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Energy Efficient Building Design and Legislation

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Preface

The RILEM International Conference on Sustainable Materials, Systems and Structures (SMSS 2019) was organised by the Faculty of Civil Engineering University of Zagreb as a supporting event of the RILEM Spring Convention in Rovinj, Croatia. These events are held in the year the Faculty of Civil Engineering in Zagreb celebrated its 100-year anniversary of its founding, making 2019 the ideal year to host such an important international event. The purpose of the conference was to bring together scientists, practitioners, members of technical committees and users of technical recommendations, to jointly discuss and envision the future of sustainable development of materials, systems and structures in a holistic, global way.

The SMSS 2019 conference had participants from 50 countries, from Argentina to United States of America, who presented a total of 290 papers. The conference was sponsored by 10 international industrial partners, supported by 6 international organisations of scientists and practitioners and organised under the patronage of 4 governmental bodies. A total of 450 contributions were reviewed by more than 150 prominent reviewers from different fields. The events Organizing Committee consisted of 16 local members and 6 invited international members.

As part of the RILEM SMSS 2019 conference, the **Energy Efficient Building Design and Legislation** segment was organized as a separate international segment with the aim to bring together leading academic scientists, researchers, research scholars and industry professionals involved in building physics and sustainable construction, giving them the opportunity to exchange and discuss current ideas and knowledge in both the background science and practical applications of advanced materials, systems and methods for design of energy-high performing, healthy and sustainable buildings; as well as current legal framework and policy instruments. All papers submitted for this segment were subjected to a full review process, and the Proceedings contain only those papers that were accepted following this process. The review of manuscripts was undertaken by members of International Scientific Committee. This invaluable assistance, which has greatly enhanced the quality of the Proceedings, is gratefully acknowledged. The spectrum of relevant research topics covered encompasses enhancement of energy performance and indoor comfort in buildings; heat transfer problems; legislation framework and policies for energy efficiency in buildings; Building Information Modelling (BIM) for energy modelling applications; hygrothermal performance of building materials and elements; innovative building envelope systems; materials and systems for energy retrofitting; and sustainability through recycling.

Outstanding papers were nominated by Reviewers for post-conference publication in Special Issue of international Journal of Advances in Building Energy Research. Journal is focused on most important developments across the rapidly expanding fields of energy efficiency and environmental performance of buildings

Finally, the Editors wish to thank the authors for their efforts to produce and deliver papers of high standard. We are certain that these Proceedings will be a valued reference of research topics in this important field and that it will, together with the other volumes from SMSS conference, form a suitable base for discussion and suggestions for future development and research.

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CA EPBD SUPPORTING TRANSITION TOWARDS NZEB BUILDINGS

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Abstract

Energy efficiency in buildings depend on actions and decisions of many individual stakeholders and owners. Especially in the residential sector these counts for many millions, even hundreds of millions of individuals cross over Europe. Efficient measures therefore often depend on mandatory requirements for minimum standards and for mandatory information initiatives.

Since the adaptation of the first Directive 2002/91/EC of the European Parliament and of the council on energy performance of buildings from 16 December 2002, it has been mandatory for Member States to implement energy efficiency minimum requirements for new and for existing buildings, as well as it has been a requirement for Member States to develop mandatory information schemes in form of certification of buildings. These have to be based on overall energy performance of these buildings. With the recast of the Directive 2010/31/EC from 2010 this included the requirements for countries to develop building codes based on an aspiration of Nearly Zero Energy Buildings.

The development of overall performance requirements (Building Codes), Nearly Zero Energy Buildings (NZEB) and Energy Performance Certification (EPC) has been a major challenge for the EU Member States. In order to help these a special project was developed in 2004 called Concerted Action EPBD or CA EPBD. The aim of this project is to help countries and regions to develop the different elements of the EPBD directive. This is done though the share of experience, information and free discussions on specific topics of common interest for member states.

Today the fifth version, CAV EPBD, is a collaboration between all 28 Member States plus Norway and more than 26 large conferences, Plenary Meetings, has been held to support the implementation of the EPBD in all countries around Europe, and many other activities has been taking place in the CA EPBD. At the plenary meetings information on best practices, good as well as bad experience and many technical details are shared freely among the up to 150 participants. These experts are appointed by the member organisations of the project from each country, because of their relation to the development and implementation of the EPBD initiatives on national or regional level. The CA EPBD network, which is based on 200-300 key experts, is therefore a huge and very unique network in the field of implementation of Energy Performance Policies for Buildings and for NZEB in particular. Close to 500 sessions of 1,5 hours have been held on presentations, discussions and interactive work on energy consumption, energy performance and particular policies of the EPBD and this accounts for many sessions on NZEBs including design and calculation rules. Plenary sessions and working groups have further supported the collection and dissemination of information.

Since the first of January 2019 all new public buildings must be NZEBs and from 31^{st} of December 2020 all other new constructions must comply with the nearly zero-energy buildings rules, which means a building that has a very high energy performance, as determined in accordance with the directives Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.

Countries must set these minimum requirements based on a value for overall energy performance and this must be based on cost optimality calculations as well for new as for existing buildings. This has requested large affords as well in development of calculation methodology, design guidance, control systems as well as information, implementation and control systems. The direct minimum requirements are supplemented by information activities such as the Energy Performance Certificates, which document the overall energy performance of individual buildings. This accounts for as well new as existing buildings as for residential, commercial and public buildings.

Through the CA EPBD such information and experience has been collected and shared, based on as well good practices as on failures in each of the member states. All together the experts of the CA EPBD represent many hundreds of years of country-experience in implementation of building codes, EPCs and NZEBs. The CA EPBD information system includes as well external communication as internal communication, which is shared by members only in a confidential environment. The major part of the external communication is the website, the CA EPBD Book / database on knowledge and information papers such as fact sheets of Key Implementation & Decisions (KI&Ds). External information can be found on; https://www.epbd-ca.eu/

Many good examples have been collected as well in the residential as in the commercial or public sector, guidance has been made, lessons has been learned and much of this information has been shared publicly or through dissemination events or other activities. It has also been used to feed back into the further policy and regulation development as well on EU level, national as in an international / global context.

With the individual NZEB buildings and the many millions of EPCs done every single year a very large information on the best buildings as well on the worst buildings all over Europe is collected and evaluated. A very big challenge for the future is how to ensure that this information is collected more systematically and more widely spread, as this could actually help on improving our knowledge on the overall European building stock. This could take the CA EPBD results from policy and implementation to an overall information system on buildings and energy performance. Currently the CA EPBD works on improving the access to such information.

The CA EPBD also organise public events and collaborates with many other initiatives, this includes in particular the other CAs; CA EED for the Energy Efficiency Directive, CA RES for the Renewable Energy Directive, the Building Stock Observatory, finance organisations such as EIB and many European stake holder organisations.

A prime focus in the recent years has been on the new constructed building stock, but as the major problem in the building sector is in the existing building stock, which is the largest share of buildings and often with a very poor energy performance / with a high consumption per m^2. Recently the initiatives has therefore been turning towards the existing buildings and renovation activities. Especially with the amending directive 2018/844/EU on EPBD from 19th June 2018 increase the EPBD focus on the existing building stock among other by the change of the regulation of the Long Term Renovation Strategies, but also on initiatives on smart finance and information activities, such as one-stop-shop, focus on energy poverty or long term objectives.

Existing buildings should also have an aspiration for NZEB although there are special restrains and special issues on cost optimality or cost efficiency for exactly this group of buildings. Many lessons are still to be learned from the work on transforming the existing building stock into nearly zero energy. Perhaps the boundaries in this part of buildings has to go beyond the individual building.

The amending directive also includes many new other topics into the work of the CA EPBD such as electro mobility, smart buildings and renovation passports. It also expands the scope beyond energy savings, economic issues and direct impact; and into other benefits of energy efficiency, such as health and comfort or energy poverty aviation. Much experience is still to be shared and many lessons to be learned in the CA EPBD.

A large team of experts helps in the management of the Concerted Action EPBD and this includes the 9 Central Teams (CTMs sand CTAs), as well as special functions and the information team. The management team therefore has a special role in the collection of information and in the dissemination as well as in the organisation of the CA. This team actively supports the development of the CA, but the true strength of the CA EPBD is the engaged group of experts from countries having hands on the development of policies and rules for all types of buildings, and who are participating actively in the CA plenary meetings. Once lessons are learned these can be implemented or used to improve systems in the individual countries and specific policies directly.

The presentation will present the CA EPBD and its special role in the implementation of the changing EPBD directives, general results of the work as well as some lessons learned and many good examples from the work and especially from the public part of the work.

Keywords: CA EPBD, NZEB, nearly zero energy construction, energy performance certificates, implementation of overall energy performance

FROM LOG HOUSES TO NEAR ZERO ENERGY BUILDINGS

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Abstract

This paper starts at humble beginnings of building science reaches development of net zero energy buildings. The knowledge accumulated from observed failures in construction slowly formed a basis for a predictive capability. In doing so it became evident that interactions between energy efficiency, indoor environmental quality, and moisture management are so important that these three issues must be considered simultaneously. Now we talk about environmental control of indoor environment and a clear change in the mindset of the scientific community is in progress.

Forty years after completion of the first ten passive homes there was a shocking observation; an adequate technology exists but our lack of vision prevents wide-spread use of this technology. We need to modify our vision to deal with the dynamics of buildings to maintain comfort and building durability with affordable cost. If the quest for sustainable buildings is the goal we should learn more from nature; e.g., termites appear capable of optimizing transient conditions to maintain a stable interior comfort zone. Thus, we propose a new compact design package called environmental quality management (EQM) that is applicable to different climates with modifications of some hygrothermal properties. This will be the second step for a building science (physics) needed to become a leading force in the transition to sustainable built environment.

Keywords: Building physics, building science, system integration, thermal upgrade, thermal rehabilitation, ventilated cavities in multi-layered walls, Environmental Quality Management

1. BUILDING SCIENCE IS BORN FROM CONSTRUCTION PRACTICE

Commonly accepted building science principles have been derived from experience and observations of the performance of the existing building stock. Failures have provided important lessons, and they still do. Hutcheon [1] wrote in 1971:

‘‘Trial-by-use, although it was the basis of much of the tradition in building, is by no means outmoded, since satisfactory service is still the real and final proof of adequate performance. There is a vast difference, however, between trial-by-use as the primary way of arriving at prediction and use as a confirmation of prediction based on evidence…. Tradition places the emphasis on how things should be done; science sets out to explain why so that the experience can be carried over to different materials and circumstances.’’

As in the adage, ‘‘necessity is the mother of invention’’, most of the innovative thinking of the 1920s and 30s came from the prairie regions of North America. The climatic extremes fostered the need for buildings with envelopes that provided protection and environmental control for human occupancy in a durable way.

Control air infiltration through the wall – introduction of building paper

Pioneering work at the University of Minnesota on air leakage through frame walls led to acceptance and use of building paper as weather barriers, as distinct from roofing materials. Building paper was placed on the exterior side of the wall sheathing to impede the movement of air and rain while permitting some water vapor to permeate to the outdoors. The building paper reduced heat losses by limiting air leakage, improved indoor comfort by reducing drafts, and reduced moisture damage to the walls by preventing wind washing which decreases the temperature of air and surfaces in the wall cavities during cold weather.

Thermal insulation in wood-frame cavities

To improve thermal comfort wall cavities were filled with insulation – first using wood chips sometimes stabilized with lime, shredded newsprint in 1919, and then mineral fiber batts. The use of insulation in wood-frame cavities and attics increased during the 1930s.

In 1926, pneumatically applied cellulose fiber insulation (CFI) was used to fill the empty cavities of an existing wall. To this end, holes were drilled through plank sheathing. In contrast with today’s CFI, the initial CFI products were not treated with chemicals except for small quantities of lime and boron salts that were added as protection against mold and rot. Despite this minimal protection, no moisture damage was found when the walls of this house were opened 50 years later.

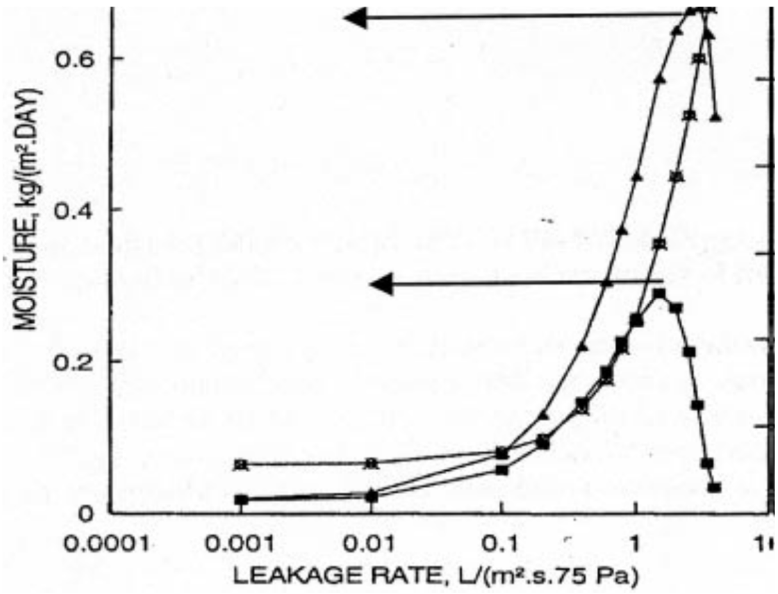

Figure 1. Water content (condensed vapor) as a function of air leakage, L/(m^2·s) @ 75 Pa in a wood-frame cavity filled with mineral-fiber insulation [2]

Figure 1 shows the amount of water (condensed vapor) initially increases with the increase of air exfiltration, eventually reaches a peak, and then decreases when the air leakage rate is high. There are two effects associated with air exfiltration. Moisture-laden indoor air that enters the wall cavity brings with it a significant amount of heat. Furthermore, the phase change that occurs during water vapor condensation also produces heat. As the rate of leakage increases, there comes a point where the warming effect dominates the propensity for condensation and the amount of condensate is dramatically reduced. In the extreme, there would be no condensation – one would end up with a very energy inefficient building.

The appearance of condensation inside wood-frame walls initiated research on condensation in wood-frame walls, a new area of research. This research is discussed in a review by Bomberg and Onysko.[3] The review contains references to the many contributors to the literature. Rowley in 1938[#] began a study concerning moisture movement through insulated walls and developed the theory of water vapor movement through materials in parallel with Babbitt. Because of these studies, vapor barriers were introduced to control the flow of vapor coming from the warmer indoor environment. The walls of homes built as early as the 1940s already included some cavity insulation and with an outside weather resistant barrier and a vapor barrier of some form located on the inner side of the wall. Soon people observed that air flow is a more effective carrier of moisture than vapor diffusion. There was widespread publication of these and similar results: Wilson in 1960; Torpe and Graee in 1961; Sasaki and Wilson in 1962; Garden in 1965; and Wilson and Garden in 1965, highlighting the significance of airflow in transporting water both vapor and liquid. There were also a significant number of publications that stressed the need for control of air leakage; Wilson in 1960 and 1961; Tamura and Wilson in 1963-1967; Garden in 1965. Building practitioners, however, were still preoccupied with vapor diffusion and ignored air tightness and water transported by bulk air movement.

[#] The reference here are given only to acknowledge researchers who contributed to the progress of building science and not as an indication for further study.

The breakthrough came when practical experience confirmed the scientific knowledge of the few. Only then did the significance of moisture (water) carried by air become appreciated by the building community. The singular trend that brought this to the fore was the promotion of electric baseboard heating in the 1960s. Builders were attracted to this form of heating because it eliminated the need for a combustion flue, but it caused condensation problems in attics as observed by Stricker in 1975, Orr and Tamura et al. observed in 1974 that the situation is much worse in cold regions.

Studies by Wilson in 1960, Tamura and Wilson in 1963, and Tamura in 1975 showed that two interrelated factors influenced indoor relative humidity:

- changes in the efficiency of natural ventilation, and
- changes in the position of the neutral pressure plane

Kent in 1966 and Dickens and Hutcheon in 1965 observed that variations in humidity and condensate accumulation in attics and roofs were simply the consequences of the above factors.

