibits thermal lag of 3-4 hours and 2 hours in summer
Loupa, Charpantidou [11]	The thick walls of the churches attenuate the effect of outdoor climate conditions
Browne [12]	Unless there are substantial internal heat sources, it can take several days for a high-mass building to adjust to outdoor changes
Varas-Muriel, Martinez-Garrido [13]	Due to lack of insulation historic buildings are not designed to retain heat from space heating systems
Govaerts, Hayen [14]	Excess levels of dampness contribute to poor thermal performance
Historic England [15]	Maintaining the building's ability to regulate moisture levels is fundamental to its effective thermal performance Different parts of the building are affected by very different micro-climates. A single wall will often contain more than one material with quite different performance characteristics

3.2 Hygrothermal characteristics

Historic building construction frequently exhibits high internal humidity and a response to the moisture present outside the building. The masonry walls of historical buildings lack damp insulation and were designed to allow the absorption and evaporation of moisture [4]. In a study of The Basilica di Collemaggio, installation of space heating has altered the operation of the building, resulting in a change to the natural state of the building fabric [18]. Repeated heating and cooling cycles related to human comfort can initiate problems with moisture in the building fabric [19]. Careful consideration should be given to hygrothermal behaviour within the building fabric before any energy efficiency schemes are implemented. It is important to note that historic building materials are not always accounted for in hygrothermal publications. Establishing a suitable environment for all components within a historic church continues to be a challenge. A summary of findings related to hygrothermal performance are contained within Tab. 2.

Tab. 2 *Summary of findings related to hygrothermal performance*

Author	Hygrothermal: Main observations
Larsen and Brostrom [5]	Historic buildings naturally exhibit high humidity. Humidity comes from outside air and in some cases from rising damp or rain penetrating walls
Martinez-Garrido, Aparicio [20]	In San Juan Bautista Church, Talamanca de Jarama, Spain on rainy days the indoor relative humidity rises from around 45% to about 70–75% where it remains for several days
Georgescu, Ochinciuc [21]	Climate change scenarios show that humidity is going to be the main threat in decades to come. Recommend solutions directed toward the elimination of humidity causes and effects
Ashurst and Ashurst [22]	Historic buildings usually had a mortar composed of lime that was breathable
Torney, Forster [23]	Breathability is a term defined as 'a measure of a combination of moisture transfer mechanisms' including water vapour permeability and water permeability
Maroy, Steeman [24]	The risk of surface condensation is a frequent problem in buildings with high thermal inertia that can contribute to the degradation of several materials and the deterioration of the interior environment
Biseniece, Zogla [25]	Energy efficiency renovation of historic buildings in cold climate is a very complex issue due to hygrothermal behaviour of the building envelope

Author	Hygrothermal: Main observations
Calle and Van Den Bossche [26]	Interventions designed to limit moisture in the historic building can have damaging effects upon the fabric. Hydrophobic treatments can intensify the risk in existing cracks, missing joints and cavities
Varas-Muriel, Fort [27]	Moisture in the liquid and gaseous phase is the principle carrier of various aggressive substances transported into the interior structure of building materials
Jenkins [28]	Maintenance and upgrade work to the walls and roof of a building to prevent water ingress should be seen as integral to energy improvement
Hansen, Bjarløv [29]	All buildings behave differently to parameter changes. Careful assessment of hygrothermal performance before application of internal insulation
Walker and Pavia [30]	The Sustainable Traditional Buildings Alliance reporting on the responsible retrofit of buildings notes that there are knowledge gaps on the hygrothermal performance of insulated walls
Hola, Matkowski [31]	Determine microclimatic conditions prevailing in walls before attempting restoration and conservation work

3.3 Artefact degradation

Attempting to reach human comfort thresholds in a short time frame can result in rapid temperature fluctuation. Changes in the associated relative humidity are also problematic for preservation of many artefacts. Artefacts are important in many church buildings as decorative features or as part of the worship service. Many materials can tolerate short term changes in relative humidity and any damage may have already occurred during the many years of residence within the church environment. When assessing the requirements of the existing artefacts it is considered appropriate to maintain the current climate rather than attempt to create a new ideal climate for the item after many years of existing within the church [32]. The desire to achieve human comfort may cause degradation of important heritage items [18]. A summary of findings related to artefacts can be found in Tab. 3.

Tab. 3 *Summary of findings related to artefacts*

Author	Artefacts: Main observations
Aste, Della Torre [18]	Heritage objects in a church are generally quite sensitive to environmental factors such as air and surface temperature, relative humidity, etc. Periodic air temperature and relative humidity changes may cause dry and wet cycles and air movements that are usually responsible for deterioration and soiling. Human thermal comfort and artworks preservation often conflict with each other
Tabunschikov and Brodatch [33]	Artefacts are capillary-porous physical bodies. The pores are partially filled by moisture which include dissolved salts. If the humidity increases, frescos, icons and wood absorb the water from the air
Legner and Geijer [34]	When space heating was installed the frequency of conservation of wooden artefacts increased. The most common damages reported were cracking of paint and desiccation cracks
Bencs, Spolnik [35]	Particularly important is the concentration and distribution of water vapour within the church, since it can be absorbed by hygroscopic material. Water can react with acid-forming gases producing strong acids that can trigger the deterioration of artworks
Camuffo, Sturaro [36]	Laboratory tests on wood samples have shown that wood takes one day or more to adapt to new environmental conditions.
Silva and Henriques [10]	One of the biggest challenges in historic buildings, such as museums, is to reach an equilibrium between the conservation requirements and the energy economy
Cardinale, Rospi [37]	There are many ‘tables’ which advise optimal environmental conditions, often presenting very different ranges. In general we can say that the temperature range 16−22ºC and humidity range 45−55% must be complied with in order not to degrade the artwork

4 Discussion

Despite their age, traditionally constructed historic buildings demonstrate thermal characteristics that are desirable for public buildings. High thermal mass can retain any heat within the building fabric and buffer short term fluctuations in temperature. With a desire to improve thermal performance insulation can be applied to the internal structure without affecting the aesthetic appeal of the building façade. However, this approach might prove harmful to the building if measures are not taken to prevent moisture accumulating on the inside of the masonry structure. Walker and Pavia [30] discussed reasons for problems experienced with insulating a historic structure. Their study revealed that all the insulation materials lowered the wall temperature, thereby increasing the risk of interstitial condensation.

Several authors identified the perception that energy performance of traditional construction was poor. Historic buildings are not uniform in construction and detailed thermal and hygrothermal properties may not be known for the locally sourced construction materials. In addition, a lack of knowledge relating to the uniformity of historic construction was suggested as the reason calculated U-values fell short of actual energy performance. Ongoing development of construction technology may present an opportunity to improve the thermal performance of existing historic structures. Lucas, Senff [38] investigated Phase Change Material (PCM) in lime mortars for heritage applications. PCM would allow retention of higher energy in the wall structure, reducing the energy loss over a given period.

Repair work through replacement of fabric components is an ongoing process for historic buildings. The use of unsuitable mortars may initiate new problem for historic fabric, resulting in formation of ettringite and expansion of the mortar, pushing the brickwork apart. Intact brickwork dissipates excess moisture in the construction through the mortar bedding, and if the joints are sealed with an impervious material such as cement mortar, the moisture is forced into the brickwork itself, ultimately damaging it. Mortar joints should be regarded as a wearing layer that protects the more valuable masonry [23].

Where possible, appropriate steps should be taken to limit sources of excess moisture in the building fabric. Rainwater goods must be maintained and checked regularly to prevent water ingress and damage to sensitive areas of the church. Excessive moisture content in the building fabric increases thermal transmittance resulting in increased energy loss. Heating systems installed in the church can cause cycles of salt re-crystallisation in porous structures, such as masonry, stone, plaster, or wall painting. Intermittent heating may also result in walls that are colder than the air, which may cause increased particle deposition, cold draughts and condensation [39]. The application of nanotechnology has been linked to the control of relative humidity and the conservation of stonework used in traditional buildings. Zornoza-Indart and Lopez-Arce [40] reported on silica nanoparticles and their influence on humidity in degraded stone. Sierra-Fernandez, Gomez-Villalba [41] reported on the advantageous properties displayed by nanoparticles when applied to stony materials. These properties are defined as consolidant, water repellent and protective treatments. The appropriate application of nanotechnology may have considerable impact upon heritage buildings in the future.