Measurements of air pressure in houses showed that substantial air leakage into attics to be a common occurrence. This led to recommendations that air tightness of the ceiling construction and partition-to-ceiling details needed to be significantly improved. The increased construction of flue-less houses and the use of high levels of insulation led to a reduced frequency of operation of combustion furnaces and led to a growing concern for indoor air quality. These typically oversized heating systems and later high-efficiency furnaces did not drive air exchange as effectively as the old, less efficient furnaces that used indoor air for combustion in leaky construction. In this situation, recognizing that natural ventilation could not be relied on to provide enough air exchange. In 1980, the Canadian model code required that all dwellings have a mechanical ventilation system and in 1990 it was modified to require 0.3 ACH.

In 1977, the ten passive houses built in Saskatchewan were based on the 1976 design from the University of Illinois. Based on this success, Canada introduced the R 2000 program in the mid-1980s that included:

- use of mechanical ventilation to provide control on indoor air quality requirements for a vapor/air barrier system
- design to avoid thermal bridges
- control of moisture entry from the ground using polyethylene film under concrete slabs.
- control of the house air tightness with a mandatory limit of 1.5 ACH at 50 Pa.
- commissioning of mechanical ventilation systems.

Based on the success of this program, the Building America program offered 50/50 sharing of the cost increase resulting from research team recommendations to reduce the level of energy in their production buildings. The building physics (or building science) has become a firmly established branch of science.

2. THE ENERGY CONUNDRUM

Traditionally, buildings in North America had a bias toward heating season performance, with most of the advances in thermal insulation, air barriers, and glazing focused on energy efficiency in the heating season. Since the energy crisis in the1970s, energy efficiency became an important design consideration and more recently achieved national recognition. It is difficult to compare energy use in commercial buildings as the change in use conditions is rapid. We can, however, compare energy use in multi-unit residential buildings (MURBs). Typical 1990 energy use of MURBs in North America was 315 kWh/m^2. Since 1990, energy use in those buildings steadily declined, reaching 250 kW h/m^2 in 2002. [4]

Yet surprisingly, the energy figures of 2002 are equivalent to those of MURBs built in 1929. In other words, the uninsulated masonry buildings in the 1929 and the shiny, glass-clad buildings of today use the same amount of energy, despite all the energy-saving measures now available.

Masonry buildings in 1920.

Masonry construction developed over the course of centuries as small improvements in construction efficiency and durability accrued. The load-bearing function required thick masonry walls, and heavy floors gave the building a huge thermal mass. As a result, these buildings responded very slowly to changes in the exterior climate, leveling out much of diurnal (day–night) shifts in temperature and thus tempering the building interior climate against temperature extremes occurring outside. In temperate climates, these masonry buildings were relatively comfortable without air conditioning but using high ceilings, fans, and natural ventilation. In cold climates, heavy masonry stoves or, when possible, hydronic boiler–operated radiators that operated a few hours a day provided the needed heat. The thermal mass of the building served as the "heat battery," releasing energy over the period without energy supply, of course in proportion with the decreasing indoor temperature.

The walls in these buildings were airtight because of exterior and interior, field applied, lime-based plasters. Lime develops strength slowly, allowing settlement of walls while maintaining adhesion and continuity, thanks to its elasticity lime-based plaster also resists macro-cracking. Plaster and masonry walls were serviceable and easily repaired. Double-hung windows (or casement in Europe) were heavy, well-integrated into the masonry walls, and repainted every few years with oil paint. Although not perfect at resisting infiltration, small window areas limited their impact on the thermal performance of buildings.

Because of the slow thermal response of these buildings to the exterior climate and to the building heating systems, the indoor temperatures would vary between periods of comfort and discomfort as the exterior conditions changed. Thermal zoning was simple, with devices such as radiators controlled simultaneously by users and by the supply of heat from boilers.

Building science: explaining the process deficiencies

In the past, architects had a holistic view of occupants and the building, this is not the case today. In 1900, there were about 500 different construction products to choose from in the Swedish market, by 1950 the number increased to about 5000 and today there are 55,000–60,000 different products. This highlights the growth of specialized expertise and the fragmentation of design process that has erased the capability of an architect to control all stages of the design and construction process. Yet today, more than in the past, the architect must be able to produce an integrated product satisfying all occupants and all aspects of building performance.

In the past, moisture has not been a serious consideration because masonry is resilient to moisture (unless exposed to freezing and thawing). The masonry wall could wet and slowly dry and thus temper large changes in moisture introduced by climate or people. Knowledge of water vapor transfer and condensation preceded the moisture problems introduced by use of thermal insulation in frame walls. Scientists knew about diffusion theory and the calculation of condensation as early as 1982. While the scientific understanding of moisture remained within the building physics community, North American buildings were developing moisture problems, especially in wood-frame housing.

In 1958, Glaser described a method to calculate condensation of water in layman's terms; while the concept was not novel, it was simple. As a result, moisture transport by diffusion became a worldwide accepted concept, and the building community had a new way of rationalizing moisture problems.

Buildings in 1950–2000

As more insulation was added to walls, one could also increase the area of glazing. Increased glazing area resulted in increased air leakage. While the opaque envelope offered improved insulation, radiative heat exchange from the sun in summer or cold snow in winter could cause discomfort to occupants near those large windows. The modern envelope lacked the mass of the old envelope, and it could not offer the climate mitigation effects of the former. Mechanical systems were called to the rescue. Technology evolved to provide full, centralized, forced-air HVAC systems that could provide all year heating/cooling and dehumidification. Thermostatic controls for these systems operated with tight set points, one for the whole summer and another for the winter period. Effectively, the HVAC system became the only means for controlling indoor environment.

From a science viewpoint, a lightweight, fully-conditioned building eliminated all the advantages that had existed with the old masonry buildings. The effects of thermal mass are greatly reduced when interior temperature is constant. Without thermal mass, the HVAC system must deal with peak loads in heating and cooling, and the delivery system size must be increased to deal with peak loads.

Another significant problem came with zoning of these systems. Lightweight, heavily glazed and leaky walls create a multitude of microclimates within the same building and thermostats covering large zones could not provide good control. Furthermore, zones in large buildings are designed as if the air was static, whereas thermal stratification, multizonal air flows, and other factors caused poor operation of systems in which ventilation was combined with heating/cooling. Finally, while people react to a complex set of environmental parameters, including the dry-bulb temperature, mean radiant temperature, relative humidity, and velocity of moving air, the HVAC systems operate on the dry-bulb air temperature in a selected place.

The art of forgetting the lessons of the past

Today, electrical grids barely cope with the energy demand during days and have large energy surpluses during the nights. We use a lion's share of energy to cope with peak loads in heating or cooling while we could design and operate buildings with very small energy peaks.

The reason why we do not use available technology is simple, tradition. We simply **got used to a wrong tradition.** With inexpensive energy there was no initiative for using science and all needs of human comfort were to be satisfied by air conditioners of different types. Either an expensive central air system (with simultaneous heating and cooling channels to mix in each room at will), or inexpensive air conditioners placed in windows. The latter were, with time, replaced by air-to-air or split heat pumps. Observe that all these mechanical devices replaced the art of designing the building with the view to maintain good indoor climate.

Now, we need to start again where we were about 100 years ago, when buildings responded very slowly to the exterior climate. Old buildings were leveling out much of day–night shifts in temperature and thus tempering the building's interior climate against temperature extremes occurring outside. The thermal mass of the building served as the "heat battery".

Observe that today, we can easily design highly insulated airtight building to have 8 hours of thermal lag-whether construction is wood, steel or masonry. Let us be clear, we are not talking about reducing total energy needed for a building, we are talking about eliminating thermal and humidity peak loads so that buildings use energy during the night and let industry-use it during the day time

3. OPTIONS TO IMPROVE THE SUSTAINABILITY OF BUILT ENVIRONMENT

It is obvious that one needs to restore balance between building enclosure and mechanical devices; and stress the input of building enclosure. Nevertheless, selecting some aspects of envelope performance such as excessive airtightness and super-insulation makes little sense in economic terms. Sustainability means equilibrium between three different areas, social, environmental and economic. [5]

4. THE CHANGE IS NOT LIMITED TO ENERGY

Sometimes we talk about the third industrial revolution. The first caused using steam power, the second brought by the electricity and the third being a distributed energy production and IT technology used for its management. How does the road from buildings that are losing 40 percent of the national energy to the buildings being a net energy producer - looks like?

In 2008 American conference on building enclosure science and technology (BEST 1) we used a subtitle "energy efficiency and durability of buildings on the cross roads".[6] In 2015 in the same conference (BEST 4) we used a subtitle "performing architecture" implying that we have finally learned how to design building as a system not as an assembly of individually crafted pieces.[7] Building as a system is designed from day one by all the experts involved in the design process to consider interactions of mechanical and environmental systems. Below we exemplify some interactions. Figure 2 shows that maize of ventilation channels that create convective cooling with geothermally conditioned air provides air conditioning for a selected area in the mound. Termites use the fact that large quantity of heat is involves in latent transfer of thermal energy when the direction of heat changes between morning and afternoon (see Figure 3). We also are learning to use so called active capillary layers to move condensed water from the place of condensation to the wall surface and to integrate ventilated cavities in the wall with phase changing materials. [8]

Figure 2. Termites can maintain a reasonably constant temperature and relative humidity while ambient conditions vary dramatically. Left side from Africa shows ventilation with geothermal cooling. Right from Mexico evaporative cooling.

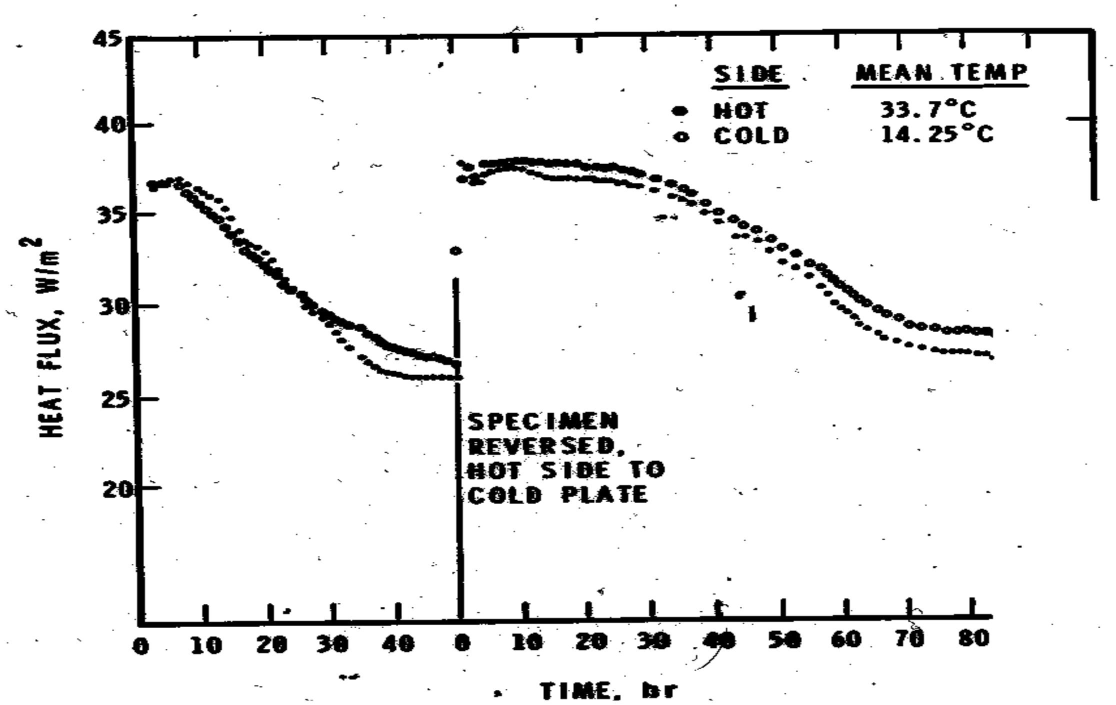

Figure 3: Laboratory test on moist sealed specimen shows that a large quantity of thermal energy is involved in the phase change when the direction of thermal gradient changes.

Harnessing the power of these interactions is the second step in design of the future building. Effectively, the process of design for future buildings involves three distinctly different stages:

1. Passive house stage
2. Geothermal and solar thermal applications for ventilation, heating, cooling and preheat of domestic hot water
3. Use of photo-voltaic technology for generating electricity

The label for the future buildings

There are variety of names that describes the goal of the new technology, namely, low energy, zero energy, near zero energy, net zero energy, positive energy. A better name of Passive House was introduced without adaptation to different climates. Furthermore, it does not include the geothermal and solar engineering and it did not understand the role of modern ventilation. No efficient Passive House can be built without advanced mechanical ventilation system because the high efficiency introduced by the passive house approach will create different climates in different rooms. In simple words, effective passive house design either restricts size of windows or requires heating and cooling in the same time.

We accept the need of simultaneous heating and cooling and advocate use of large windows e.g. 40% of the south facade area and therefore our name – Environmental Quality Management postulate that occupant is in the center and the technology is to keep the occupant comfortable and make buildings efficient. We may vary technical criteria of acceptance for different climates, but the process of optimization is the same in all cases. The name also implies that passive house can be a platform to which other renewable energy sources are attached with the view to achieving the required indoor environment quality.

5. CLOSING REMARKS

Several practical trends and scientific observations merged in the concept of passive house but the narrow focus on technology alone can only be considered as step one. Needs of occupant must be the starting point otherwise the occupant will open windows and destroy all "technological advantages". On the other hand, if we satisfy the occupant need for large windows, individual ventilation on demand and built in walls, ceiling or floor hydronic heating/ cooling systems that operate at low temperature without noise and visible heater or ventilators, we are making progress towards sustainable buildings.

As an example, consider a central air delivery system that lead outdoor air to a mechanical room, where the air condition by going through a water tank before the dust is filtered and air dehumidified. The air handler and ducts placed at the staircase deliver pressurized air to each dwelling through an adjustable valve placed above the exterior entry door. The valve is adjusted to provide the required rate of fresh air flow at the prescribed level of pressure above that on the staircase. The air pressure in the staircase is assumed to be equal to the exterior and is considered as the baseline for the management of interior air quality. Exhaust points are in bathroom, kitchen hood and above each window in the exterior walls. All exhausts are operated with double controls, manual and system-operated; when additional ventilators reduce the level of pressure in the dwelling the ventilation rate will be increased. This of course, requires a high degree of air tightness.

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A PATH TO NEAR ZERO ENERGY BUILDINGS IN THE FUTURE

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Abstract

More than forty years of experience with passive houses and other developments in the mainstream of housing forms the basis for extrapolation to the future. We have observed a change in the design approach. Instead of improving the separate pieces of the puzzle, one starts with establishing a conceptual design of the whole system. After determination of the basic requirements for the whole system, and finding the specified requirements for the assemblies, one may select materials to fulfill these requirements. We also have observed. growing integration of mechanical and construction subsystems.

In the design of the integrated construction process, a number of factors such as: climate, cost and other socio-economic conditions, vary. As a result, one must talk about a set of design principles [1], rather than a description of a specific technology. In this paper the environmental quality management (EQM) technology (Bomberg et al, [2]) was selected for such a discussion.

Keywords: building physics, building science, system integration, thermal upgrade, thermal rehabilitation, ventilated cavities, multi-layered walls, hygrothermal insulations, environmental quality management

1. A TRANSITION TO SUSTAINABLE BUILDINGS

The integrated design process (IDP) differs from traditional design where a building is ‘‘engineered in pieces’’ by experts working individually. IDP is the modern way to realize ‘‘performance architecture’’ that is, design with a view to field performance. In this process, however, all members of the design team must have some knowledge of building science to translate general user requirements into the objectives that define the performance of the end-product. While architects continue to have a supervisory and integrating role within design teams, they must understand building science (physics) to be able to communicate with other experts in the design team.

Unfortunately, many Universities teaching building physics focus on standards and differential equations instead of functional analysis and the logic needed to arrive at an integrated system. Universities should teach the principles of design and interaction between subsystems and analyze case studies to demonstrate both failures and successes. For this reason, we will continue using the North American term (as defined by the late Professor N.B. Hutcheon) "building science" to characterize the knowledge needed to predict the performance of a building under service conditions.

The imperative of near zero energy buildings (NZEB) is a comprehensive environmental control issue that impacts the design process. This design process includes the following:

- Economic considerations, including energy efficiency of the building enclosure and understanding of interactions between thermal, water vapor/liquid, and air flows.
- Durability of materials and assemblies that have been evaluated for long-term thermal performance aspects that include the costs of operation and maintenance.
- Ecological considerations that include comprehensive environmental control in building, addressing all parameters of indoor environment such as health and fire protection, acoustics, thermal comfort and air quality.

All members of an integrated design team must understand how the combined action of HVAC and the design of the building enclosure impact the indoor environment. To accomplish this ambitious objective, a design team should include: a structural engineer, a mechanical engineer, a building scientist capable of hygrothermal and energy modeling, a construction-cost estimator, and an architect to provide leadership and coordination.

1.1. WHAT IS MISSING IN THIS TRANSITION?

Including a building scientist for hygrothermal and energy modeling is now a necessary input from building science to the architectural design process. Since the 1980's, building science has advocated integration of testing and modeling. Yet, as discussed below, the expectations are larger than the building scientist can deliver.

1.1.1 A new paradigm - integrated design

A new EU call for research on sustainable cities talks about both new buildings and retrofitting of existing buildings for sustainable and livable cities. We postulate that a new paradigm of thinking is needed to accomplish the goals of the new program. Why?

Throughout the history, building design was based on tradition. Since 1950, air conditioning became so economical that all comfort requirements were satisfied by air conditioning. The point that brought this fact into the public view and we call "the energy conundrum" resulted from an observation that in 2002 and 1929 large residential buildings in the city of Vancouver used the same amount of total energy [3]. This highlighted the role of thermal mass and an adaptable comfort approach that prompted a re-examination of the approach to the design of low-energy buildings.

Reduction in the use of air conditioning was an obvious goal. The strategy is the use electrical energy in buildings mainly at nights with energy savings enabled by the passive house measures along with geothermal and solar engineering. Examination of different nature-based solutions suggested a focus on the indoor environment. We realized that the previous attempts to use large amounts of thermal mass and night setback of thermostats did not produced the energy savings, because these changes were not related to the weather changes. To save energy the system must be based on active controls and therefore the term of **environmental quality management** (EQM) was introduced.

Two aspects of energy management must be recognized:

- Spatial energy management of the built environment
- Buildings with the environmental quality management (EQM)

The first one is well known in the architectural community, while the second is not known at all. Therefore, the first step towards the sustainable cities should be to introduce environmental quality management (EQM) concepts to new buildings and to the retrofitting old buildings. To ensure the adaptability of new technology to local climate and socio-economic conditions, a cost-benefit analysis that is based on comparison with a reference building is needed. Some countries, e.g., Poland, with nearly 1.5 million dwellings built with large panels or blocks [4] and China with millions of concrete buildings, need an affordable technology not only for energy reduction but also for improving the indoor environment in old buildings.

Technology proposed as EQM not only changes the paradigm of thinking, but it also integrates HVAC with the building structure, uses transient but controlled changes of indoor conditions to control the use of thermal mass and moisture buffers, introduces recent developments in algorithms for system optimization and effectively reduces CO_2 emissions and energy consumption while maintaining a high-quality indoor environment. In a nutshell, over the last 5000 years society has been improving each piece of the puzzle before putting them together. This time the objective will be to design an ultra-efficient building system and at that stage configure the pieces so that they would fit together in the already designed system. This is the essence of the EQM technology.

1.1.2 Link improved hygrothermal models with energy modeling

Multi-directional heat-flow patterns created by thermal bridges at corners, wall-window or wall-floor connections and response to transient weather conditions require thermal modeling. Moisture response of airtight, highly insulated wall requires also the hygrothermal modeling. Unfortunately, the current heat, air and moisture modeling may only be used for prediction of long periods e.g. yearly changes in water accumulation in the building enclosure [5]. For shorter periods it leads to questionable results particularly if there is air flow inside the walls.

Inter-zonal air-flow models are important for estimating the impact of air flows on heat, water vapor and pollutant transport but they do not communicate with hygrothermal models. The inverse solutions of inter-zonal air flow models produce a multitude of solutions and therefore require additional information. This creates the situation in which an effect of air flows on the thermal performance of a ventilated wall is difficult to establish.

In particular:

- We do not know the boundary conditions for air flow as they are influenced by other spaces in the building [6]
- Some paths of air flow are unknown because they are not part of the design,
- There is both natural and forced convection in wall ventilation channels,

- The film resistance for water vapor flow changes with the water concentration in the material layer adjacent to the air layer. As most of the hygrothermal models neglect capillary hysteresis it results in errors in the distribution of water in the material.

The lack of good information about the boundary conditions for air transport in the real buildings leads to large differences between laboratory and field tests for airtightness. The criterion for acceptance of a wall under service conditions is 10 times greater than that for the same wall when measured in a laboratory with one-dimensional air flow under controlled and known boundary conditions.

In summary, there is a systematic gap between the actual field performance and that calculated from computerized tools. Furthermore, all currently used of hygrothermal models are parametric i.e., they provide valid comparisons between different calculations. These models should be improved to deal with the real-time solutions and linked with energy models. These improved hygrothermal models should also include information on air leakage through the walls and estimate the impact of air and water-vapor transport on energy. This would also improve the reliability of energy models.

Incorporating hygrothermal models into energy calculations is important because moisture buffering not only modulates the indoor relative humidity, but it also reduces peak-energy loads [7, 8]. Uncontrolled humidity affects both indoor air quality and the durability of building materials. Enhancement of hygrothermal modeling is necessary because water is a phase-change material (PCM) that affects both indoor environment and heat transfer [9].

1.1.3 A need for advanced control systems

The best building enclosures and HVAC systems will not deliver high energy efficiency and optimized indoor environment conditions under variable climatic conditions without smart operating systems. EQM technology includes developemnt of an integrated control system that performs optimization of different sub-systems such as the water-based heat pump, solar thermal and photovoltaic panels, air intake ventilator, pre-heat or pre-cooling of the ventialtion air, modificaton of humidity levels, heat exchangers for the exhaust air; instantanous delivery of hot water (or to a hot-water tank), cold-water tank and rain and/or gray-water tank, illumination, control temperature in several spaces taking into account their functions. The use of surface heating/cooling features that are integrated with building partitions will modulate the contribution of thermal mass to reduction of energy consumption. With an adequate steering algorithm based on the history of use and predicted values of the outdoor conditions, optimization of energy use for any type of use and geographic location is possible.

The above list explains why we changed the name of the building automation control (BAC) system to highlight the process of optimization, namely BACOS. The BACOS includes two sub-systems: (a) a specialized metering system to study changes in the selected parameters at specific locations inside walls or spaces, and (b) the traditional building management system that controls processes in walls, windows and spaces to ensure the required quality of indoor environment. These two sub-systems are interrelated in both equipment and software applications.

The need for BACOS is two-fold; (1) to improve the capability of discovering malfunctions in separate units or subsystems, (2) to introduce self-learning functions of the steering algorithms to permit optimization of these sub-systems in the post-occupancy period. Sub-system (a) includes dedicated software that aims in improving quality of the indoor environment and energy efficiency. To optimize performance information is collected over four different seasons, i.e., a minimum of one year of post-occupancy. The information collected from this specialized metering system will lead to development of a guide for the process of evaluation and optimization.

Previous work [10] showed that optimization during building operation is a very important component for number of reasons:

- In different rooms one needs to heat and cool at the same time
- Additional sensors must be placed in critical places as the backup for the control system, there is a need for early warning when cooling generates water condensation.

While the charging of motor vehicles and PV systems are now common practice for residential properties, any combination of AC and low-voltage DC in the same grid may impact the frequency distribution of electrical current and associate with it loss of quality in the energy systems. Thus another, yet not discussed, function of the BACOS is to ensure the quality of electrical current.

1.2. SUMMARY OF THE TRANSITION TO SUSTAINABLE BUILDINGS

The EQM approach provides a vision of the integration of buildings with their environment. Cold-climate buildings must be designed as clusters using the ground between them for geothermal applications. It could be a block enclosed by four adjacent streets (Atelier Rosemount [11] in Montreal, Canada) or a free settlement. Both thermal storage and rain-water management must be included in the design of city clusters.

Progress in district heating resulted in lowering of the temperature of delivered water to a minimum and function as a sink for a dedicated heat pump. Some cities e.g. Montpelier (Vermont, USA) are already switched to resource combinations producing yearly zero energy.

While housing research funding (Building America in the US, Horizon 2020 in Europe) focused on new buildings, but old buildings because of their select locations, can be of much higher value if we change the thinking paradigm. Since 1946, we have been fascinated by glass and air conditioning. The Energy Conundrum [12] highlighted the role of thermal mass and the adaptable comfort approach that prompted a re-examination of the approach to low-energy building design. This includes reduction in the use of mechanical air conditioning; use of electrical energy mainly in the night and combine the passive house measures with geothermal and solar engineering. We believe that nature-based solutions will not only support more resilient responses to climate change, but also provide a stronger economic base for adaptation of the new construction technology.

2. DESCRIPTION OF THE EQM TECHNOLOGY

There is no conflict between building science and codes because the latter specify the minimum requirements and experts design for requirements much higher than the minimum. Furthermore, codes deal mainly with safety and health while the remaining categories are left for a qualified designer.

2.1 LAYERS IN THE EXTERIOR WALL

For the sake of discussion, consider four layers in any exterior wall; (1) exterior cladding (façade), (2) exterior continuous insulation, (3) wind load transmission (middle) layer, and (4) interior trim and finish. The facade layer controls fire, rain, air and water vapor entry, light, sound, solar radiation, and vermin; the exterior continuous insulation controls heat, and controls air, water vapor, and sound transport; the middle layer provides strength and rigidity but also impacts air, water, and vapor transport. Finally, the interior trip and finish layer controls fire, air, water and vapor movements, and sound transmission.

(1) The facade layer is either directly attached to the structure or be a rain screen with air gap (like a brick veneer) to provide rain control. In this case, the next layer, on the interior side of the air gap, should be a thermal insulating composite with a surface that fulfills all of the facade requirements.

(2) Thermal insulating composites must also affect acoustics. This means that if concrete is not used for the structural layer, then the finishing surface on the thermal insulation must contribute to the attenuation of structural vibration. Today, however, the most popularly used materials such as mineral fiber insulation with wind protection or polystyrene boards with taped joints do not fulfill all of the requirements for air, water vapor, and vermin control.

(3) The selection of the loadbearing layer depends on the height of the building but light-weight concrete that may or may not have reinforcement is a suitable solution for a low- rise buildings.

(4) The requirements for airtightness and fire resistance of interior finishes are fulfilled by gypsum board that is water-vapor permeable but does not have any moisture buffer capability.

In a nutshell, one may observe that some multifunctional materials are better at controlling acoustics, protecting thermal insulation from air ingress or providing fire protection. There is, however, a new category of materials that function like traditional lime plasters or wood planks, namely materials with a moisture-buffering property. These materials are needed for the next generation of low-energy buildings.

2.2 HEATING / COOLING SYSTEMS IN INTEGRATED EQM BUILDINGS

Coupling of thermal mass and large surfaces of water-based heating or cooling systems that use water-based heat-pump technology has been recommended [13]. This type of heating/cooling is more efficient than air-borne systems [14] or other air-based heat pumps, because of the large thermal mass of water that is present in the system. EQM technology requires simultaneous presence of heating and cooling and for this reason water-source heat pumps are recommended. Having both cold and hot tanks one can easily organize hydronic heating supported by solar thermal panels. Incidentally, those panels can be designed to have shading devices on the wall exposed to solar radiation and be folded down in the winter.

To achieve better control of the thermal mass contribution, one uses a hydronic heating on the surface of the interior walls. Evaluating heating/ cooling panels for retrofitting of an old building in Nanjing, China [15] found that the impact of radiant panel location is significant as illustrated in Table 1.

Table 1: Effect of radiant panel location on dynamic energy demand

Panel location	Heating Demand (GJ)	Cooling Demand (GJ)
Wall surface	58	24
Floor surface	98	31

These values were calculated using Energy plus with film coefficients typical for horizontal and vertical orientations, see also Fadiejev [8]. Hu also found that to achieve more than 90% efficiency in the desired heating one must use XPS insulation with a minimum thickness of 30 mm or when using EPS, one must increase the minimum thickness to 40 mm (to achieve thermal resistance of about 1 (m^2K)/W). Typically, temperature changes of one degree per hour in dynamic operations that last a minimum of six hours a day (during either summer or winter) permits maintenance of occupant thermal comfort. Experience from other advanced zero energy buildings [15] indicates that traditional air-mixing methods are not effective in equalizing the temperature differences between rooms. We propose, therefore, additional measures to achieve the dynamic temperature equalization:

- Individual ventilation on demand in rooms with solar input
- Use of a hybrid ventilation system with overpressure of the supply air.

Use of air overpressure in the indoor space will also improve management of moisture in the walls.

2.3. HYBRID VENTILATION SYSTEMS IN THE EQM BUILDINGS

Use of cold and hot tanks for water-to-water heat pumps permits pre-conditioning of outdoor air to within a few degrees of the required room temperature and subsequent air filtration and dehumidification. Clean air is then mixed with a predetermined fraction of clean, return air (Romanska-Zapala et al [18]) and sent to each dwelling or a designated thermal zone with 10 Pa over pressure. Kitchens and bathrooms in each dwelling have a separate, manual or automatic (for night cleaning) operated exhaust. Furthermore, individual ventilation-on-demand is installed at one window in all solar-exposed rooms.

Sending supply air with overpressure permits inducing air flow to points of the exhaust and operation of natural ventilation driven by the pressure difference in the space. Furthermore, it permits a break in operating exhaust ventilation. The time of operating for fresh-air delivery, exhaust ventilation delivering the return air to clean air handling unit and natural ventilation will be included in each system but experience from the High Environmental Performance House [10, 14] showed that fresh air may be delivered only for 20 minutes each hour.

Bomberg [9] highlighted that a ventilated air gap within the wall may be used to introduce a difference between the heat flux in different layers within the wall. This concept is not new, it was the basis of double façade approach used to refurbish old concrete buildings in East Germany. Studies on dynamic walls in CRIR (Centre Recherché Industrielle de Rantigny), France, in the 1980s, showed that the difference between static and dynamic performance of the wall is negligible. So, if one uses indoor air for cavity ventilation the wall may act as the heat exchanger and the energy loss is minimal. Nevertheless, the ventilation concept is useful for moisture management within the wall [7].

2.4. COMMISSIONING OF THE EQM BUILDING

The quality assurance (or commissioning) must also be considered during the design and construction of the building. From the construction practice one can formulate two air-flow criteria that must be met during the building construction:

- *Air flow between two adjacent floors*

  Criterion is 0.3 ACH for the floor at 50 Pa pressure difference. To measure the floor connectivity, one may use two blower door systems or a perturbation method combined with inter-zonal air-flow models. If doors separating staircase from the corridor have a small opening that can be opened or closed tight, the measurements are much simpler.
- *Air flow from the floor to / from outdoors*

  The criterion for air leakage and ventilation through exterior walls (if measured on each floor) is 1.5 ACH. This is thought to correspond to the airtightness of 0.8 L/(m^{2}s) at 50 Pa pressure difference. We postulate a criterion that is much higher than that for passive houses in Germany for a number of reasons [6].

For the final quality assurance, we recommend *on the basis of experience* that the following parameters be tested for indicating a set of benchmarking values for the expected performance:

- *Cooling time in heating failure*

  Benchmarking criterion: with outdoor temperature (t_o) between 0 and minus 3 ^oC, the period of cooling from t_i= 20 ^oC to t_f =14 ^oC should not be shorter than a prescribed time, e.g. eight hours. If the same temperature difference is used but different room temperature is applied, one can perform this test using dimensionless temperature $(t_f – t_o)/ (t_i – t_o)$
- *Heating effectiveness.*

  Benchmarking criterion: temperature increase from 15 to 20 ^oC when the ventilation system is operating should not take more than a prescribed time, e.g. 120 minutes.
- *Estimating the age of indoor air*

  Benchmarking criterion: the age of air in the middle of a room calculated as the average of three measured values should not be higher than 70 minutes implying that the whole air volume is exchanged in one hour.
- *Effectiveness of air re-circulation*

  Benchmarking criterion: increase in one step the concentration of CO_2 in one room supply channel to 50 +/- 5 percent for one minute and check if after 20 minutes. The difference in this and two adjacent rooms should be less than 10%. This is an important test and should be included in the list of required commissioning tests.
- *Risk for interior surface condensation*

  Benchmarking criterion: using an IR camera when exterior temperatures are below 0 °C, measure temperatures at the floor, corners of the exterior walls, on the structural beam over the window, and all possible locations of thermal bridges. With inside air temperature of 20 ^oC, the surface temperature should not be lower than 14 ^oC. If the exterior temperature is much lower than -3 ^oC one may use the concept of dimensionless temperature as discussed in the cooling test.