While a building is affected by its location and exposure to weather events, the presence of people inside the church affects its natural and induced environments. Human metabolism radiates heat and humidity, which are taken up into the church atmosphere [27]. Relative humidity remains the main concern for the internal environment of historic churches. As a means of degradation, it can affect many items, not necessarily to the same extent. British Standard EN 15757 highlights the requirements of organic hygroscopic materials (wood, stone etc.). In general mid-range relative humidity is required for most objects, as the extreme (high and low RH ranges) can result in structural damage, deformation and cracking [42]. Managing the requirement to heat the building for the occupants and maintain a suitable environment for the artefacts will continue to provide significant challenge.

Ventilation remains an important method for control of the church internal environment. High levels of moisture and pollutants following services can be dispersed through simple opening of doors and windows. Many church buildings are naturally ventilated, rather than employing mechanical means. Natural ventilation is defined by BS ISO 17772-1:2017 as ventilation provided by thermal, wind, or diffusion effects through doors, windows or other intentional devices in the building designed for ventilation [43]. Natural ventilation can be operated through automatic systems which actuate windows or vents when high concentrations of CO_2 or high relative humidity are sensed within the church. Depending on the design of the building and changes made during its lifetime, natural ventilation may be an adequate method of control, if maintained and operated correctly. Ventilation openings and their important function are not always appreciated in historic churches. In a study of a Romanian historic church Georgescu, Ochinciuc [21] reported on the effect modern alterations had made to the performance of the building. Historic frescoes within the building were degraded through the rise of water by capillary action in the building fabric. During an investigation into the cause of the degradation, it was discovered that in the 1960s, tighter window seals and the closure of many existing openings limited the natural ventilation that was inherent to the design. Historic buildings tend to have greater air infiltration, achieved through passive design features, construction methods or degradation of components. Strategies for appropriate ventilation can be modelled using software. CFD modelling and microclimate monitoring proved to be a powerful tool in deciding on an appropriate ventilation strategy for preservation and climate management in the Crypt of Lecce Cathedral [44]. In the case of Lecce Cathedral the Crypt is usually closed to the public. The correct number and location of windows and doors need to achieve adequate ventilation of the crypt was indicated through simulation. Sinivee, Kurik [45] designed a simple ventilation controller for an unheated medieval church in Estonia to improve air exchange rates. The system was specifically designed for church buildings which are not in regular use and where there is no one present to take action when high humidity conditions are favourable for mould and algae growth.

The movement of air in a large open space, such as a church, can cause discomfort to those seated near windows, doors or ventilation ducts. The design and introduction of box pews may have been in response to draughts in unheated churches [46]. The speed of air movement must be appreciated when designing and operating ventilation systems, natural or mechanical. Individual perception of ventilation requirements is also a factor difficult to predict and fulfil. In the discussion following the presentation of 'Occupant Perceptions of Thermal Comfort in Office Buildings', Rowe acknowledged the difference between perceptions of air freshness, air movement and ventilation comfort [47].

Through sensible appraisal and planning, change can be correctly balanced with retention of heritage value [48]. Careful assessment of relative humidity requirements will help to guide the operation of suitable space heating systems. The installation of energy saving measures will be a challenging area for many historic churches looking to prevent damage and loss of heritage value. Stability of temperature and relative humidity are considered to be important for modern operation of a historic church. Introducing wide ranging temperature and relative humidity fluctuations for short periods of time should be avoided if possible. The associated cost of operating space heating may preclude the practice of maintaining background temperature during the time the church is not in use. Alternative approaches for controlling the internal environment focus on humidity rather than temperature. It is important to establish how water vapour will eventually move through the building and structure when installing relative humidity control in a historic building [49]. Conservation heating can be used as a successful strategy for control of humidity levels in historic buildings. By monitoring and responding to the changes in relative humidity, through the use of humiditstat control rather than a thermostat, space heating operation aims to keep fluctuations within established tolerance levels for valuable items contained within the building. Such a strategy results in temperature being of secondary concern and therefore has limited capacity to achieve human thermal comfort levels in a historic church. The choice of heating technology should seek to fulfil the requirements of temperature stability for comfort, relative humidity control within established parameters, environmental sustainability and reduced cost, where possible.

5 Conclusions

This paper has identified and reviewed the thermal and hygrothermal characteristics of historic buildings in Europe, to help establish the criteria for continued use of historic churches. Churches continue to provide a challenge for future sustainable operation in the face of climate change. Many limits exist when trying to improve the energy performance of building fabric and the desire to preserve historic value may render many technologies incompatible. The literature suggests that historic fabric energy performance may be better than expected due to lack of knowledge of historic materials and construction uniformity. Some novel technologies were identified in the literature and the future application of these may help to improve fabric performance without the loss of historic value. Artefacts contained within the building may dictate the range of temperature and relative humidity fluctuations acceptable during space heating events. Operation of natural ventilation and space heating systems should aim to create stable internal conditions for many criteria without excessive cost burden. The establishment of heating systems capable of achieving these criteria will form the main focus of future research. Improved control of separate 'zones' within the church and the incorporation of low to zero carbon technologies appear to show promise in historic church setting. Technology, such as heat pumps, have been used in pilot studies to provide more stable base temperatures in churches, therefore limiting the potentially damaging fluctuations associated with the operation of space heating systems. Establishing the internal environmental conditions for human comfort, preservation of the building fabric and artefacts requires further research and study before recommendations can be given.

Acknowledgement

This research forms part of a PhD study at the University of Brighton. This Science and Engineering in Arts Heritage and Archaeology (SEAHA) study is funded by the Engineering and Physical Sciences Research Council (EPSRC) and is a collaboration between University College London, University of Oxford and University of Brighton.

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The Innovative Approach of Biomimetica and its Application to Sustainable Retrofitting of Existing Buildings

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Abstract

In recent decades, elements and technological systems inspired by the natural world have become more widespread in architecture and construction industry, in order to improve the energy efficiency and thermal behavior of buildings. The best known example are green facades, increasingly used to improve the energy efficiency of new buildings and the bioclimatic comfort of urban settlements. Through biomimetic studies, innovative solutions are being proposed, from the use of living biological systems (e.g. bio-reactive facades) for climate control to new natural materials (e.g. metal-sensitive wooden sheets) that react directly to external factors such as light, heat, humidity, opening and closing without the use of energy or mechanical aids. All these systems contribute to improving the energy efficiency of both buildings and the urban system in which they are located. The contribution aims to examine technological solutions based on biomimetic methodology, to assess their applicability in the retrofitting of existing buildings.

Keywords: *biomimetic, energy efficiency, retrofitting*

1 Introduction

Biomimicry' is a subject that has recently entered the world of architecture and building construction, as a result of the need to improve the comfort of buildings and to optimize the energy performance and behavior of buildings in cities, thanks to the help of nature. One of the main innovators of biomimicry is the American Janine Benyus, founder of the Biomimicry 3.8 Institute in Missoula, Montana, with the book "*Biomimicry: Innovation Inspired by Nature*". [1]

In her book she describes in detail how science is studying the best ideas of nature to solve the most difficult challenges of our millennium. *"Biomimicry opens an era based not on what we can extract from nature, but on what we can learn from it. This shift from learning about nature to learning about nature requires a new method of investigation, a new set of lenses and, above all, a new humility.".*

Biomimetics is a branch of technology that is used in multidisciplinary fields: biomimetic architecture is therefore only one of these branches. Biomimetic architecture is a contemporary architectural philosophy that seeks solutions for sustainability in nature, not by replicating natural forms, but by understanding the rules that govern them. Over the decades, the field of biomimicry has shifted from looking at nature as a form to a more functional vision, trying to replicate its processes and systems.

Moreover, two main levels of analysis can be identified: the study of the behavior of the individual organism or of a part of it, and the study of the ecosystem in which it is inserted, with the modes of exchange and collaboration that are triggered in the process. There are therefore many variations in reference to architecture: the use of vegetable elements integrated in buildings, the application of a technology, derived from nature, that is applied to buildings or parts of them, the definition of architectural forms that reproduce behaviors of vegetable or animal organisms, and so on. There is the possibility for architects to learn more deeply from nature and to use biomimetic materials and technologies in better buildings in the near future.

2 Biomimicry for architecture

As far as architecture is concerned, there is a movement called 'Living Architecture' [2], which focuses on the integration of natural elements and processes with the building. These processes are manifold and include, for example, the collection, storage and filtration of water, the exploitation of sun and wind energy, water microfiltration processes and nutrient treatments. To implement the idea of a living organism in a building, the system must be seen as a complex system, in which all parts interact and combine to form a whole. Consequently, the technological elements must be thought of as parts that interact with the natural ones. Biomimetic architecture includes this branch of 'Living Architecture' as it focuses on understanding the systems and processes of natural forms. This understanding can be used in two different ways: the first finds an example in nature and imitates it in a new project, while the second finds in nature the example that best suits the design needs.

The concept of Living Architecture is important because, among all the benefits, it considers the positive effects on health deriving from contact with living systems in the built environment. [3]. The Living Architecture tradition was born in Berkeley, California, with Christopher Alexander as the main protagonist and from there many followed in his footsteps [4].

The levels of a biomimetic analysis are different depending on the purpose of the study. "*Integrating the understanding of the functioning of the living world and ecosystems into architectural and urban design is a step towards the creation and evolution of radically more sustainable and potentially regenerative cities*". [5]. Zari also stresses the importance of human beings as decision-makers, in fact he says: "Human beings are undoubtedly effective ecosystem engineers, but they can gain valuable insights by observing how other species are able to change their environment while at the same time creating a greater capacity for life in that system."

3 Urban sites and Vertical Green Walls

The best known and most used example of Living Architecture's biomimetic approach is green facades, which are increasingly used to improve the sustainability and efficiency of new buildings and, at the same time, improve the bioclimatic comfort of urban settlements. According to recent studies, Green Walls Systems (GWS) help buildings become more energy efficient and reduce carbon emissions. They also mitigate the Urban Heat Island (UHI) effect as facades absorb and filter rainwater, reduce pollution and act as carbon receptors. These systems, if properly designed, also preserve the biodiversity of the city's plants and animals, acting as attractive oases for many species. We briefly describe the main benefits of a green façade in an urban system.

3.1 Urban Heat Island

The urban heat island effect is defined as a metropolitan area or place within a city that has a higher temperature than the surrounding environment; in particular, (in full "urban heat island") an urban area that has a higher temperature, due to the generation of heat by vehicles, emissions due to the energy consumption of the buildings present, and the absorption of sunlight by surfaces that overheat such as asphalt roads or facades and roofs of buildings. This problem has long been documented [6] and its effects on the environment are not negligible. Much of this heat comes from overheating the multitude of dark surfaces in urban areas, which consequently radiate the accumulated solar energy. Numerous studies show that vegetation reduces this effect and the negative impacts that this phenomenon has on the quality of life, for example for life comfort inside of the buildings or health problems for children or oldest people during hot summers. Mitigation strategies of urban heat islands, such as trees, vegetation and green roofs or walls, are the subject of extensive research and generally offer benefits throughout the year.

3.2 Re-use and storage of rainwater

A critical issue in highly urbanized areas is the collection and removal of rainwater, especially in the event of particularly violent events. Green walls, but above all green roofs, naturally absorb and filter rainwater. The water can also be filtered and recycled for non-drinking uses, for example to irrigate the facades themselves. Vegetation has micro-filtering elements, such as roots and microorganisms that use and remove pollutants from the water. Excess water is then eliminated through the process known as evapotranspiration. In recent years, the combined use of vertical green structures and green roofs has increasingly been adopted as a "bioclimatic" project to integrate (or partially replace) urban drainage systems, with studies on the effectiveness of green systems for rainwater collection. Most always consider the combination of green roof and vertical facade and not just the Green Wall System. [7]

3.3 Indoor Air Quality

According to modern scientific research [8] indoor environments can be ten times more polluted than the outdoor environment, due to the gradual release of substances contained in building materials: this is known as "*Sick Building Syndrome*". A major study [9] states that the person spends, on average, more than 90% of their time at home. During this period people suffer the consequences of indoor air pollution which includes: toxic emissions such as formaldehyde, VOC, trichloroethylene, carbon monoxide, benzene, toluene, xylene, xylene and countless others [10]. The solution to the problems listed below can be found in plants. As the vegetation grows, it absorbs greenhouse gases from the atmosphere and stores them in their tissues. According to a study [11] all plants absorb and clean the air of pollutants, the effectiveness depends on the species, some are more efficient than others, and on the quantity of plants. A green wall can contain more than a thousand plants: they all filter the air and create oxygen. The use of GWS indoors also brings many benefits for users, as it raises the level of perceived comfort.

3.4 Biodiversity

Modern cities and cultivated land have greatly reduced the biological diversity present on planet Earth. A possible remedy can be found in the Living wall systems (LWS) which can be considered as a replica of vertical natural habitats. According to a study published in the journal Global Ecology and Conservation [12] the potential of LWS is enormous. The outer living walls can be seen as mini ecosystems: the incorporation of such a variety of plant species attracts many organisms and insects such as butterflies, bees, ladybirds and hummingbirds. *"Cities must become a key player in global efforts to conserve and restore biodiversity. At the same time, if the goal of urban design is to create or adapt cities so that they support people's well-being, the support and regeneration of urban biodiversity must be integrated into decision-making and design interventions."* [13]

3.5 Building protection

A green wall acts with a dual function: in summer it is a sort of barrier that protects the building from solar radiation and heat, thus limiting the use of energy required by the use of cooling systems. In winter, on the contrary, the walls and the substrate provide an additional layer of insulation that further isolates the building from the cold. These characteristics of LWS act to reduce the carbon footprint of a building [14], reducing temperature fluctuations in the casing. The green wall panels and the outer shell are separated by a layer of air that allows the building to "breathe". The system is very similar to rain shielding technology, which keeps rain away from the building while allowing moisture to escape. Covering an exposed vertical surface with a green wall protects it from precipitation and wind, harmful UV rays and corrosive acid rain.

3.6 Financial Added Value

The green improves the visual, aesthetic and social aspects of an urban area and, in addition to improving health and quality of life, also has a strong influence on the economic value of a building or a neighborhood [15]. Today, people are looking for healthy green spaces where they can live, even in the city. The trend confirms this research, in fact, prices are rising precisely for homes or offices in complexes that have more green space. This is a long-term investment and the initial costs of implementation should not lead to underestimate the long-term returns and profits not quantified in purely economic terms, in the implementation of the green.

3.7 Reduction of energy consumption

It has been shown that the temperature of an exposed surface of a green wall is significantly lower than the temperature it would reach if it were made of plaster or cladding panels. [15]. Research has shown that, for example, in humid Hong Kong climates, they can achieve a maximum temperature drop of 8.4 °C [16]. On the contrary, in the summer period, the effect of shading leads to important savings. According to a study by the National Research Council Canada [17] the shading effect of vertical green systems reduces the energy used for cooling by about 23% and the energy used by fans by 20%, resulting in an 8% reduction in annual energy consumption. This is also partly due to the process known as transpiration. Plants cool the surrounding environment slightly. With each additional plant this increases and therefore a green wall, with hundreds of plants, can reduce the temperature of a room from 3 to 7 °C [18]. According to a study conducted by the University of Seville [19] the cooling effect of the living wall was demonstrated, with an average reduction of 4°C compared to room temperature, even if in warmer conditions maximum decreases of 6°C were observed. During the winter, some living wall systems serve as additional insulation. There is an additional layer of air between it and the wall that reduces the amount of heat that escapes and the cold air that enters. Vertical green layers reduce also wind speed by stagnating around building facades.

3.8 Health and Well-being

Urban greenery is recognised as a remedy to stress reduction in a large number of publications and research documents confirming its benefits [20]. Three important factors that are highlighted [21] are: a) distance, the closer open green spaces are to one's home, the more often one visits them; b) time, spending time outdoors in open urban green spaces seems to be the most important factor influencing stress levels; c) accessibility, a home with direct access to a green courtyard or its own garden seems to be the optimal situation. The use of Vertical Green Walls on tall buildings, can be the first factor, brings close to homes or offices plant elements, with careful design can also make them accessible and attractive.

3.9 Aesthetic Improvement

When visiting the botanical gardens, walking in a park or walking through a forest, it is easy to see that nature has created a wide variety of colors, textures, patterns and sizes. Using this diversity and incorporating many plant species you can create works of art. Architect Luciano Pia has created a building that is living and green art, in his 25Verde. The example of a biomimetic approach to design that created a surprising result: the architect used the knowledge of botanists in the selection of plant species and integrated them harmoniously inside and outside the building complex. Designing a green wall that is different, captivating, intriguing and simply a pleasure to look at is a complex task. It requires strategic planning, in-depth knowledge of countless plant species, a strong eye for design.