2.5 DISCUSSION ON BUILDINGS WITH EQM

Elimination of the summer overheating, good ventilation of indoor space and large windows exposed to sun are encouraged by many architects in response to the wishes of the occupants. Glass connects occupants with the outer world and is here to stay. Thus, an engineer has to solve the technical problem instead of trying to go backwards and prescribe small windows to avoid the summer overheating. We know that large windows expose occupants to asymmetric heating and cooling surfaces and dynamic changes in air temperature. To alleviate discomfort, we need to re-examine two sets of control issues, namely:

- Dual control for water-to-water heat pump to address both heating and cooling required to compensate for the summer overheating,
- Re-circulation of the ventilation air to equalize temperature in sunny and shaded areas

The complex of factors interacting on indoor environment is presented in Figure 1.

The framed area postulates the need of individual ventilation in each room with large widow and large area of heating /cooling devices such as wall surface behind which we have hydronic heating/ cooling devices. This is a simple conclusion from the basic premises of indoor climate design but note that this simple solution addresses eight, uncorrelated with each other dimensions of indoor environment: visual comfort, indoor air quality, personal control of IAQ, noise control, connection to the outdoor environment, individual ventilation, thermal comfort, thermal and humidity buffers to reduce rapid interior changes. Those are the critical elements for comfort in work or home, building durability and satisfaction, productivity and health.

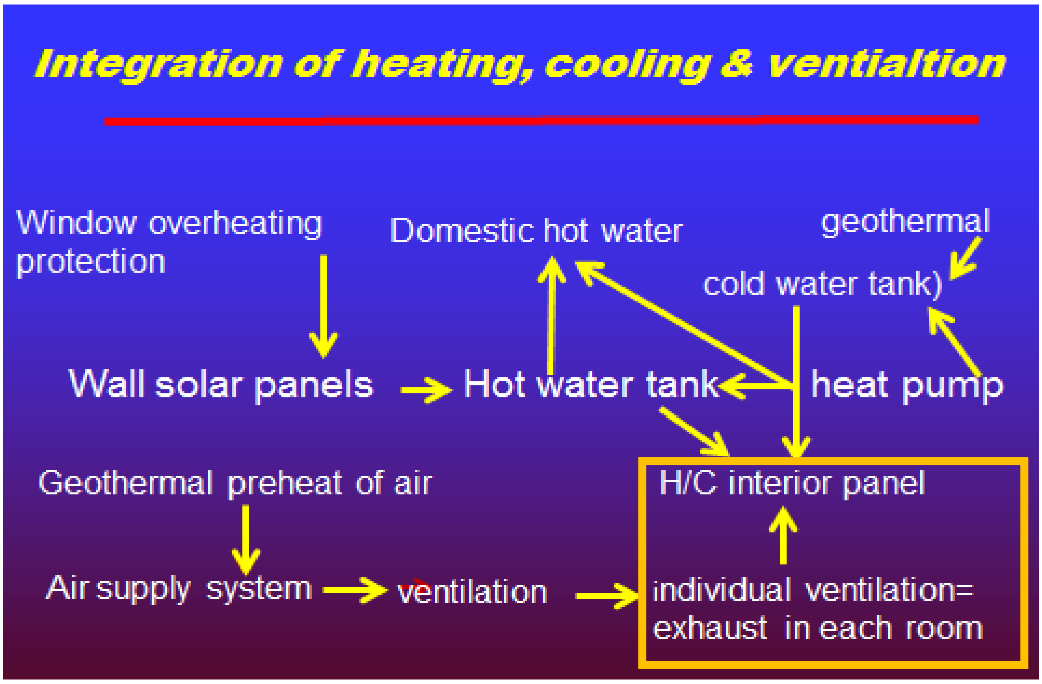

Figure 1: Two fundamental requirements that are shown in a frame in the right, bottom corner is the key to the process of integrated design of environmental control

3. CLOSING REMARKS

Several practical trends and scientific observations merged in the concept of passive house but the narrow focus on technology alone can only be considered as an interim step. When an occupant opens windows during inclement weather, he/she may destroy all the "energy efficiency of the technology". The history of building science from its beginnings almost 100 years ago up to the development of net zero energy buildings implies that the next generation of buildings will be designed with the indoor environment as the starting point. If we satisfy the occupant need for large windows, individual ventilation on demand, hydronic heating/ cooling systems built in walls or floors we are making progress towards sustainable buildings. Furthermore, when out heating/ cooling system operates at low temperature without noise and visible heaters or ventilators we have basis for the next generation of buildings.

We highlighted that a central air delivery system must deliver cleaned and dehumidified air. Exhaust points in bathroom, kitchen and in the exterior walls are operated with double controls, manual and automatic to maintain the required ventilation rate in the dwelling. Of course, a high level of thermal insulation and air tightness and several technical features of the EQM technology can smoothly interact only with the assistance of advanced control systems.

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PARAMETER ESTIMATION FOR HEAT CONDUCTION IN CRUMB-RUBBER MODIFIED MORTAR: COMPARISON OF DIFFERENT OPTIMISATION METHODS

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Abstract

Parameter estimation of heat conduction properties of construction materials plays an important role in green building and sustainable design. Based on a heat conduction problem solved through a numerical method, an inverse problem rises. The thermal conductivity of each component of crumb-rubber-modified mortars (quartz sand, crumb rubber, cement paste and air void) was estimated though three methods of minimization of the least-squares norm: the Levenberg-Marquardt method, Nelder-Mead Simplex Method, and Genetic Algorithm. The performances of these methods were compared in terms of the computational time with different number of parameters (from 1 to 4) and two accuracy levels for stopping criteria. These methods were able to converge to the parameters values, in good agreement with the literature values. Because of high efficiency and accuracy, the Levenberg-Marquardt method outperformed the other methods.

Keywords: parameter estimation, crumb-rubber-modified mortar, Levenberg-Marquardt method, Nelder−Mead Simplex Method, Genetic Algorithm

1. INTRODUCTION

Crumb rubber recycled from waste tyres can be used as a partial substitution for natural aggregates in conventional concrete. Crumb rubber gives the least thermal conductivity and entrains amount of air pores in cement matrix, which directly related to the improvement in thermal insulation properties of concrete [1][2][3][4]. Based on the knowledge of the initial and boundary conditions, as well as the thermophysical properties presented in the formulation, the calculation of the temperature fields in multi-component material constitutes a direct problem of heat transfer. We note that many analytical techniques have been used to solve heat transfer problem [6][7][8]. Later the development of numerical models achieves a major step for this purpose [9][10][11][12][13]. Moreover, a high precision in the parameters involved in the model, such as thermal properties of components [14][15], surface conditions [16] and energy production [17], is essential to ensure a good modelling results. However, determining these factors require a series of highly time-consuming measurements. Besides, there are limited studies providing accurate input values.

Focusing on this issue, several studies appear in the literature dealing with the solution of inverse problems of heat transfer based on the knowledge of the temperature measurements. Wagner and Clauser [18] estimated the thermal conductivity of thermal capacity of ground by the minimisation of the objective function, which is represented by the squared differences of borehole heat exchangers corresponding to the reference and modified conditions. Mejias et. al. [19] used Levenberg-Marquardt (LM) method [20][21] and Conjugate Gradient method [22] to apply the identification of the thermal conductivity components of an orthotropic solid, and compared the performance of them in terms of number of iterations, CPU time and accuracy of estimated parameters. Fguiri et. al. [23] used LM to estimate the heating source strength and the heat transfer coefficient of parallel hot wire technique.

In this paper, we extend the analysis of our previous work [24]. Based on three-dimensional numerical meso-structure of crumb-rubber-modified mortar, the thermal conductivities of components were predicted. Three parameter estimation methods were used: (1) Levenberg-Marquardt algorithm; (2) Nelder−Mead Simplex Method, and (3) Genetic Algorithm [25]. Moreover, their performances was compared in terms of computational time and number of iterations.

2. STATEMENT OF THE DIRECT PROBLEM

The basic principle of this model is Fourier's law of heat conduction, which can be expressed as:

$$Q = -\lambda A \nabla T, \tag{1}$$

where, Q (W) is the heat flow rate by conduction; λ ($Wm^{-1}K^{-1}$) is the thermal conductivity of a medium; A (m^2) is the cross-sectional area normal to the isotherm; ∇T (Km^{-1}) is the temperature gradient. When Fourier's law is combined with the law of thermal energy conservation, the three dimensional heat conduction problem without internal heat generation can be expressed as:

$$\lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} = 0. \tag{2}$$

where, $\alpha=\lambda/(c\rho)$ (m^2s^{-1}).

Heat conduction takes place in z-direction from the hot slab to the cold slab. The other four sides of the system are ideal thermal isolated. Thus, there is not heat transfer between the system and the surroundings. Based on the analysis of a representative volume element (RVE) [26], the crumb-rubber-modified mortar is assumed as a homogenous material. Therefore, the effective thermal conductivity (ETC) λ_i of the mortar is equal to the effective thermal conductivity $\lambda_{i,z}$ calculated in z-direction,

$$\lambda_i = \lambda_{i,z} = -\frac{Q_z}{L^3} * \left(\frac{L+1}{T_{hot}-T_{cold}}\right). \tag{3}$$

where, Q_z (W) is the heat conduction rate in z-direction; L (m) is the side length of the system; $(T_{hot} - T_{cold})$ (K) is the temperature difference between the hot and the cold slab.

3. PARAMETER ESTIMATION

The direct heat conduction problems are concerned with the determination of temperature at interior points of a region with the influence parameters, like: boundary conditions, thermophysical properties of material and/or heat generation in a system. However, in most situations, thermal conductivities of components of multi-component compositions are difficult to determine by experimental methods accurately. In this case, the inverse heat conduction problem is raised [27]; that is, the determination of the thermal conductivity coefficient of each component in cementitious mortar: quartz sand λ_s, crumb rubber λ_r, cement paste λ_c and air void λ_a are regarded as unknown, while the other quantities appearing in the Eq.(2) are assumed to be known. The parameter estimation problem is defined as the minimization of an objective function that measures the difference between the model's simulations and the given experimental values, subject to constraints. The objective function considered in this research is to find $\lambda_{sum}(\lambda_i)$ to minimize:

$$F(\lambda_i) = [\lambda_{sim}(\lambda_i) - \lambda_{exp}]^T[\lambda_{sim}(\lambda_i) - \lambda_{exp}], \tag{4}$$

where λ_i is thermal conductivity coefficient of the i-th component, $F(\lambda_i)$ is the objective function, $\lambda_{sim}(\lambda_i)$ is the effective thermal conductivity of a composite, which is calculated based on the thermal conductivities of components and their spatial distributions. The unknown parameter λ_i (i = s, r, c, a) is obtained which can minimise the objective function. λ_{exp} is the experimental ETC of a mortar. The solving algorithms are described below:

(1) Levenberg-Marquardt gradient method

Matlab's built-in function *Lsqnonlin* is employed to implement Levenberg-Marquardt optimisation, which is aimed to solve the nonlinear underdetermined problem [28]. This method is more similar to the gradient-descent method, when the difference between the parameters and their optimal values are very big, and it acts more like the Gauss-Newton method when the parameters are very close to their optimal values [29].

(2) Nelder-Mead simplex method

Matlab's built-in function *Fminsearch* is employed to implement Nelder-Mead simplex optimisation. The principle of the iteration procedure is to compare the function values at *N* vertices of polygons or polyhedrons [30]. The vertex, where the value of the objective function is largest, is rejected and replaced with a new calculated vertex. After forming a new polygon or polyhedron, the same search is continued until the convergence criteria are met.

(3) Genetic Algorithm

GA is an evolutionary optimisation algorithm which is inspired by the natural process of "evolution of specie" and "survival of the fittest" principle [31]. The implementation of GA mainly consists of three steps: (1) coding and encoding the decision variables of a search problem into strings, (2) evaluating the fitness value of each string, (3) applying the genetic operators, which are selection, crossover and mutation, to generate the new generation of strings.

4. EXPERIMENTAL DESIGN

The *Lsqnonlin* and *Fminsearch* are tested with the initial point for quartz sand, crumb rubber, cement paste and air void as 2.8 ($Wm^{-1}K^{-1}$), 0.147 ($Wm^{-1}K^{-1}$), 0.685 ($Wm^{-1}K^{-1}$) and 0.026 ($Wm^{-1}K^{-1}$), respectively. Those initial values are expanded by ± 20% as a new starting point for each parameter to avoid local minima. For the GA, a roulette-wheel selection mechanism is used as a selection procedure, by which the probability of selected individuals is in direct proportion to their fitness value. In order to prevent the premature convergence, the linear fitness scaling is used. For the crossover process, the uniform crossover is used. Furthermore, the mutation procedure is based on the biological single point mutation and is applied with a low probability. Constraints on the parameter are: $\lambda_s \in [2, 7]$ [32][33][34][35], $\lambda_r \in [0.1, 1]$ [36][37], $\lambda_c \in [0.5, 1.5]$ [38][39], $\lambda_a \in [0.024, 0.026]$ [40][41], which are imposed by weighted penalty functions. The penalty function accelerates the exclusion process for worse individuals, which will be then replaced by the stronger individuals.

For all algorithms, the search process is stopped if the value of the objective function is lower than a given tolerance or the number of evaluation exceeding a threshold value (equal to 400). The computational optimisation time is the average of 10 numerical realisation tests. Numerical experiments are performed using Intel i7-6500U CPU 2.5 GHz with 8 GB of RAM and MATLAB (R2017a).

The computational efficiency is test in terms of different accuracies (1e-4 and 1e-6) and the number of unknown parameters. Moreover, the number of iterations of three methods was compared.

5. RESULTS AND ANALYZE

Table 1 shows a relevant result of parameter estimation for three parameters by using three methods. The value of air void was fixed (0.026 $Wm^{-1}K^{-1}$). They methods were used for the same starting points at each test, except the GA. The accuracy is calculated from 10 tests according to the previous research [24]. It can be seen that, *Lsqnonlin* has the highest accuracy. Because of a stochastic technique of the GA, its results show a lower accuracy.

Table 1: Parameter estimation results of three optimisation methods

	λs	λr	λc	
initial points	2.800	0.147	0.685	accuracy
Lsqnonlin	3.114	0.206	1.082	± 30.0%
Fminsearch	3.243	0.138	1.442	± 34.5%
GA	2.657	0.434	1.498	± 40.4%

Comparison of computational efficiency in terms of accuracy

Figure 1 shows the effect of accuracy on computational time. The computational time of three methods increases as the accuracy increases. For *Lsqnonlin* and *Fminsearch*, the accuracy level does not affect the computational time so much, however, the GA performs much more slowly, especially at a high accuracy level.

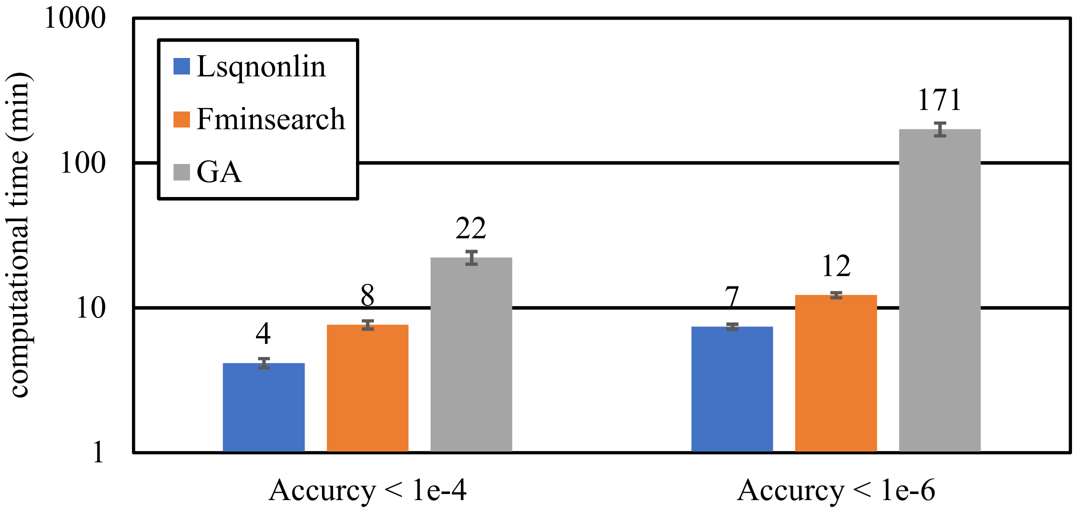

Figure 1: Effect of accuracy on computational time

Comparison of computational efficiency in terms of number of parameters

Figure 2 shows the results of determination of the computational time as a function of the number of parameters based on the accuracy level of 1e-6. Overall, the convergent speed of the GA is much slower than the other two methods. *Lsqnonlin* has the fastest convergence rate. This is because, the *Lsqnonlin* by using the partial derivatives of the objective function is able to quickly obtain a search direction and to find the approximate optimal results. For the GA, when the number of parameters to be estimated increases, the computational time decreases and is even shorter than that of one or two parameters. This is due to the different "degrees of freedom". In statistics, the number of degrees of freedom is the number of variables in the data that are free to vary in a statistical calculation. For the four-parameter-estimation, the degree of freedom is three, whereas the two-parameter-estimation has only one degree of freedom. As the number of parameters increases, the possible combinations of parameters improve, which let the GA find the optimal results more quickly. Hence, the GA is more appropriated to solve the problem with a high number of unknown parameters.