3.10 LEED Credits

Considerations on the design of green and living walls are discussed in USGBC courses[22]. Vertical Green Wall design can be used to earn additional LEED® credits. LEED® (Leadership in Energy and Environmental Design) is an internationally recognized green building certification system. The use of this type is very important for the environment and the agency promotes it with extra LEED® credits. Using Living Wall System directly qualifies 2 credits and helps you earn another 30 points.

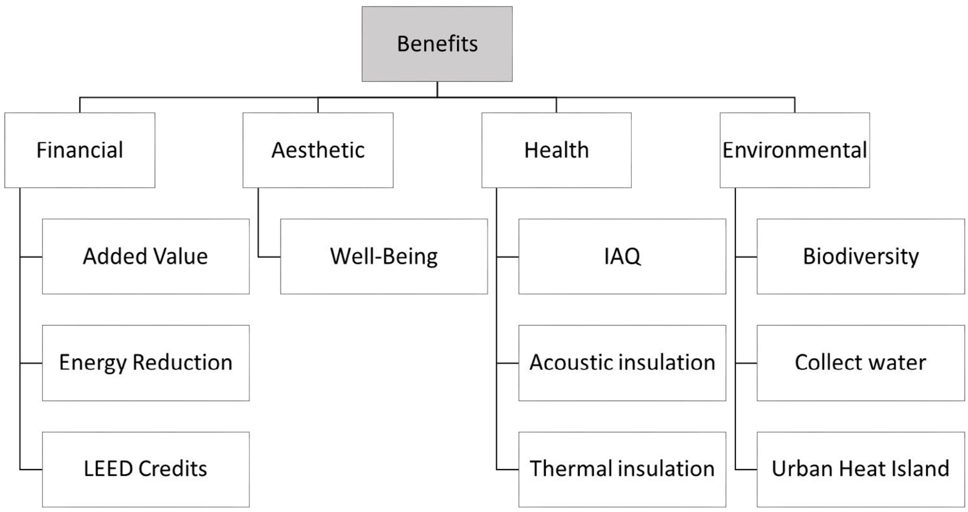

Fig. 1 *Overview of the benefits of using the Vertical Green Wall*

4 Biomimetic solutions evaluation method for retrofitting

There are several biomimetic solutions that can be used for retrofitting buildings in urban settings, to limit the criticality of urban areas and introduce the advantages listed above. The subdivision has been set according to: integrated vertical greening systems integrated in the architectural envelope, vertical greening systems juxtaposed with the perimeter wall of a building, external greening system.

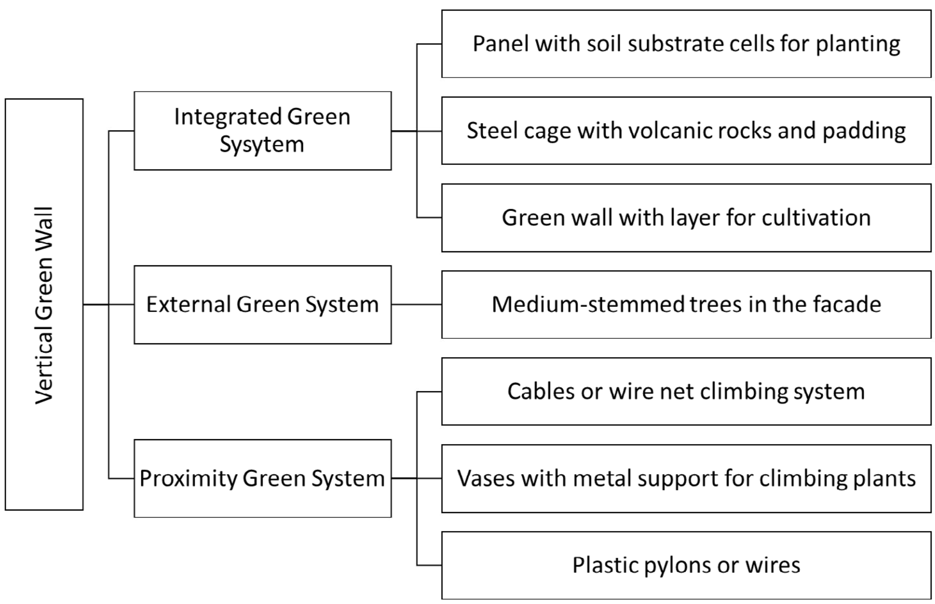

Fig. 2 *Overview of Vertical Green Wall*

4.1 Integrated Green System

Integrated systems of total or discontinuous vegetable coating of the facades of a building can be realized with different technologies: Panel with soil substrate cells for planting, Steel cage with volcanic rocks and padding, Green wall with layer for cultivation.

Fig. 3 *Panel with soil substrate cells for planting*

Fig. 4 *Steel cage with volcanic rocks and padding*

Fig. 5 *Green wall with layer for cultivation*

This type of living wall differs from the climbing facade in many respects but the fundamental is that they have roots for their nourishment in a special support and not in the ground. The walls are self-sufficient vertical gardens that are fixed to an independent frame either outside or inside a building. There are two ways to grow these walls: the soil-based substrate is the traditional way, while hydroponic growth is a more advanced technique that does not use the soil to provide the necessary nutrients to the plant but water [23]. From a functional point of view, compared to the adjoining green façade, most of these systems require a more complex design, as it is necessary to consider a greater number of variables, such as: the involvement of more layers, attention to the mechanism of water and nutrients, the supporting materials. [24]. The hydroponic system brings a new level of sustainability through intelligent water management and stable system dynamics. Plants are generally contained within discrete panels that contain an inert culture medium. Plants take root and anchor in the growing medium and each row of panels is irrigated and fertilized using precise pressure compensated drip technology. Careful attention must be paid to the design phase of the system. This is a delicate operation because the parameters of the site (location, appearance, adjacent characteristics) must be taken into account.

4.2 External Green System

The external systems contain some very significant interventions carried out in Italy in recent years. They consist of placing medium-sized plants on the various floors of the building in order to create the effect of a forest that develops vertically.

Fig. 6 *"Bosco Verticale" Arch. Stefano Boeri – Milano (IT)*

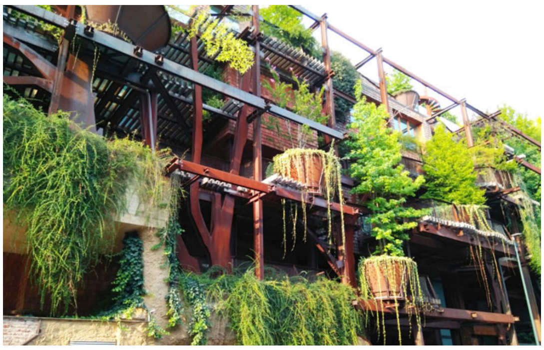

Fig. 7 *"25verde" building. Arch. Luciano Pia – Torino (IT)*

The system is particularly complex because it is necessary to have very large pots, therefore large areas and structures that support the weight of earth and trees. The positioning is outside, on balconies or terraces, and often there is a dedicated support structure. The images (Fig. 6 and Fig. 7) of Stefano Boeri's "Vertical Forest", which won the "Best Architecture in the World 2015" award, and Luciano Pia's "25verde" are reported, a striking example of how nature can be integrated with living systems, increasing the quality of life of the inhabitants.

4.3 Juxtaposed Green System

The juxtaposed systems of total or discontinuous vegetable coating of the facades of a building can be realized with different technologies: Cables or wire net climbing system, Vases with metal support for climbing plants, Plastic pylons or wires. The system uses climbing plants, or cascading plants, depending on the choice of the effect you want to give the facade and provides very simple and lightweight elements to be mounted as a support for growth. These are either modular panel nets, or plastic nets that can be adapted to the required surface or metal cables fixed to the main façade but detached from it to create a second external surface. The cables on the green facades are designed to encourage faster growth of climbing plants with thicker and denser foliage. Wire nets are often used to support slow-growing plants. This system is quite flexible and has a better degree of design applications than cables. Technologically, they work in the same way. Both systems use high-strength steel cables, anchors and additional equipment. [25]. The concept takes up what already happens naturally in many historical buildings, where climbing plants, such as ivy or wisteria, completely cover some facades, giving shows of colors and green movements.

Adaptability and lightness are the main features of these systems that offer significant advantages: protect the facade from sunlight, filter light and act as sunshades in summer, reduce overheating inside the rooms, bring the green near the windows of houses and offices. Depending on the plant species chosen, the system may change over the course of the seasons. With deciduous plants, the behavior is reversed in the winter seasons, allowing the sun's heat to reach the façade and enjoy the free heat storage.

Fig. 8 *Cables or wire net climbing system*

Fig. 9 *Vases with metal support for climbing plants*

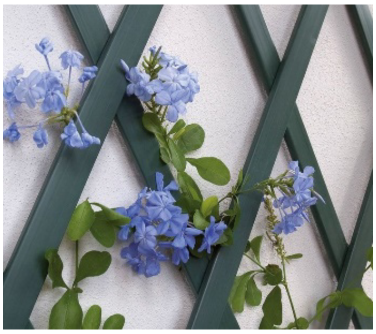

Fig. 10 *Plastic pylons or wires*

All these systems contribute to improving the energy efficiency of both buildings and the urban system in which they are located. This survey of technological solutions based on biomimetic methodology could be used in the retrofitting of existing buildings. The Vegetable Shading System improves the energy performance of the building but the design depends on the solar path based on the orientation, location in the urban context and available space. Often these solutions are used together, depending on the type of facade and the final effect that the designer wants. A summary table proposes some reflections based on some parameters: easy installation, modularity of the system, light control, strength and durability.

Tab. 1 *Comparison between different Vertical Green Wall solutions*

Vertical Green Walls		**Easy installation**	**Modularity of the system**	**Light control**	**strength and durability**
IGS	Panel with soil substrate cells for planting	✓	✓	✗	✓
	Steel cage with volcanic rocks and padding	✗	✓	✗	✓
	Green wall with layer for cultivation	✗	✓	✗	✓
EGS	Medium-stemmed trees in the facade	✗	✗	✓	✓
JGS	Cables or wire net climbing system	✓	✗	✓	✗
	Vases with metal support for climbing plants	✓	✓	✓	✗
	Plastic pylons or wires	✓	✗	✓	✗

We have chosen to give a score from 0 to 3 to classify the different solutions proposed, in order to give a useful tool to the designer for the most correct choice. Point are assigned strictly related to the technology analyzed before, in term of other factors determining the choice of the most suitable technology. Four main problems are discussed: the availability of water, the availability of land for planting, the level of biodiversity allowed by the chosen system, the area that can cover the solution.

Tab. 2 *Scale of use of the different factors (water, soil, biodiversity, area) according to the solutions illustrated*

Vertical Green Walls		**Water**	**Soil**	**Biodiversity**	**Area**
IGS	Panel with soil substrate cells for planting	2	0	3	2
	Steel cage with volcanic rocks and padding	2	0	3	3
	Green wall with layer for cultivation	3	2	2	3
EGS	Medium-stemmed trees in the facade	3	3	3	3
JGS	Cables or wire net climbing system	2	3	1	1
	Vases with metal support for climbing plants	2	1	1	2
	Plastic pylons or wires	2	3	1	1

5 Conclusions

The analysis aims to provide a useful tool for designers in order to help them choosing the best technology according to the building and to the intervention area. The scores assigned are the result of the analysis of biomimetic technologies related to the context in which they can be installed, taking into account the main aspects that the various types of vegetation and planting require. Although, the support and advice of a botanist is essential because the choice of species and the compatibility between them ensures the durability of the entire system over time.

Acknowledgement

This research is inspired by the thesis of Elio Fetolli, who dealt with the project of redevelopment of a building located in Turin, with technologies related to biomimicry. We would like to thank Elio and Prof. Carlo Caldera, one of the thesis advisor.

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Implementation of Vertical Greening as a Double Skin Envelop: A Sustainable Approach in Tropical Climates

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Abstract

Declination of greenery in urban context is becoming a common sight with the growth and expansion of built environments. Urban spaces are transforming rapidly with increasing high rises which multiplies the surfaces that absorb solar radiation and reradiate heat creating Urban Heat Islands. In addressing this scenario Vertical greening is identified and implemented as an interesting integration in improving urban environmental quality and life standards. Yet the true potentials of vertical greening are less researched in Sri Lankan context. A research series was initiated with the aim of implementing a Vertical Greening System (VGS) as the external skin of double skin walls to achieve the maximum benefit in terms of thermal performance in Tropical Sri Lankan context. Methodology of the research series includes two stages involves background study and field investigation of the thermal performance of existing VGS at stage one following development of a VGS best suited to the context at the stage two.

The paper presents findings of the field study carried out in stage one to identify the thermal performance of existing VGS in Sri Lanka and the experimental study done as the initial step of research stage two to identify the plant type best suited for the proposed VGS. Through the background study of existing VGS, it was found that new vertical greening concepts are now being embraced in Sri Lankan context, yet in a very slow pace. And the actual benefits of vertical greening are still hidden by the aesthetic value as the knowledge on vertical greening still is limited to a minority. As per the onsite field measurement Living Walls were found to be better in thermal performance with a record of maximum temperature reduction of 8°C. Reduction of surface temperature were recorded to be 6.9 °C to 9.3 °C in living wall systems, 7.1 °C to 9.5 °C in indirect green facades and 5.1 °C to 6.3 °C in direct green facades. Consequently 12 plants were shortlisted and investigated for their rate of survival, growth rate and thermal performance. From the experimented plant types Roheo spathacea and Axonopus compressus were identified as the best plant types in terms of thermal performance and survival.

Keywords: *green facades, living wall systems, building envelop, sustainable buildings*

1 Introduction

With the increasing urbanization trends urban population is rising causing dense urban contexts and space scarcity. This urbanization tendency has pressurized the demand for more and more built spaces which evidently has caused for lesser greenery in urban contexts. Concentration of heat retaining and impervious materials have altered the natural land surfaces. Increasing high rises have multiplied the surfaces that absorb solar radiation and reradiate heat creating Urban Heat Islands. On the other hand, these urbanscapes act as emitters as well as sinks of numerous contaminants which leads to many health-related issues. Thus, collectively global warming, urbanization, poor urban environmental quality and etc. will magnify thermal discomfort, health issues as well as energy demand for cooling. In this context it is vital to come up with sustainable solutions that will enable cities and people to adapt such crisis and to initiate mitigatory actions. In present, globally this topic is being highly discussed and number of researches are being carried out in finding such solutions.

Number of present researches investigate the potentials of greenery as a UHI mitigation strategy recommending increment of greenery to enhance urban outdoor thermal comfort conditions. Vegetation is identified as the best solution to overcome the effects of urban heat islands, air pollution and global warming and etc. whereas vegetative canopy cover with optimum spatial configuration are vital in UHI mitigation (Bao et al., 2016). Among various benefits of greenery cooling effect of shading and evapotranspiration, absorbing Carbon Dioxide (CO_2) and many air pollutants become significant. Therefore, increasing greenery in urban contexts is essential to balance environmental and air quality. In contrary rapid green declination due to haphazard and unplanned urban development has reduced the efficiency of favorable impact of vegetation. Declined green cover in Colombo (Fig 1) evidently demonstrate the drastic transformation of urban contexts in Sri Lanka.

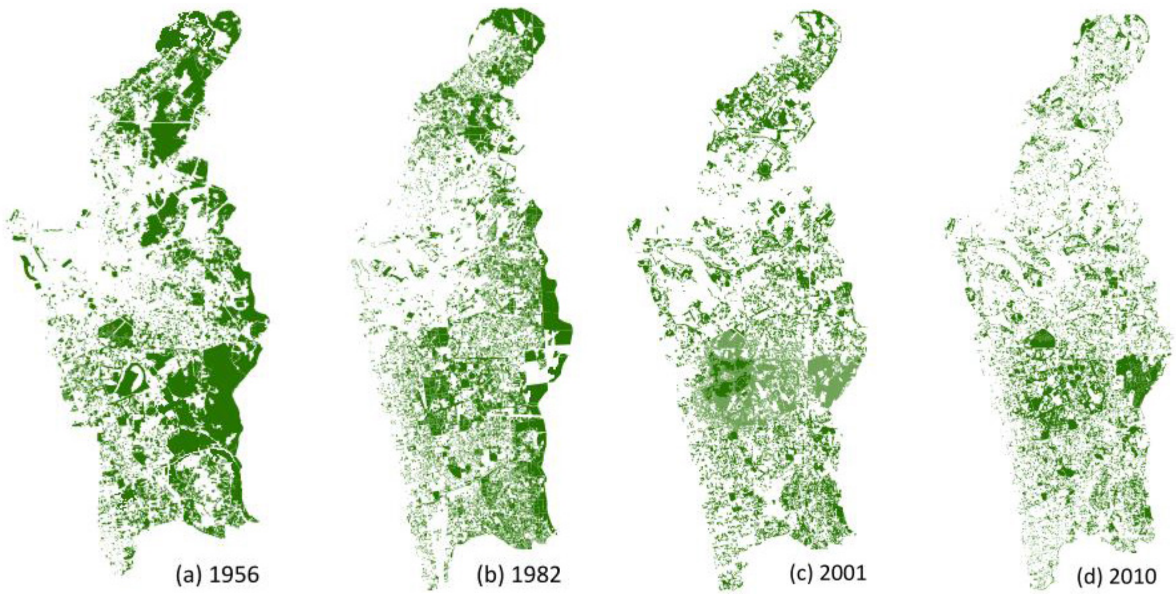

Fig. 1 *Declination of green cover at Colombo from 1956 to 2010 (a: 1956, b: 1982, c: 2001, d: 2010) (Wickramasinghe et al., 2016)*