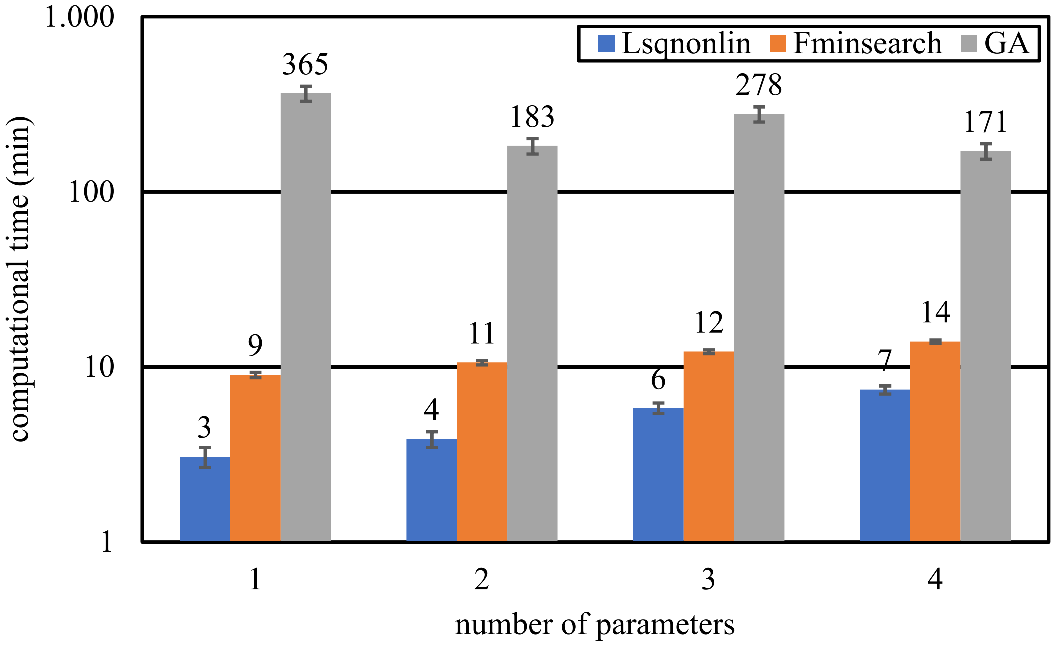

Figure 2: Effect of number of parameters on computational time

Comparison of number of iterations

Figure 3 shows the comparison of three methods from the number of iterations point of view with the accuracy 1e-6. The iteration denotes the number of steps needed to find successive approximations of local minimums. *Lsqnonlin* needs only 6 iterations. However, *Fminearch* needs 57 and GA needs 178 iterations. Moreover, the value of the objective function changes only after many generations in GA. This is attributable to the fact that a population is saturated with the same individuals and lacks diversity. Specifically, some individuals' fitness values are much higher than the average fitness value of the individuals in the current generation. This super individuals are easily selected and quickly account for a large proportion of the population. When the highest individuals' fitness reached a plateau, successive iterations can no longer produce better results. This is due to the rapid reduction of diversity in the population, which reduces the population diversity and convergence rate. Therefore, the performance of the evolutionary search is deteriorated.

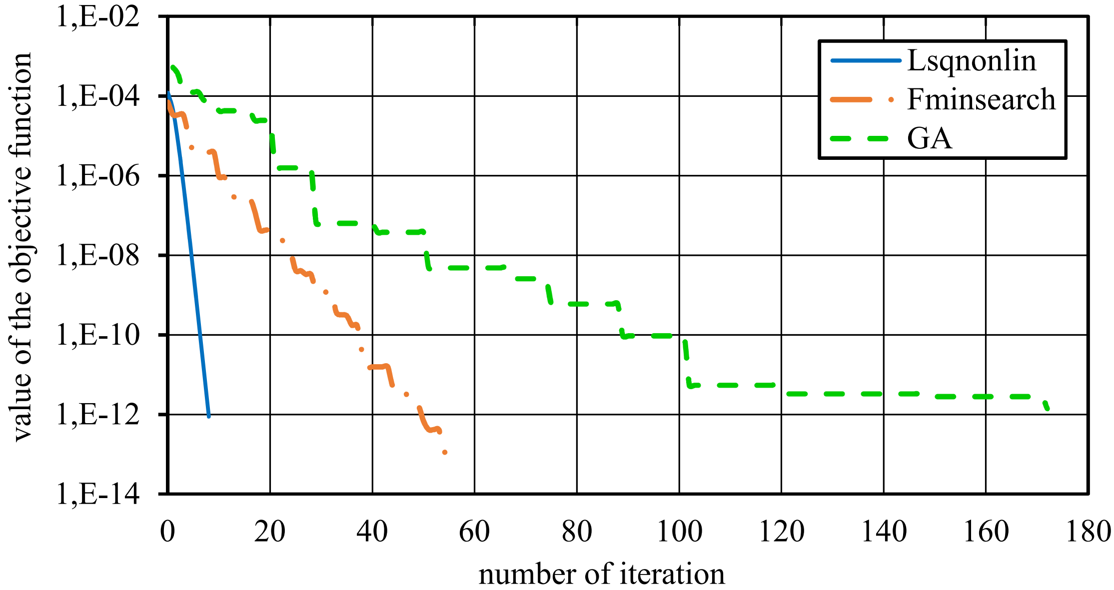

Figure 3: Effect of number of iteration on the value of objective function

6. DISCUSSION

By using the optimisation methods, it is important to check the normality of the time consumption and the accuracy of solutions. In general, the Levenberg-Marquardt method can find the optimal solution with a high accuracy in the fastest way regardless on the starting points. Since, its approach process follows a hill climbing technique. However, the weakness of this method is that the searching process is often gets stuck in a local optimum and can hardly escape from it. The approach process is based on the derivation of the objective function. The derivation of our objective function is easy to determine. Therefore, the speed of the algorithm is very fast. However, this method does not handle the problem with bound constraints. Moreover, this algorithm can converge with most of the starting points. Nelder-Mead simplex method is a direct search method that does not require calculation of a gradient but only based on the value of the objective function itself. The result with a satisfied accuracy can be achieved by setting a small tolerance value of iteration step. Compared with the Levenberg-Marquardt method, the Nelder-Mead simplex method is generally less efficient for solving large-scale problem. The GA cannot guarantee global optimality and it is not efficient to solve the problem with high accuracy. By comparing the accuracy of three algorithms it can be found that the solution of Levenberg-Marquardt method had a high accuracy, although there are no restrictions on the parameter.

7. CONCLUSION

In this study, the performances of three parameter estimation methods (the Levenberg-Marquardt method, the Nelder-Mead simplex method and the GA) for the identification of the thermal conductivity components of crumb-rubber-modified mortar were compared. The comparison was conducted in terms of the computational time with different number of parameters (from 1 to 4) and two accuracy levels (1e-4 and 1e-6). These methods were able to converge to the parameters values, being in good agreement with the literature values, even for initial guesses extended ± 20 %. Because of high accuracy and efficiency, the inverse heat conduction problem with the Levenberg-Marquardt method is considered most efficient method for the parameter estimation problem.

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SELECTION OF SUITABLE MATERIALS FOR THE DEVELOPMENT OF AN INNOVATIVE THERMOCHROMIC TROMBE WALL

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Abstract

An innovative system based on the Trombe Wall concept is under development to improve energy efficiency in buildings in different climatic conditions. The system takes advantage of the variable optical properties of a thermochromic mortar coating on the façade to optimize thermal behaviour. The mortar is based on the addition of organic thermochromic pigments to the cementitious matrix and is characterized by a high solar reflectance for temperatures higher than a nominal colour change value (Tc) and a low solar reflectance for lower temperatures.

Materials potentially useful for this innovative system were analysed in this work. As prepared thermochromic mortar specimens, mortar specimens coated with different UV protecting products and mortar specimens covered by glasses with different optical responses were exposed to controlled outdoor environmental conditions during several days. Surface and environmental temperatures were monitored during the experiment. Moreover, reflectance spectra of the samples were recorded every day early in the morning, when environmental temperature is significantly lower than Tc, and in the afternoon, when it is significantly higher than this value. Most suitable materials for the intended application were defined from an analysis of the optical and thermal properties of these specimens and their durability.

Keywords: Thermochromic mortar; surface optical properties; durability; energy efficiency

1. INTRODUCTION

Thermochromic materials are of interest in building envelops as they change from a dark colour with high absorption of solar radiation in cold environmental conditions to a light colour highly reflecting solar radiation in warm conditions. This behaviour has important aesthetic effects and, more interestingly, favours lower energy demand for indoor comfort in both extreme weather conditions [1]. With this idea in mind, a thermochromic mortar coating has been developed by our research group that is intended to be implemented in an innovative thermochromic Trombe wall based system [2,3]. According to previous work on thermochromic non-cement based materials [4], lack of durability of thermochromic mortar due to photo-degradation of the organic thermochromic pigments can occur. To avoid this problem, different solar protections may be considered.

This work studies the optical response of the thermochomic mortar in outdoor conditions in order to confirm its suitability as an external coating for the base wall in the Trombe wall design. Moreover, durability of this thermochromic mortar coating when exposed to solar radiation is studied with different approaches to avoid photo-degradation of its surface.

2. MATERIALS AND METHODS

Thermochromic mortar was prepared as described elsewhere [2] including a thermochromic pigment (a blue slurry) from LCR Hallcrest, with a colour change temperature (Tc) of 15 °C. This temperature was considered in order to assure that outdoor temperatures during the test vary from significantly lower temperatures during the night to significantly higher temperatures in the afternoon. The mortar was applied to five 10 by 20 cm concrete tiles to form a one-cm thick coating with a T-type thermocouple centred on each tile and close to the mortar surface. The five coated tiles were kept at laboratory conditions for a total curing time of 21 days, after which they were exposed to solar radiation in outdoor conditions for seven dry-sunny days. The tiles were positioned horizontally on top of a hollow wood structure to separate them from the ground (see figure 1) and located at an open area, so that shadowing from surrounding structures did not interfere with the test.

Different protection possibilities were considered for the durability test:

- two commercial UV-protecting resins from Artlux Europa (Ace SP Flex and Aliflex) each covering one mortar coated tile (top left and top right tiles in figure 1, respectively).
- five glasses with different optical response in the UV-VIS range covering different mortar areas (two tiles at the bottom line).
- uncovered plain thermochromic mortar coating (middle line) was also tested.

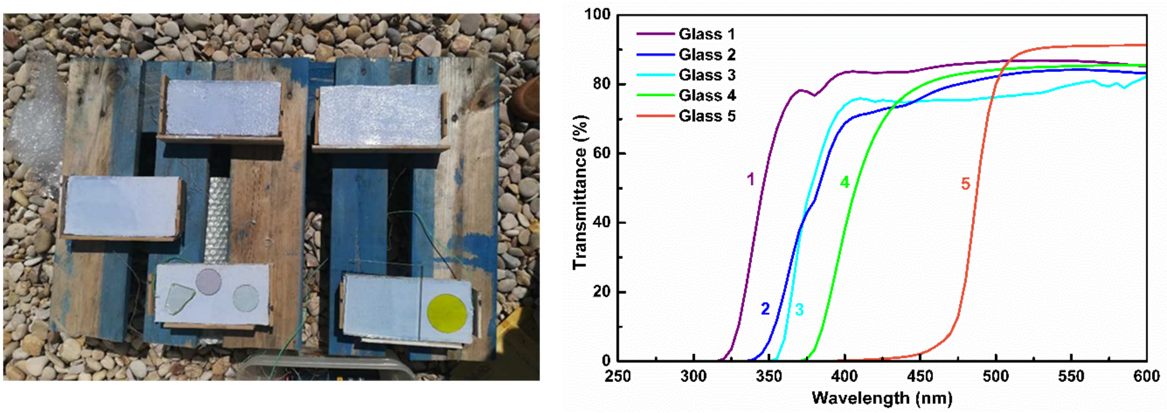

Figure 1.: Location of thermochromic mortar coated tiles during the test (left) and transmittance spectra of the glass protections (right).

The transmittance spectra of the five glasses are included in Figure 1 (right). All of them are cut-off filters with low transmittance below a characteristic value (λc) that increases with number from glass G1 to G5. The extreme low wavelength case is G1 (transparent-squared glass on the tile at bottom right position in figure 1), which protects only from part of the UV solar radiation. On the other hand, G5 protects in the widest range, covering all the UV and part of the visible solar range with wavelength lower than around 450 nm (yellow-circled glass on the same tile as G1). G2, G3 and G4 may be seen covering different areas in the bottom left tile in figure 1.

In order to monitor the optical behaviour of the thermochromic mortar during the test, a portable optical fibre spectrometer from Stellarnet was used to measure reflectance spectra of the specimens every day early in the morning, when the environmental temperature is significantly lower than the nominal Tc, and in the afternoon, when it is significantly higher than this value. The surface and environmental temperatures were also monitored during the experiment by the thermocouples embedded in the coating of each tile and by a portable device, respectively.

3. RESULTS AND DISCUSSION

3.1 Thermochromic response characterization

The reflectance spectra of the plain thermochromic mortar, with no protection, measured along the durability test are shown in Figure 2.

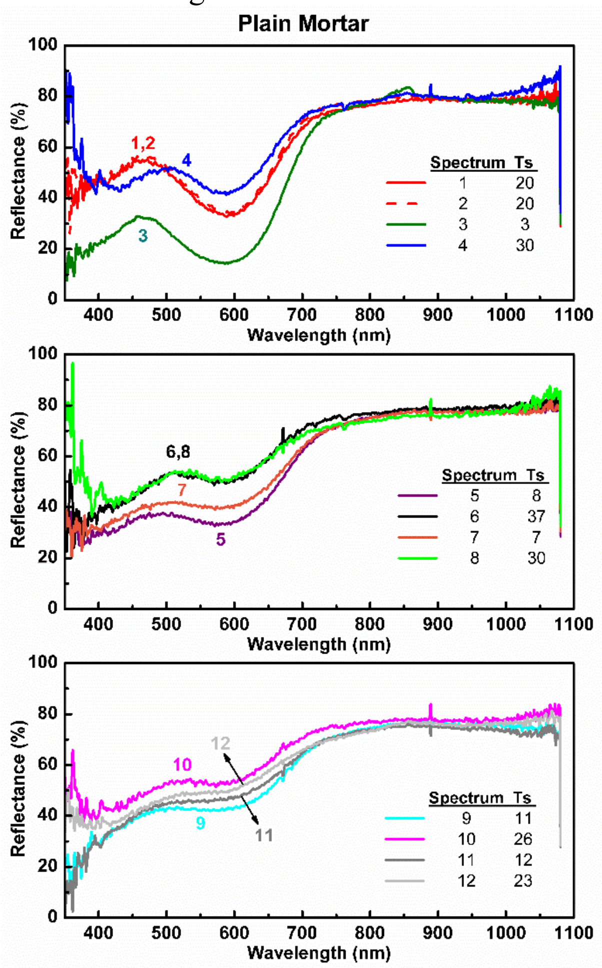

Figure 2.: Reflectance spectra of plain thermochromic mortar.

Spectra 1 and 2 were measured in the laboratory prior to exposure to outdoor conditions and following spectra correspond to subsequent measurements made at the mortar surface temperature (Ts in °C) indicated in each case. A clear decrease in reflectance is observed between Spectrum 2 (at 20 °C) and 3 (at 3 °C) that confirms the thermochromic behaviour of the mortar and corresponds to the observed change from a light to a dark blue colour of the mortar as shown in Figure 3.