2 Integration of Vertical Greening

Building facades have been identified as one of the main building components that can be manipulated to achieve sustainable goals. With the growth of high rises in urban contexts the increasing building population provide abundant vertical surfaces to be utilized for this purpose. On the other hand, with many identified benefits such as improving the urban environmental conditions by promoting air quality, reducing heat island effect and etc. vertical greening is becoming a current sustainable trend as an approach to improve environment quality as well as thermal performance of buildings. Also, vertical greening offers the opportunity compensate to nature by restoring the greenery lost due to man-made constructions while recreating the link of man and nature.

Simply Vertical greening can be defined as plants grown on vertical surfaces which can be established on interior or exterior building walls using one or more plant types to be naturally grown or man-made in a way of standing independently or with structural supports to attach the wall (Perini et al., 2011a; Safikhani et al., 2014; Shiah and Kim, 2011; Wong et al., 2010a). In present number of vertical greening methods have been introduced with different characteristics varying from plant types, growing medium, layers included in the system, method of maintaining and etc. According to literature, vertical greening is classified mainly into two categories based on the growing and construction method used; façade greening and living wall systems.

3 Research Context of Vertical Greening

Using vegetation to improve a building's microclimate has long been investigated by a number of researchers. The comparative study conducted by Parker (1987) on energy consumption profile of a United States residential building before and after introducing plants adjacent to the building indicated potential cooling energy savings of up to 60% during warm summer days could be achieved. Existing research studies (Perez et al.,2011, Perini et al.,2011a) implies that in evaluating the performance of vertical green systems in terms of minimizing heat gain, energy saving, mitigating noise and air pollution and etc. type of vertical green system, plant type, and maintenance must be considered. Such variations in vertical greening systems cause deviations of the effectiveness in each type (Perez et al, 2011). A study conducted in Singapore resulted a maximum of 11.8 °C temperature reduction at Living wall system (Wong et al., 2010a) whereas temperature reduction by living walls was recorded as 5.4 °C in Netherland (Perini et al., 2011a) and 5.5 °C in Mediterranean continent (Perez et al., 2011). In Thailand indirect green facades has recorded a maximum temperature reduction of 9.93 °C (Sunakorn and Yimprayoon, 2011).

When considering the functional aspects such vertical greening systems require complex design approach considering the above variables. Characteristics of vertical greening systems, materials used and etc. determines the influence of the system in terms of performance either positively or negatively in terms of improving building envelop behaviour, moderating the outdoor climatic conditions and the life cycle of the system itself (Perini & Ottele, 2014). According to Manso and Castro-Gomes (2014) vegetation cover, its size and shape and particularly anisotropy determine and influence the capable cooling distance. Several research studies have been conducted on investigating the possibility of temperature regulation through vertical greening systems. As per the findings by Wong et al., (2010a) temperature difference at 0.6m distance from vertical greening is barely noticeable. However, research evidence reveals air temperature reduction at 0.1m from vertical greening varying from 0.17 °C–0.02 °C depending on vertical greening type where living walls record the highest air temperature reduction of 0.17 °C (Perini et al., 2011a).

4 Vertical Greening as a double skin envelop

The requirement for and the advantages of environmentally friendly buildings in the context of sustainability is not to be doubted. It is identified that in use and construction process, buildings are harmful to the environment. Published research propose to recommend that, more advanced or "intelligent" building envelops as well as more effective insulation design need to be effectively applied to design of buildings. Over the years, researchers, architects and engineers have given considerable interest on the external perimeter design of buildings with the concerns for energy efficiency, aesthetic appearance and sustainable design. Building façade is a main component of the building envelop that separates the building interior from the outside. Thus, it has a greater potential of being the climatic filter to take only the favourable impacts from the outside. Double skin envelop is identified as a better option in terms of climatic filter to maintain comfortable indoors in tropics (Rajapaksha et al., 2015). When compared with the identified benefits of the double skin envelop (Rajapaksha et al., 2015), it can be assumed that integrating green wall as the external leaf of the double skin is undoubtedly much more beneficial (Fig.2). Thus, a vertical green wall system as the external layer of a double skin envelop plays the dual role of moderating the building interior conditions while compensating for the negative impacts of man-made highly dense structures and pollution causes by modifying outdoor environments as well.

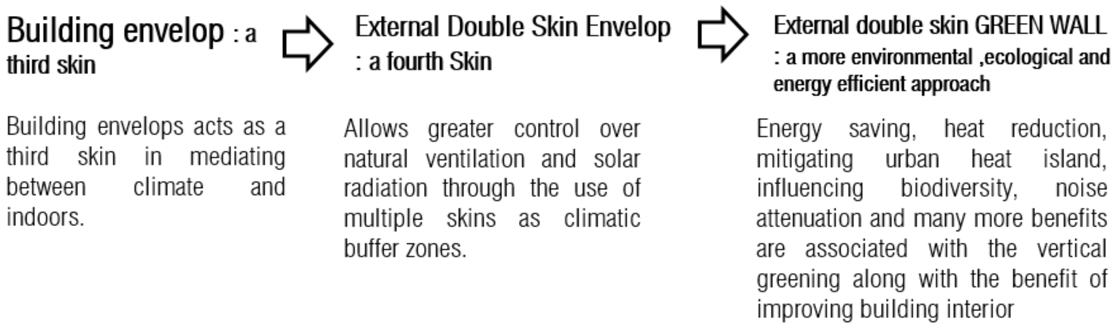

Fig. 2 *Benefits of integrating Vertical Greening as a double skin envelop*

5 Research in progress

Even though many researches have been carried out throughout internationally in relation to green building facades to address the sustainable requirements, it is less researched in tropical contexts specifically in Sri Lankan context. Thus, the possibility of using green wall as sustainable building envelop is still not appropriately identified. Thus, to address the gap, a research series was initiated at University of Moratuwa with the aim of developing a sustainable green wall system as a double skin envelop and to investigate the potential thermal benefits to building interior and exterior. The research is designed to conduct in two stages where in the first stage a background study is conducted including investigating the existing VGS and the thermal performance. In the second stage it is aimed to develop a VGS with maximum thermal benefits by identifying the more suitable plant types, maintenance methods etc. The paper presents the findings and results of the first stage of the research and the initials step of second stage.

6 Methodology

Research Stage one
The Stage one of the research intended to investigate the background theories and practical situations to create a platform for the vertical green panel development. The work aimed at investigating the existing vertical greening systems of Sri Lankan context along with the plant selection, watering systems, maintenance details related to vertical greening. Method of the research stage one involved a case study approach inclusive of field investigation, structured interviews and on-site experiments.

Initial step of research Stage 2
The stage two of the research series is designed to develop a VGS that is more appropriate to tropical Sri Lankan context with maximum thermal benefits. As the initial step of the stage two an experimental design study was conducted to identify most suitable plant type for vertical greening in tropical Sri Lankan context.

6.1 Field investigation of existing situation (Research stage one)

To identify and evaluate the existing situation of vertical greening in Sri Lankan context and. As a part of the research study existing vertical greening types of Sri Lankan context along with the plant selection, watering systems, maintenance and issues related to vertical greening were investigated. The context for case studies were limited to Colombo and a photographic survey was done to identify existing green wall types. From observations well established twenty cases were identified from Colombo context for the detailed VGS analysis. From the sample cases, nine cases representing each vertical greening type were selected for on-site measurements to observe the surface temperature reduction with the introduction of vertical greenery. Measurements were recorded at selected nine cases for 48 hours using Graphtec-midi GL820 data logger with 10-minute intervals. Points of measurements (temperature at 1m distance from vertical greening surface, temperature on the green surface, temperature of the wall shaded from the vertical greening, temperature of the adjacent bare wall etc.) were decided based on Perini et al. (2011). The readings obtained from each type were evaluated and compared with the measurements taken from adjacent bare walls.

Consequently, a questionnaire surveys was conducted involving 150 occupants to study the respond of occupants of the case buildings on vertical greening concept and practice of integrating vertical greening. Expert reviewed questionnaire was executed to obtain the personal observation and perception on each situation and the responses were evaluated.

6.2 Selection of plants for Vertical Greening (Initial step of research stage two)

Parallel to the field investigation, a study was initiated to select plant types with best thermal benefits and high survival rate and easy maintenance to be used in the proposed modular green wall system. Twelve different plant species were selected based on its growth form and the growing medium with the assumption that these species would be best suited to the extensive green wall environment: shallow soil, high winds, intermittent flooding and drought, and absence of tree cover (Cameron et al., 2015) and replicated in three panels which were observed over three months. Five plant species with best performance were selected out of the sample cases and were further observed for their growth, nutrient and water requirements, maintenance and thermal performance.

Modular green wall system was selected to be followed which consists of self-contained units that can be assembled and planted ex situ and later install on the wall vertically. Each module represents a repetition, all modules have the same growth medium and protective layer, only different planting plant between the modules. Green wall panels were prepared by using timber (60x30 cm) as shown in Fig.3. Coir fiber was used as Growing media because of its light weight, high water holding capacity and its binding ability.

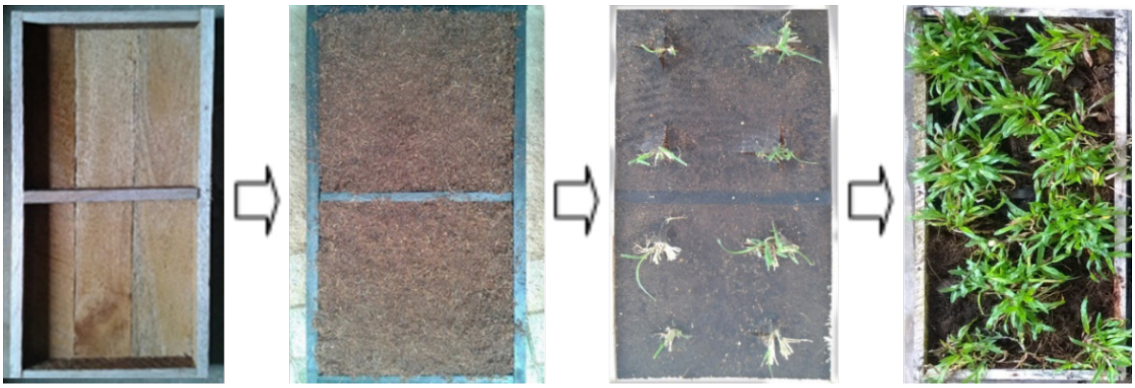

Fig. 3 *Fabrication of sample modular panels*

Horizontal panels were irrigated twice a week morning (9:00 am) by sprayers manually until the growth medium become wet. But applying too much water was avoided in early stages of the plant and was taken care to avoid moisture loss and retain enough heat. 0.5L water was applied to each panel. After one-month period of time the panels were hand-watered as required to maintain plant health, with 0.5L of water slowly from the top of each module. Nutrient supply is not needed until true leaves appear. Until this time only clean water was applied. However, as the leaves unfolded, the nutrient supply gradually began because the growing medium contains very little plant nutrients. Nutrient solution was prepared by dissolving 0.5 g of Albert's mixture in 0.5L of water for each panel and applied twice per week.

Monthly plant evaluations were conducted for three months. Plant height was measured along with visual assessments of plant development stages (flowering and seed set) and pest/disease incidence. Leaf length and width were measured using graph paper method during the study period. Canopy temperature for each species, substrate surface temperature, wall surface temperature shaded by the panels and ambient air temperature (20 cm above canopy level) were recorded for 48 hours using a data logger GL 820 midi.

7 Results & Discussion

7.1 Field investigation of existing situation

Based on the literature review, the selected cases were identified according to the vertical greening classification: green façade or living wall. Three basic types of vertical greening systems were identified as; living wall systems, indirect green facades and direct green facades.

From the observed twenty cases three buildings were found with direct green facades. However, many cases were found with direct greening at boundary walls. Through the case investigation it was identified direct greening for façades is commonly used for boundary walls in most occasions either intentionally or unintentionally. Where such walls are covered intentionally only the aesthetic aspect is considered. Seven cases were identified as indirect green facades supported by mesh structures, trellis or ropes. In Colombo context many buildings were found with indirect green facades at their initial stage of installation which were not considered for the study. Ten living walls were identified where seven were outdoor and three were indoor. Based on observations, indirect green facades are found to be a popular vertical greening system when vertical greening in Sri Lanka is considered.

Nine cases as shown in Fig.4 (three cases representing each type) which were well established as vertical greening were selected for further investigation. Temperature measurements of wall surfaces shaded by the vertical greening application were recorded and compared with the adjacent bare wall surface temperature readings in each case. The temperature difference on exterior wall surfaces were considerably high for walls integrated with vertical greening compared to the bare walls. An average temperature difference of 6.90 °C to 9.31 °C was recorded during 10:00am to 3:00pm in living wall systems and the maximum reduction of 9.31 °C was recorded at 1:00pm. Indirect green facades recorded a difference of 7.19 °C to 9.59 °C during 10:am – 3:00pm and maximum temperature difference of 9.59 °C was recorded at 2:00pm. Surface temperature reduction of 5.14 °C–6.39 °C was recorded with integration of direct green facades during 10:00am–3:00pm while the maximum reduction was recorded at 1:00pm. All three vertical greening types proved to be effective on reducing surface temperature of building exterior walls (Fig.5) which directly contribute to reduce internal gains thus reducing cooling load requirement.

Further, living walls proved to be more effective in reducing heat gain from the investigated three vertical greening types. With the on-site investigation results living wall systems were identified as the best vertical greening type to be implemented in tropical Sri Lankan context to achieve the best possible benefits.

Fig. 4 *Selected nine cases for further investigation*

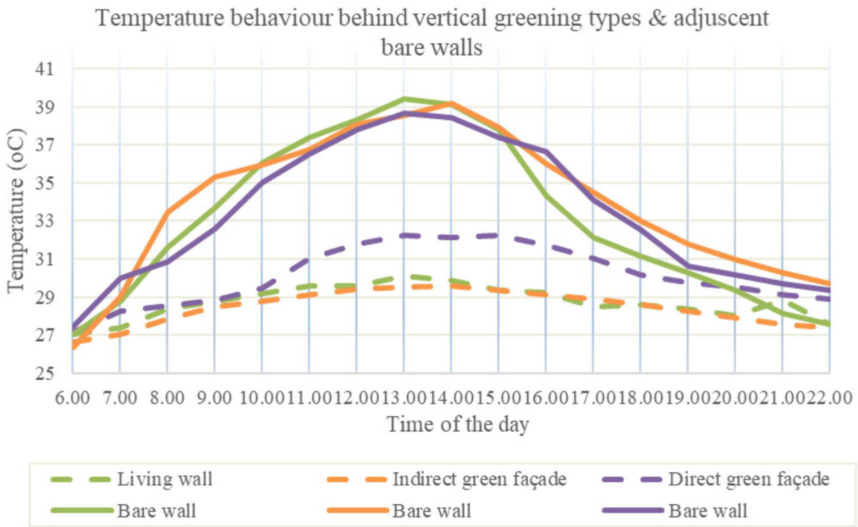

Fig. 5 *Temperature behavior of wall surfaces shaded by vertical greening compared to adjacent bare wall controls*

7.2 Occupant satisfaction Questionnaire

From the 150 responses all the participants were positive on vertical greening intervention based on different reasons varying from aesthetic appeal, temperature control, shading, air purification, dust and noise attenuation, psychological comfort and etc. However, a majority (46%) believed aesthetic appeal to be the main benefit whereas 21% emphasized on temperature control and 8% on shading effect where the remaining respondents stated dust, noise control, air quality improvement, mental relaxation as purpose of integrating vertical greenery. Compared to aesthetic appeal the potential temperature reduction was less identified. 34% of the occupants were highly satisfied on thermal comfort gained through vertical greening while 49% and 45% respectively were highly satisfied on psychological and visual comfort as shown in Fig. 6. Overall more than 50% of responses were satisfied or highly satisfied on physical, psychological and visual comfort achieved through vertical greening.