When Ts increases to 30 °C due to solar heating during the first day of exposure, an increase of reflectance is observed in Spectrum 4 to a level close to that of Spectrum 1 that confirms the reversible character of the thermochromic effect. More interesting is the fact that the maximum of the curve shifts to higher wavelengths, accounting for a slight yellowing of the mortar surface. As the test proceeds, this shift increases and the contrast between the spectra at temperatures beyond the mortar Tc of 15 °C and below this value clearly decreases. In fact, an insignificant difference is observed between spectra 11 and 12 and only very small difference is observed between spectra 9 and 10. These results indicate that exposure to outdoor conditions for seven days gives rise to a loss of thermochromic behaviour and a yellowing of the mortar surface, in accordance with the appearance of the plain mortar tile in Figure 3. Similar behaviour was obtained in previous studies on durability of organic pigments under solar radiation [4].

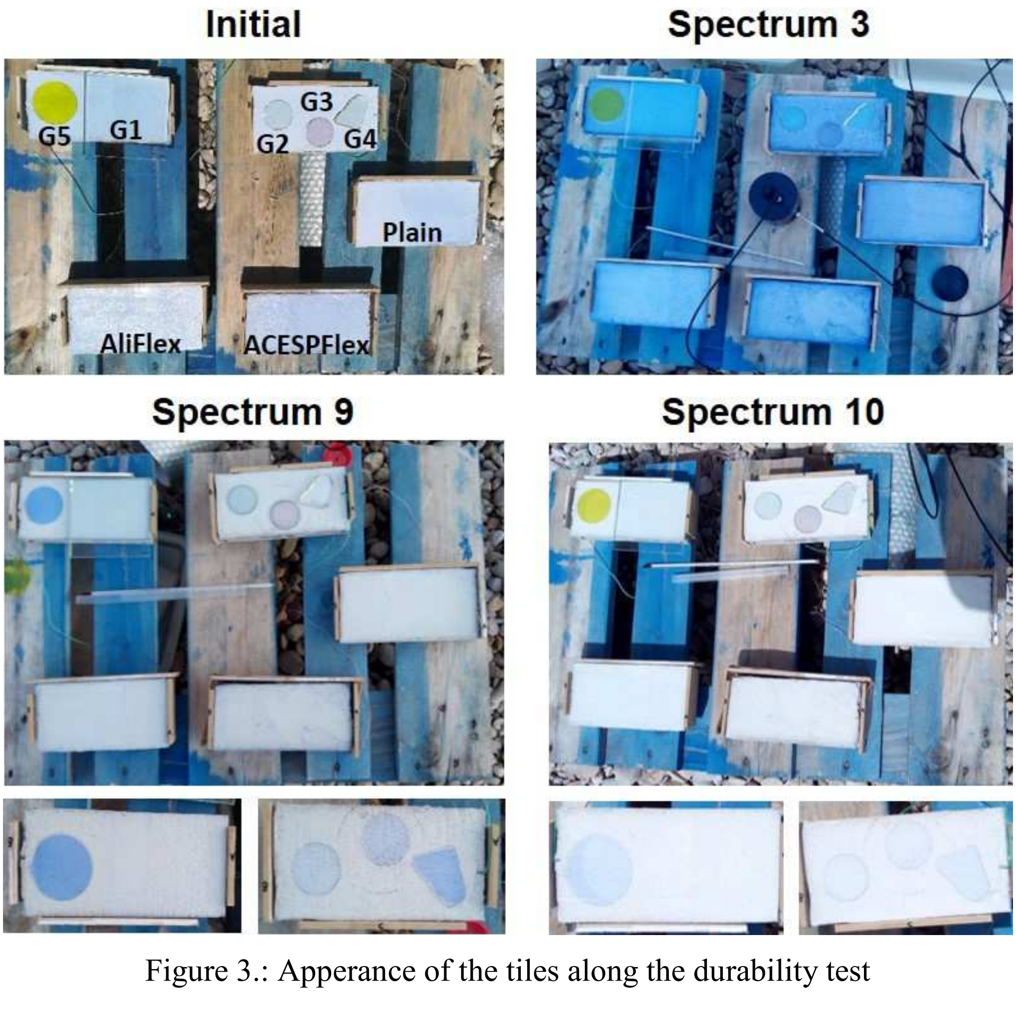

Figure 3.: Apperance of the tiles along the durability test

According to the spectra shown in Figure 2 and the images collected in Figure 3, the thermochromic mortar is initially suitable as external coating for the base wall of the Trombe wall, but an adequate strategy must be implemented in order to increase its durability under solar radiation. Also important is to note that this suitable dynamic behaviour of the mortar may be obtained for different surface colours and with different values of colour change temperature. In fact, in previous works a black pigment with Tc equal to 31 °C has been used in the thermochromic mortar formulation [2].

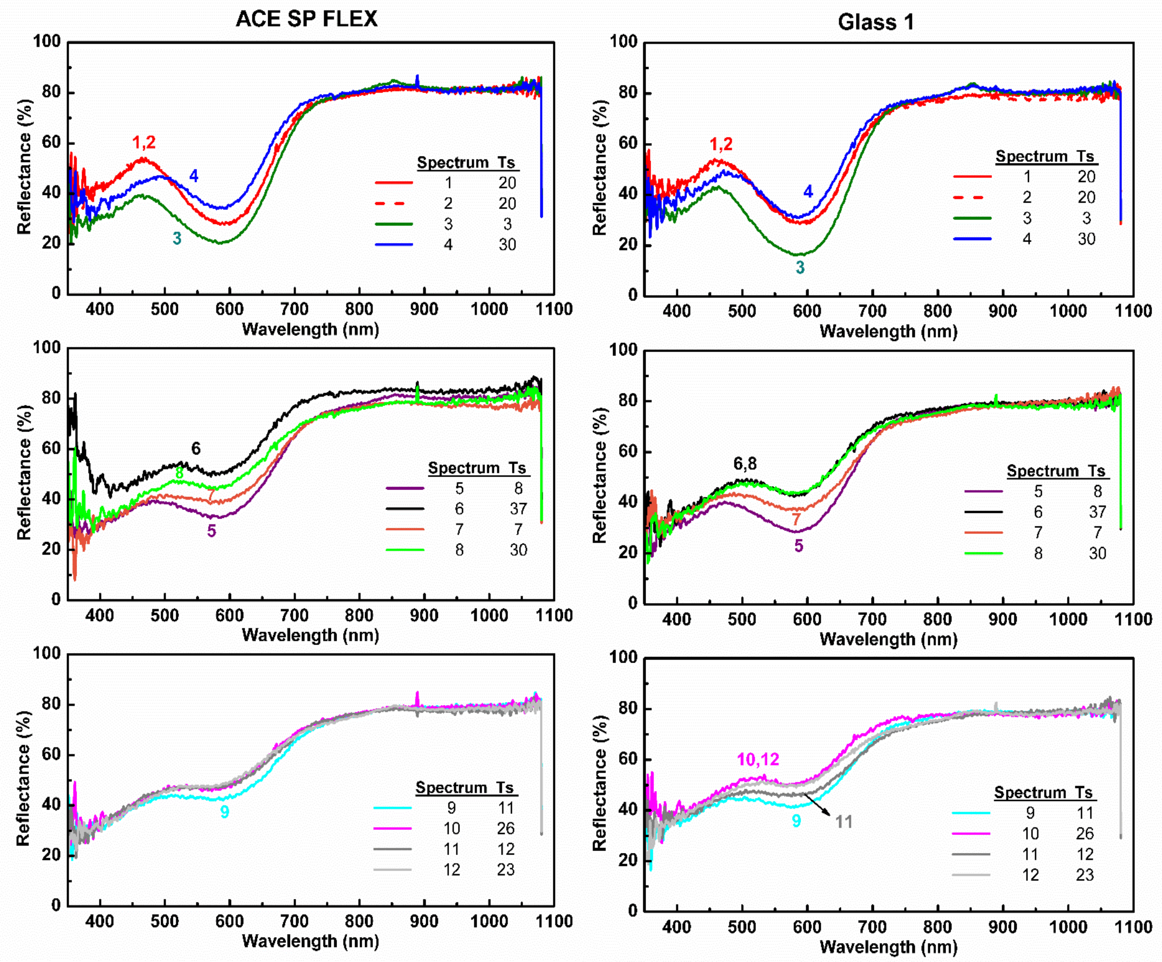

Figure 4.: Reflectance spectra of thermochromic mortar covered by ACE SP FLEX resin (left) and by Glass 1 (right) along the durability test.

The reflectance spectra measured on the thermochromic mortar surface covered by both resins and by Glass 1 show a very similar tendency to that of un-protected mortar, as can be seen in Figure 4 (the case of ALIFLEX is not included as it is similar to ACE SP FLEX). This result confirms that, avoiding incidence of solar radiation in the UV range, does not avoid degradation of the thermochromic behaviour of the mortar.

The curves corresponding to the mortar covered by Glass 4, included in Figure 5, show a better stability of the thermochromic effect as compared to Glass 1. In fact, significant contrast between measurements at high and low temperatures, with no appreciable shift in wavelength, is observed until measurement 8 (middle graph). Although these two effects are present in the measurements made in the last part of the test (spectra 9 to 11), indicating that mortar degradation is not avoided by the presence of Glass 4, it is clear from the curves that the degradation process is delayed by this glass.

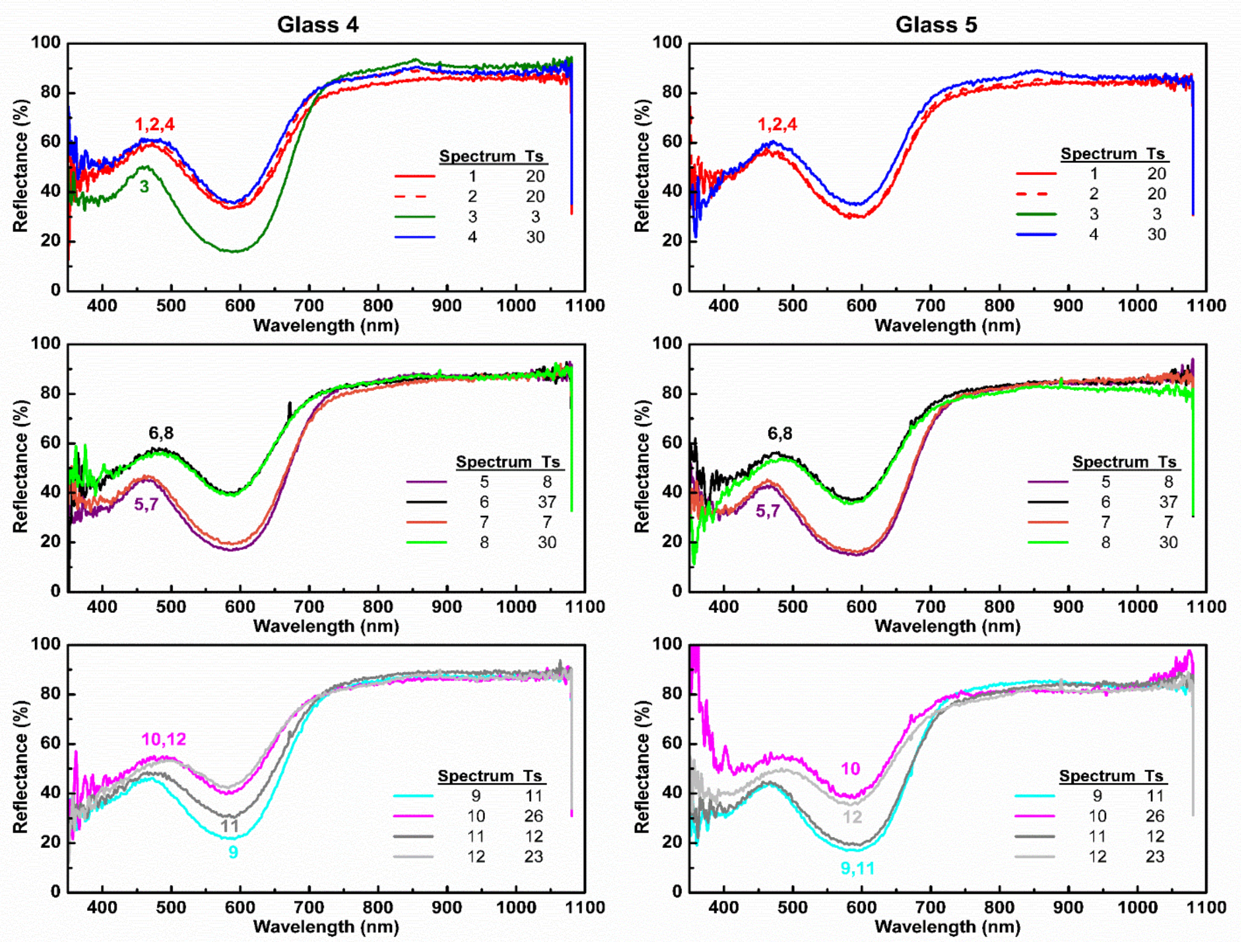

Figure 5.: Reflectance spectra of thermochromic mortar covered by Glass 4 (left) and by Glass 5 (right) along the durability test.

Finally, in the case of thermochromic mortar covered by Glass 5, no shift in the spectra is observed during the seven testing days and the curves for high and low temperatures keep a stable contrast that confirm that this glass is a proper protection for the thermochromic behaviour of the material. In fact, the mortar surface in the area covered by this glass keeps clearly changing its colour with temperature until the end of the test. Only slight changes remain in the areas covered by Glass 2, 3 and 4 and a constant yellowish appearance is observed in the mortar throughout the test in areas covered by both resins or by Glass 1 as shown in Figure 3.

Analysing the transmittance spectra of the test glasses in Figure 1 it may be stated that degradation of the thermochromic effect in the mortar coating is related to solar radiation in a wavelength range that extends beyond the UV region, up to a value close to 450 nm. Consequently, to assure a stable thermochromic behaviour in the façade, the glazing implemented in the Trombe wall design must be opaque in the wavelength range from 250 to 450 nm. This result is similar to that previously published [4] for a similar analysis of thermochromic coatings that are not based on cementitious materials.

3.2 Effect of thermochromic response on mortar surface temperature

Figure 6 compiles the temperature data measured during the durability test by thermocouples inserted close to the surface of the different tiles and data measured at the environment surrounding the tiles by a portable device. These data confirm a similar behaviour for plain mortar and the mortar covered by the resin, with a temperature higher than the environmental value during the day and significantly lower than environment during the night.

The tiles covered by Glass 4 and by Glass 5 show a similar temperature behaviour, but in this case with a higher overheating during the day and a clearly lower overcooling during the night, as compared to plain mortar values.

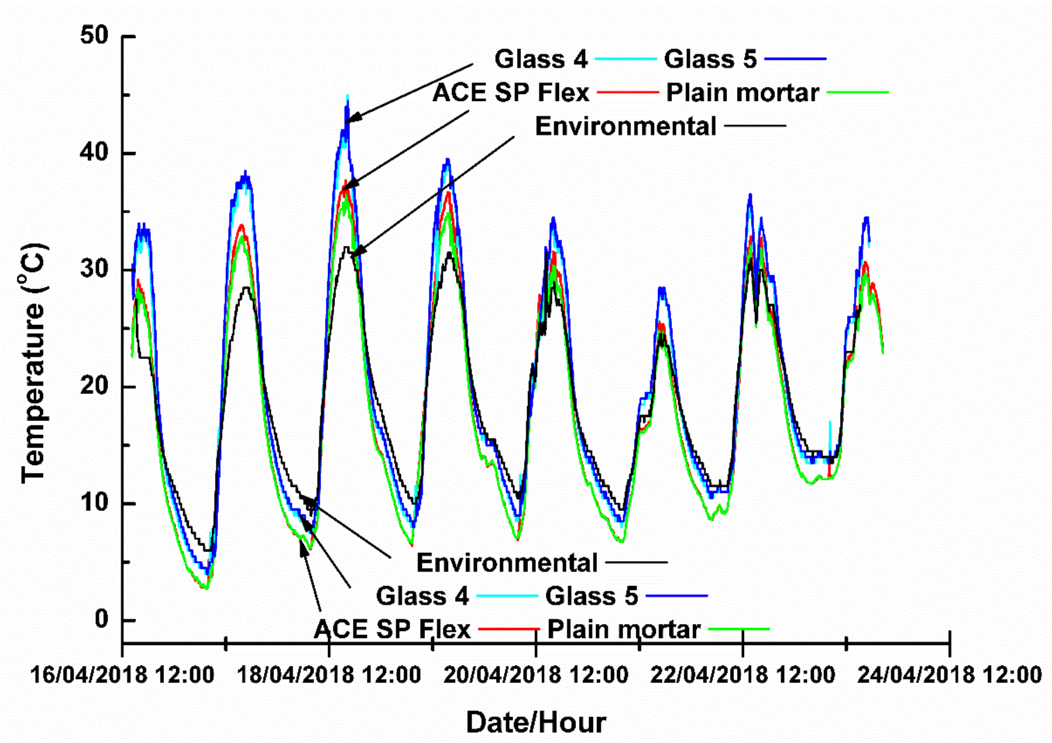

Figure 6.: Temperature values measured along the durability test.

The thermal response of the tiles surface observed in Figure 6 would be suitable for reducing heating demand in climates with mean temperatures closer to the Tc value of 15 °C considered in this work, with lower maximum and minimum temperatures than those measured during the durability test. In any case, the properties of the mortar (colour and colour change temperature) must be optimized for application in each climate.

4. CONCLUSIONS

– The thermochromic mortar developed by our group is initially suitable as external coating for the base wall of the Trombe wall under consideration as it shows a significant contrast in reflectance when temperature changes from below to beyond the characteristic colour change temperature (Tc). Tc value is 15 °C in this study, but may be changed, by changing the thermochromic pigment used in the mortar formulation

- The change in reflectance gives rise to a significant aesthetical effect, with the surface of the mortar initially changing from a dark blue colour at low temperatures, to a light blue at high temperatures. Other colours may be implemented by changing the thermochromic pigment.
- The plain thermochromic mortar shows a yellowish surface of constant optical response after being exposed to outdoor environment for seven days.
- Degradation of thermochromic behaviour of the mortar is related to solar radiation in the wavelength range from 250 nm to 450 nm.
- When the mortar is covered with a glass that is opaque along this wavelength range, the thermochromic effect is confirmed up to seven days of exposure to outdoor conditions: the optical response of the mortar changes with temperature and the corresponding change in colour is observed at the material surface.
- The temperature profiles of the tiles surfaces confirm the behaviour observed by reflectance measurements and tiles appearance. The mortar colour and colour change temperature must be properly selected in each application to take advantage of the dynamic optical response in terms of energetic demands.

ACKNOWLEDGEMENTS

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DESIGN AND OPTIMISATION OF A THERMOCHROMIC TROMBE WALL

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Abstract

Most of the existing buildings in Spain lack of any thermal insulation in their envelope and need to be refurbished to reduce their energy consumption, in order to meet compliance with current European Directives. The standard solution for facades consists of the incorporation of thermal insulation to reduce the thermal transmission. At the moment, diverse alternative constructive systems are in development. One of these measures may be the installation of Trombe walls on sunny facades. Combining the thermal accumulation capacity in the walls and the greenhouse effect, these systems allow taking advantage of incident solar energy to heat the inhabited space.

The work presented here proposes an innovative solution that incorporates an outer layer of thermochromic mortar in the façade. The objective is to improve the energy efficiency of the construction system designed from the concept of "Trombe wall".

In this communication, the design and configuration of the system is analyzed through determining factors for its operation, such as the surface characteristics of the outer layer. The results of the identification of the parameters that influence the thermal performance of the solution are exposed. Their effect is evaluated, optimizing the use of the variable optical properties of the thermochromic mortar and its transition temperature is set to achieve maximum efficiency.

Keywords: Energy refurbishment, passive solar heating; surface optical characteristics

1. INTRODUCTION

The aim pursued with building energy refurbishment is to lower the greenhouse gas emissions associated with energy consumption [1]. Solar energy can be used in facades for the improvement of buildings energy efficiency. For instance, passive solar building systems can reduce the winter heating demand and summer cooling demand. Low-energy buildings today improve on passive solar design by incorporating a thermal storage and delivery system[2].

Trombe walls, which are also known as storage walls and solar heating walls (SHW) can be adapted to various climates, purposes, and seasons [3]. A Trombe wall is a wall facing the sun, to the south in the northern hemisphere. It is built with materials that can accumulate heat under the effect of thermal mass, combined with an air space and a glass sheet.

Some accessories, such as insulation, shading devices, vents or fans can be used to improve its energy efficiency. Moreover, the parameters for the opaque wall composition contribute to the effectiveness of the system, improving the wall heat storage (high storage capacity), convection, and conduction (insulation, avoiding reverse heat transfer). The coating material is another important component for the system performance. A study in Turkey revealed that the annual heat gain varied from 26.9% to 9.7% for concrete, 20.5% to 7.1% for brick and 13.0% to 4.3% for aerated concrete according to surface colour [4].

In this case, the prototype is designed for the energy rehabilitation of existing facades in inefficient buildings. For this reason, the thermal mass is dumped from the existing materials. It is an indirect passive solar energy collection system, which can be used for the internal heating of buildings through the transfer of heat, either by conduction, convection and / or radiation. It is an indirect system because the capture is done through an element arranged between a glass and the interior of the house.

The objective of this paper is the parametric definition for the construction of a new Thermochromic Trombe wall prototype, which includes the incorporation of a thermochromic coating with optical response to solar radiation changing with temperature [5]. The design takes advantage of the dynamical behaviour of the coating to maximize solar energy collection in winter, while reflecting it under summer conditions. In order to understand the system seasonal performance, wall composition and ventilation in the air chamber are analysed, using an energy model.

2. SIMULATION MODEL GENERATION

The thermochromic Trombe wall (TTW) will be deployed in a test cell situated under monitored external climatic condition at the GESLAB (Global Energy and Sustainable Laboratory in Building) experimental platform sited on the Technical University of Madrid's Montegancedo Campus. Once the prototype is constructed, it will be able to gather data under different weather conditions and environmental control profiles.

The model presented here is studied in order to define the best theoretical conditions of the TTW prototype. The parameters studied on this paper will be useful for its construction, and collected data will permit to validate the design, and/or introduce modifications based on scientific evidences.

2.1. Geometry

The prototype optimized by the calculations described in this paper will be constructed in a test cell which is specifically designed for façade testing. It will have a south orientation (Fig. 1). The dimensions of the façade will be 2,16m x 2,16m. The air chamber will be ventilated under monitored controlled conditions. Its dimensions are 2,16m x 2,16m and the thickness of the air chamber is 15 cm. This dimension is chosen in order to permit the installation of fans to control air temperature inside the chamber. The total air volume contained is about 0,70m^3 of air.

A solar protection is needed in order to protect the system from unwanted solar radiation during the summer. A fixed upper horizontal sunshade has been chosen. Its dimensions are 70 cm wide, for the entire length of the facade and located 40 cm high above the glass surface. This dimensions permit to collect solar radiation in the entire glazed surface during winter solstice at 12:00, while blocking it completely during summer solstice at 12:00.

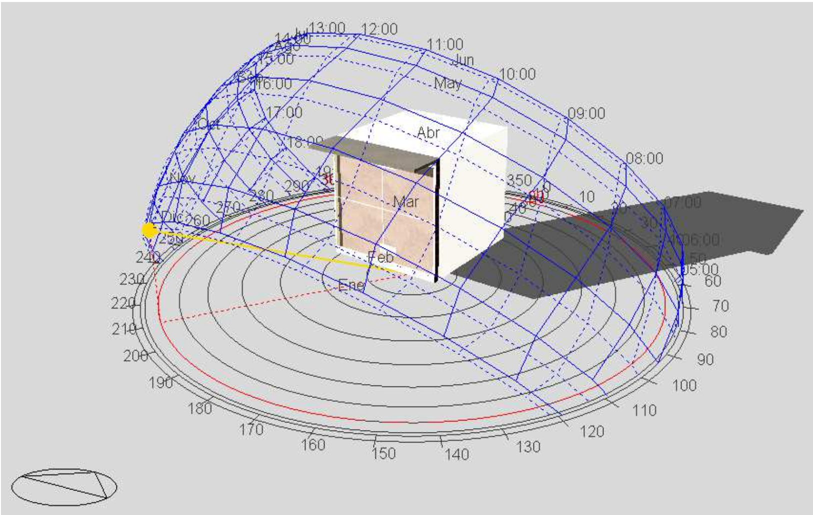

Figure 1: Image of the model under winter conditions

The prototype include motorized ventilation gates in both the base wall and on the plane of the glass surface, in order to control air renewal into the chamber. The dimensions of these air gaps are 2,16m * 0,10m, both in the base and the top of the wall. These gates permit to change the system operation according to summer or winter conditions. Figure 1 and 2 presented an aspect of the model under winter conditions, and, a scheme of summer and winter operation of the proposed system.

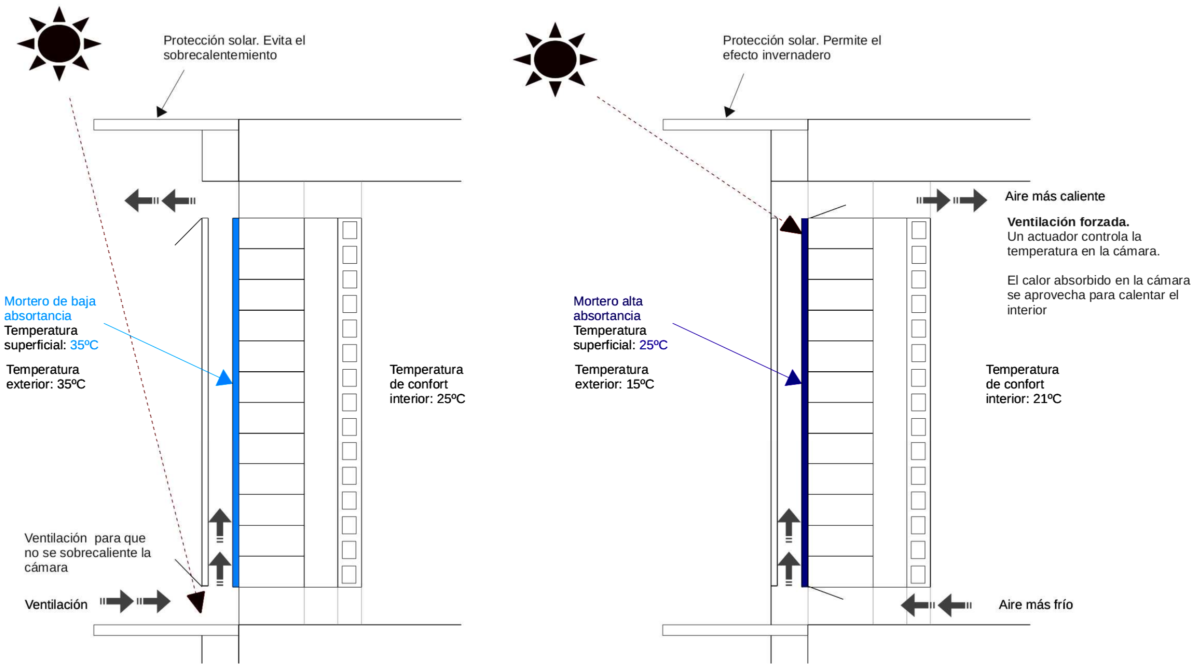

Figure 2: Scheme of summer and winter operation of the proposed system

2.2 Elements of the Trombe wall

The total construction solution is composed by the base wall, the ventilated air chamber and a glass coating.

Base wall

The base wall (fig.3), on which the TTW will be displayed, represents a typical facade of Spanish buildings built before the entry into force of the first standards that include thermal conditions for buildings. The choice of the solution is based on the conclusions of a previous research project [6]. The configuration most frequently found was an 11.5cm brick outer wall, an air chamber and a 4 cm brick partition wall (Fig.3). This typology, which prevails in social housing in the city of Madrid, exhibits a number of shortcomings. One is the scant energy efficiency induced by its high thermal transmittance, which ranges from 2 to 1 W/m^2K, considerably in excess of the present legal ceiling (0.66 W/m^2K in climates such as Madrid's). On the inside, a plaster lining of approximately 1 cm thickness has been assumed. On the exterior, the most common coating in these solutions, a cement-sand mortar with a thickness of about 2cm, has been substituted by a thermocromic coating. This coating shows a light colour at high temperatures, associated with a high reflectance (low absorptance) of solar radiation and reversibly changes to a dark colour (low reflectance and high absorptance) when temperature decrease below a certain critical value (Tc).

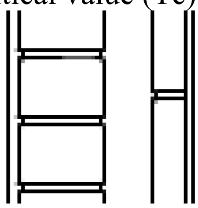

Figure 3: Base Wall section

Simulation of thermochromic effect of the surface of the mortar is introduced into the model by the parametrisation of its absortance (visible and solar) and emissivity as in [7]. Two models had to be created, in order to compare different results of separate simulations with light and dark mortars characteristics (Table 1). Also, some typical variations on the composition of the base wall are studied, such as the demolition of the partition wall, or the inclusion of some thermal isolation material on the outer brick wall, in order to determine its influence on the behaviour of the model.

Table 1: Optical properties introduced (%)

	Light mortar	Dark mortar
Visible Absortance	0,59	0,71
Solar Absortance	0,43	0,50
Emisivity	0,90	0,90

Ventilated air chamber

The external surface temperature of the wall on the air chamber is very important in order to control the thermocromic properties of the external mortar coating. The air velocity is dimensioned so that solar radiation does not heat the mortar above the color change temperature during winter. The heat trapped by the greenhouse effect dissipates into the living space, taking advantage of it as heating. The exchange of heat between the thermochromic mortar and the renewal of air in the chamber is controlled in the model by the surface convection coefficient. Its calculation in an air chamber is made according to the following equations (1), and the results are shown at table 2:

$$Hc = 5{,}8 + 4{,}1 * v \tag{1}$$

$$Qv = hc * A * \Delta T$$

v = airspeed
hc = surface convention coefficient
Qv = heat flow by surface convection
A = Area
ΔT = difference between the surface temperature and the air temperature

Table 2: Calculation of the relation between air change and surface convention coefficient

Vol	Air renovation			Area	Air speed	Surf conv coeff
m^3	R/H	m^3/h	m^3/s	m^2	m/s	
0,7	60	42	0,0117	0,32	0,036	5,95
0,7	120	84	0,0233	0,32	0,073	6,10
0,7	180	126	0,0350	0,32	0,109	6,25
0,7	200	140	0,0389	0,32	0,122	6,30

Glazed surface

Due to the dimensions of the prototype, and for security reasons, a laminated glass has been chosen. More specifically, a double glazing 4+4 of the type Stadip Color described on [5]. The laminated glass has a low transmission in the low wavelength range of the solar spectrum, in order to protect the thermochromic mortar coating from degradation caused by radiation in the range from 250 to 450 nm. This optical behaviour gives rise to a characteristic yellow appearance to the double-glazing implemented in the TTW. The parametrisation of the glazed surface on the model was made by data offered by the commercial supplier (Table 3).

Table 3: Glazing parametrisation

SHGC	0,71
Light Transmission	0,78
Uvalue (kW/m2K)	5,6

2.3 Activity and HVAC

The model represents a test cell for controlled laboratory conditions, no human occupation is expected. For this reason, no internal or equipment loads have been included in the model. The set point comfort temperatures used for HVAC systems are 20º C during the winter period and 25º C during the summer period.

The air change in the air gap will be equipped with artificial ventilation, designed to create air flow to reduce the surface temperature of the thermochromic mortar. This will permit to control surface temperature of the thermochromic coating. Since the simulation tool does not permit to control openings in the base wall (since it considers it as an internal partition), heat gains in winter will be evaluated by the convective heat loss through the external air gaps.

The interior space of the cell (OCC), whose habitability conditions will be monitored, will have no air exchange. Cells are equipped with heating/cooling facilities, which permit to store data about energy consumption. A wider description of the HVAC systems can be found at previous publications related to other experiments tested in GESLAB [3].

2.4 Simulation Model

The calculation tool used to model the Trombe wall was EnergyPlus, using DesignBuilder Software v4.7 as an interface. This software does not offer an "object" defined as a Trombe Wall, but it can be modelled combining existing components in order to handle the needed parameters (Fig. 1). Convection coefficients in the vertical chamber are calculated by attaching a very narrow area (air-gap) to the heated surface as a "glazed chamber", using an inter-zone partition. A conduction transfer function (CTF) has been used as general calculation algorithm. Also, the most accurate solar radiation calculation was selected by "advanced complete interior and exterior solar distribution" algorithms.