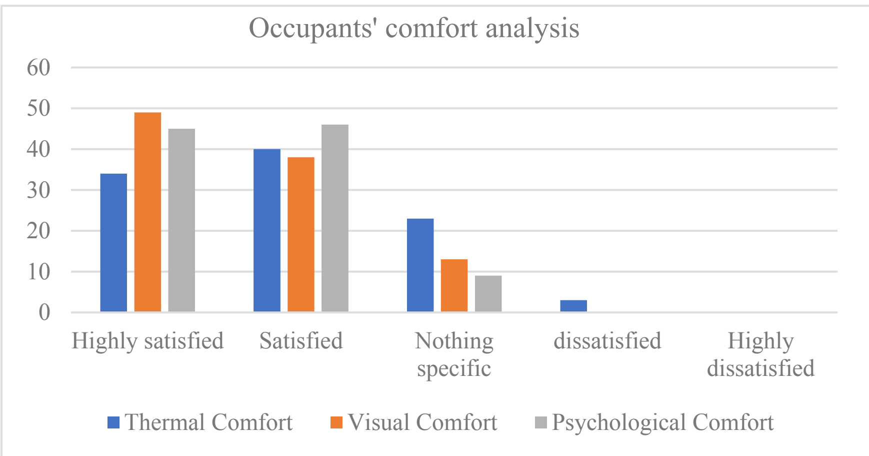

Fig. 6 *Occupants perception on integration of Vertical greening*

Application of vertical greenery seemed to be very less where 79.3% respondents stated not to have vertical greening in their private residents. However, from the total 78.7% preferred the idea of integrating vertical greenery. High construction cost (36%) and frequent maintenance requirement and maintenance cost (24%) were indicated as the main issues amalgamated with vertical greening while few claimed of pest and insect attraction (20%) and possible health issues (16%) and other (4%) as limitations.

7.3 Selection of plant type for Living Wall System

Plant survival rate varied significantly between each species (Fig.7). Health of the plants for these species were consistently high, with only minor bacteria blight spots observed during late October. Vegetal survival rate over the trial period was hieghest in Rhoeo spathacea species whereas Axonopus compressus, Ophiopogon japonicas, Portulaca grandiflora, Axonopus fissifoliu and Elusine indica too showed a high survival ability. Tectaria spp and Desmodium triflorum displayed a decline from 100% in September to 33% and 62% respectively. Centella asiatica displayed comparatively slow growing rate and were not capable to survive in this environment. Begonia spp did not show any significant growth rate. Even though Dieffenbachia spp did not survived in the vertical environment, it has indicated that 100 % survival rate in the horizontal environment over the trial period. The dense canopy of variegated foliage also makes *Rhoeo spathacea* an attractive choice for green walls. Most of the other trial species such as Axonopus compressus, Ophiopogon japonicus, Zoysia , *Elusine indica* reached heights between 10 and 15 cm. This is an ideal height range for an extensive green wall, as per short plants have a tendency to be less likely to wind damage and maintenance capability. *Desmodium triforum, Centella asiatica, Begonia spp* did not survived in the green wall panels within the study period.

7.3.1 Thermal performance of plant species

Plant species that showed the best growth performances were selected to the initial study of thermal performances of green wall plants. Selected plant species were *Rhoeo spathacea, Axonopus compressus, Portulaca grandiflora, Ophiopogon japonicas and Elusine indica*. From the results (Fig. 8) *Rhoeo spathacea, Axonopus compressus* proved to be most appropriate in terms of survival, maintenance and thermal performance to be used for living wall systems.

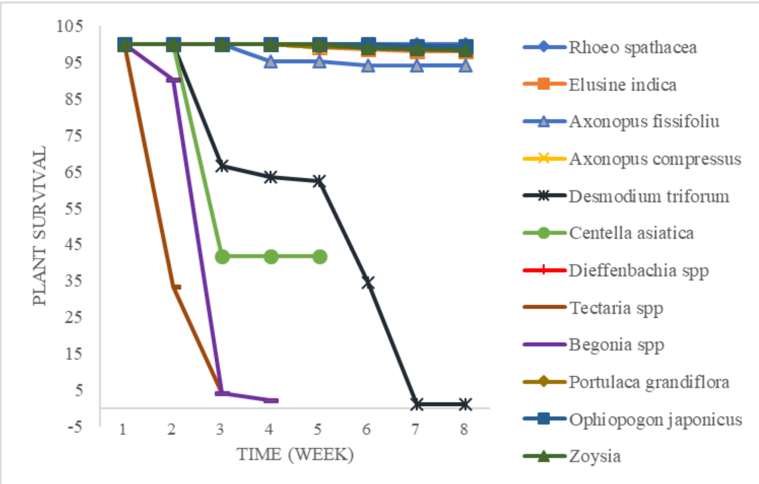

Fig. 7 plant survival rates during the trial period

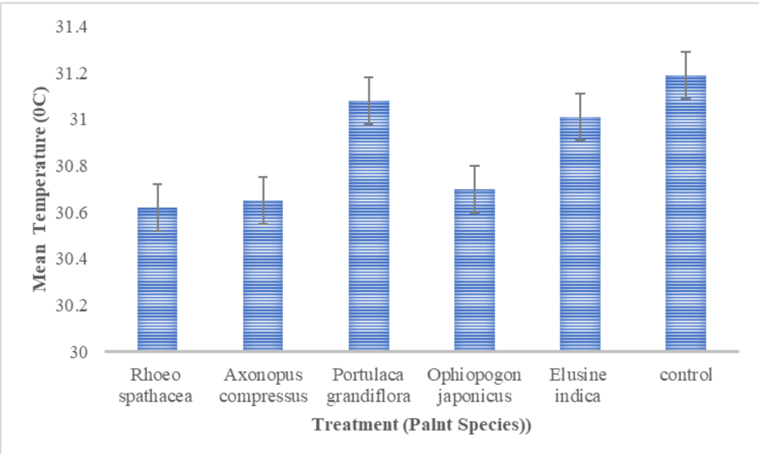

Fig. 8 Mean temperature of the wall surfaces shaded by the green panels

8 Conclusions

The true potentials of green facades in Sri Lankan tropical context is still not fully explored due to inadequate research evidence and shortage of data to quantify the performance of them. Trend of vertical greening is now popularizing in Colombo context where it is mainly used to label the building as "green" from the outer look and to enhance the aesthetic appeal. Yet, Vertical Greening can be used to achieve multiple benefits for outdoor urban environments as well as building indoor environments as well. Considerable surface heat gain reduction that directly influence to reduce cooling load requirement can be achieved by integrating Vertical Greening as the outer leaf of the double skin envelop of buildings. Thus, it becomes vital to make awareness on the total environmental benefits of vertical greening focusing on the potential of cooling load reduction, increasing productivity, dust and air pollution control and etc. to be considered when deciding on implementing vertical greening.

In terms of actual performance, Roheo spathacea, Axonopus compressus and Elusine indica showed highest rate of survival and coverage on the vertical green wall. Desmodium triflorum, Centella asiatica, Axonopus compressus, Dieffenbachiae spp, Tectaria spp, and Bigonia spp have declining survival rates in the vertical green walls. Growth rates of Roheo spathacea, and Axonopus compressus and Elusine indica were higher than the expected and they achieved full coverage within 12 weeks of transplanting. Through this study it could also be concluded that the temperature of the wall surface can be decreased by covering walls with vegetation. The study reveals in selecting the plant species for vertical greening apart from aesthetics the survival rate and their thermal performance must be considered to achieve the maximum potentials of the vertical greening systems.

The studies need to be conducted for longer terms exposing the plants to year-round climate conditions to further investigate their actual performance throughout the year. Moreover, studies on a broader range of plant species, substrate preparations and irrigation management are mandatory to assess for long-term usage in green infrastructure for Sri Lanka. It is necessary to determine the sustainability of green wall plants and media in a tropical context, both with and without supplementary irrigation

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