Another difficulty for the definition of the model lies in the impossibility to incorporate the dynamic properties of the thermochromic coating in the software. This problem has been addressed by carrying out two different simulations, one for the month of January (including high absorbance capabilities of the material) and a second one for the month of August (including high reflectance surface properties).

3. PARAMETRICAL ANALYSIS

Wall composition (both mortar colour and wall composition) and ventilation in the air chamber are analysed in order to understand the system seasonal performance (Table 4).

Table 4: Description of the parameters for each case

Case N.	name	mortar	Vent. (h-1)	Wall composition
1	mCl_15cm_Vforz120_cEA	light	120	Existing
2	mCl_15cm_Vforz180_cEA	light	180	Existing
3	mCl_15cm_Vforz200_c1h	light	200	one layer
4	mCl_15cm_Vforz200_cEA	light	200	Existing
5	mCl_15cm_Vforz200_cEPS	light	200	insulated
6	mOs_15cm_Vforz120_cEA	dark	120	Existing
7	mOs_15cm_Vforz180_cEA	dark	180	Existing
8	mOs_15cm_Vforz200_c1h	dark	200	one layer
9	mOs_15cm_Vforz200_cEA	dark	200	Existing
10	mOs_15cm_Vforz200_cEPS	dark	200	insulated

Table 5: Main results for each simulated case

Case N.	cooling consumption. Indoor (kWh)	Sensible heat loss. Airgap (kWh)		Wall surface temperature (ºC)				Surface heat gain (kWh)	
	August	August	January	August		January		August	January
				max	min	max	min		
1	-23,15	-54,18		40,72	14,93	32,43	3,35	-20,73	45,53
2	-22,31	-58,46		40,61	14,57	31,45	2,77	-19,78	49,05
3	-36,88	-51,26		39,80	14,70	32,45	4,24	-33,43	84,41
4	-22,13	-59,40		40,59	14,49	31,24	2,65	-19,57	49,82
5	-10,70	-66,40		41,31	14,31	33,17	1,30	-7,86	18,97
6	-23,93		-125,32	41,05	15,01	33,50	3,42	-21,6	43,88
7	-23,05		-135,73	40,92	14,63	32,48	2,84	-20,6	47,47
8	-38,12		-159,42	40,09	14,77	33,43	4,27	-34,8	82,24
9	-22,86		-138,00	40,90	14,56	32,26	2,71	-20,38	48,25
10	-10,97		-119,52	41,64	14,37	31,23	1,40	-8,22	18,28

Conduction heat gain is higher for cases 3 and 8. These are the cases with a single layer, uninsulated concerning the wall composition. This heat gain is higher in winter as the solar radiation in the vertical surface is higher (due to the system shading device and the sun path).

In summer the light coloured mortar has also a positive effect in cooling consumption, improving from 2,5% in the one layer wall to 3,2% for the insulated wall.

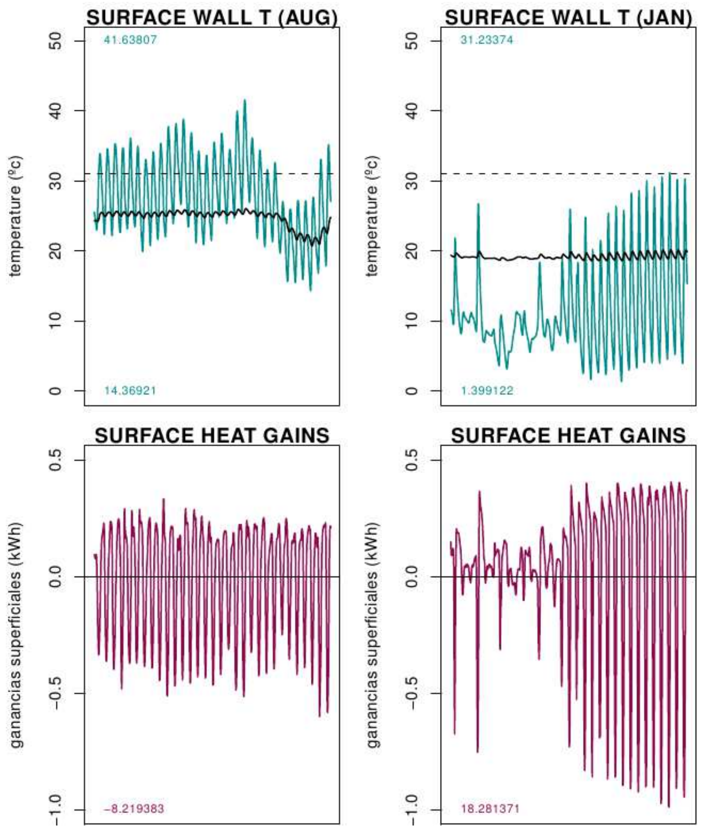

Fig 4: Surface wall temperature and surface heat gains in August and January for case 10

The dark mortar has an influence on this conduction gains. In august it would increase 4% and 3% in January. The mortar colour change will therefore have a positive effect in this conduction transfer, reducing the heat gain in august and increasing it in January.

In January the maximum surface temperature does not exceed 31ºC. So this could be considered as the adequate critical value for transition of the optical solar response of thermochromic mortar.

In August the maximum temperature in the wall surface is 41,6ºC for case 10, but the differences are not significant for all cases. This maximum is coincident with the highest outdoor temperature, as so the minimum is registered at night.

The sensible heat loss in the air gap is much higher in winter than in summer. As it is said in the simulation configuration, this heat loss would represent the heat gains for heating the indoor environment in winter conditions. This heat gain increases with higher ventilation, as the convection heat transfer is higher. It is also higher for the one layer wall, as the exterior wall surface temperature is also higher.

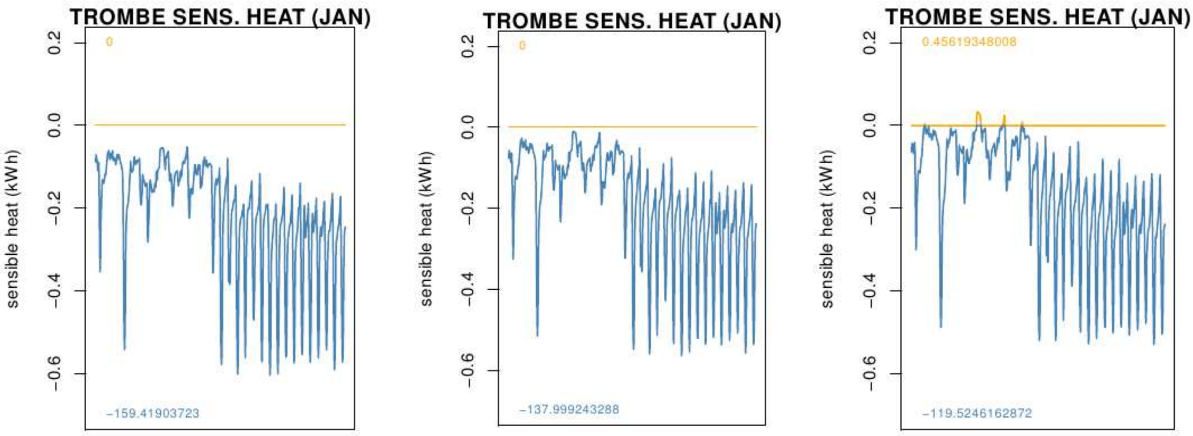

Figure 5: Sensible heat gain in cases 8,9,10.

4. CONCLUSIONS

Colour change has an influence in the seasonal performance, reducing summer heat gains and reducing winter heating demand. To maximize this effect, mortar temperature for changing the colour should be fixed around 30ºC-31ºC. An experimental model under real conditions is required in order to precisely determine energy savings. Conduction heat gain is higher for uninsulated single layer wall composition.

ACKNOWLEDGEMENTS

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INFRARED THERMOGRAPHY FOR DYNAMIC THERMAL TRANSMITTANCE DETERMINATION

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Abstract

The aim of this paper is to show a new possibility for in situ U-value determination using infrared thermography (IRT) method and its comparison with heat flux method (HFM). It also gives procedure for conducting the experiment and for the analysis of measured data. Average method and dynamic method given in ISO 6869 were used for data analysis, and results obtained using dynamic method show higher level of accuracy than ones obtained by average method. Results obtained using IRT method are much closer to theoretical values with differences between 0-19% respectively of the method used to approximate surface heat transfer coefficient. Since dynamic method is much more sophisticated than average method, its procedure had to be implemented using Excel VBA. The main conclusion was that use of infrared thermography could be used, together with dynamic method of analysis, for relatively fast and accurate in situ U-value determination.

Keywords: heat transfer coefficient, infrared thermography, heat flux method, dynamic method, average method

1. INTRODUCTION

Thermal properties of building elements are determined by heat transfer coefficient or U-value [W/m^{2}K], which is the initial parameter for determining heating and cooling energy demands [1]. If one dimensional heat flow is assumed, then thermal transmittance, or U-value, is determined as the inverse value of total thermal resistance according to ISO 6946 [2] – equation (1).

$$U = \frac{1}{1/h_{si} + \sum_{k=1}^{n} d_k/\lambda_k + 1/h_{se}} \tag{1}$$

where d_k is thicknesses [m] and λ_k are thermal conductivities [W/(m K)] of each layer, and h_{si} and h_{se} are surface heat transfer coefficients [W/(m^2 K)] which quantify heat transfer from internal and external air to element surface.

U-value determined using equation (1) does not consider the irregularities of the materials and degradation of external coating elements caused by aging, and these effects can significantly affect the difference between the theoretical and actual U-value of the element [3]. It is necessary to measure the heat transfer coefficient in situ in real atmospheric conditions to check if real heat losses through building elements are close to designed values. In the case of existing buildings energy efficiency (thermal characteristics) will decline during period of exploitation. These buildings require a means of reducing energy consumption and improving energy efficiency, but to know a baseline value of energy consumption, and to be able to calculate energy savings as well as return on investment, one needs to know the real U-value of building elements [4].

ISO 9869 [5] gives easy and efficient method for determining real thermal resistance and U-value using a heat flow meter method (HFM). Method described is based on measuring heat flow density while simultaneously measuring inside and outside air temperature. Main disadvantage of HFM method is that it gives results only for one or few data points (depending on how many heat flux sensors are used). Furthermore, to get satisfactory results, minimal temperature difference of 10 °C is needed. Measurement is also influenced by thermal bridges, mould, humidity, adhesion between sensor and element surface, etc. Because of that real U-value differ from theoretical U-value and that difference is greatest in historical buildings where it can be up to 60% [6]. In their work Gaspar et al. [7] use dynamic method to show its superiority over average method. They showed that the difference between the theoretical and measured U-value is lower when dynamic method is used. When the environmental conditions for carrying out in-situ measurements were optimal the differences were lower than ±5% when average method is used, but lower than ±1% when dynamic method was used. If average method is used for data analysis, then it is not possible to capture effect of heat storage in the building elements. Average method is valid for heavier building elements with specific heat per square meter greater than 20 kJ/(m^2 K) [5]. If large variations occur in measured temperatures and heat flow rates, then dynamic method must be used. In practice, however, HFM method can, with above disadvantages, be too expensive and time-consuming. With ideal boundary conditions, measuring time should be 72 hours, otherwise it should be more than 7 days.

This paper suggests a new method which, unlike HFM method that measures heat flux, is based on approximation of heat flux from measured surface temperatures of the element using Infrared thermography (IRT) method, and data analysis using dynamic method. Comparison of U-value calculated using theoretical formulae, HFM and IRT method is also given.

2. HEAT FLUX METHOD

2.1 U-value determination according to ISO 9869

ISO 9869 gives two methods for analysing measured data: average and dynamic method.

2.1.1 Average method

This method assumes that the U-value can be obtained by dividing the mean density of heat flow rate by the mean temperature difference, the average being taken over a long enough period. U-value is calculated by equation (2):

$$U = \frac{\sum_{j=1}^{N} q_j}{\sum_{j=1}^{n} \left(T_i - T_e\right)_j} \tag{2}$$

where q_j is heat flux density [W/m^2], T_i and T_e are internal and external air temperatures air temperatures [K] and index j enumerates the individual measurement.

If IRT method is used instead of HFM method then U-value is calculated using equation (3):

$$U = \frac{\sum_{j=1}^{N} \left(q_{rad} + q_{conv}\right)_j}{\sum_{j=1}^{n} \left(T_i - T_e\right)_j} \tag{3}$$

where q_{rad} and q_{conv} are radiative and convective heat flux densities and their sum approximates the heat flux [W/m^2]. Their determination is given in chapter 3.

2.1.2 Dynamic method

The dynamic analysis method is a sophisticated method which may be used to obtain the steady-state properties of a building element from HFM measurements when large variations occur in temperatures and heat flow rates. It considers the thermal variations using the heat equation. The building element is represented in the model by its thermal conductance and several time constants τ [4].

The assumption of the dynamic method is that the heat flux rate in some time j is a function of the temperature in that time and all the preceding times – equation (4).

$$\begin{aligned} q_j &= U \cdot \left(T_{i,j} - T_{e,j}\right) + K_1 \cdot \dot{T}_{i,j} + K_2 \cdot \dot{T}_{e,j} \\ &+ \sum_n P_n \cdot \sum_{k=j-p}^{j=1} T_{i,k} \cdot \left(1-\beta_n\right) \cdot \beta_n \cdot \left(j-k\right) \\ &+ \sum_n Q_n \cdot \sum_{k=j-p}^{j=1} T_{e,k} \cdot \left(1-\beta_n\right) \cdot \beta_n \cdot \left(j-k\right) \end{aligned} \tag{4}$$

where K_1, K_2, P_n and Q_n are dynamic characteristics of the wall and they have no physical significance. In equation (4) p represents subset of data points used for numerical integration corresponding to sum over j. The variables β_n are exponential functions of the time constant τ_n.

Dynamic method given in ISO 9869 is used for analysis of data collected using HFM method. The aim of this paper is to use dynamic method in combination with IRT without the need of measuring heat flux using heat flux meters. $\dot{T}_{i,j}$ and $\dot{T}_{e,j}$ represent backward difference derivatives of temperatures T_i and T_e in every time increment Δt.

Using enough sets of data at various times, an overdetermined system of linear equations is created using equation (5):

$$\{q\} = [X] \cdot \{Z\} \tag{5}$$

If m time constants are chosen (τ_1, τ_2, … τ_m), then we have 2m + 3 unknown parameters which are given by equation:

$$U, K_1, K_2, P_1, Q_1, P_2, Q_2, \ldots, P_m, Q_m \tag{6}$$

Writing equation (4) 2m + 3 times for 2m + 3 sets of data at various times, a system of linear equations can be solved to determine parameters given by equation (6). First solution of that system of equations is heat transfer coefficient or U-value.

According to ISO 9869 one to three time constants are needed ($\tau_1 = r \cdot \tau_2 = r^2 \cdot \tau_3$) to properly represent interrelation between q, T_i and T_e, where r is the ratio between time constants.

Even though dynamic method is more robust than average method it can be used for relatively fast and accurate in situ U-value determination. Equation (5) is solved by least square method by varying time constants τ_n through the procedure described in ISO 9869 (Figure 1).

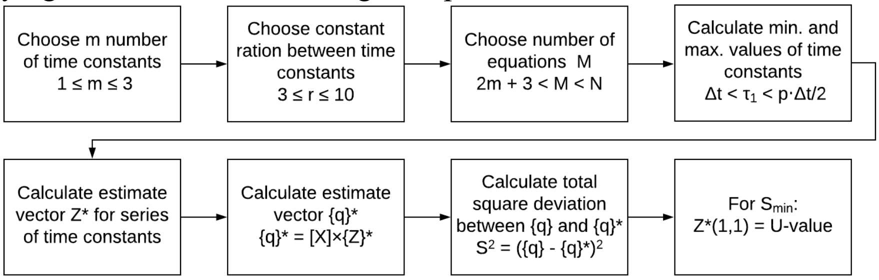

Figure 1 : Procedure for least square method described in ISO 9869

Procedure shown in Figure 1 was implemented in Excel VBA.

To evaluate the quality of results, uncertainty is calculated according to the following equation:

$$I = \sqrt{S^2 \cdot Y(1,1)/(M-2\cdot m-4)} \cdot F(P, M-2\cdot m-5) \tag{7}$$

where S^2 is total square deviation between {q} and its estimate $\{q\}^*$, Y(1,1) is the first element of the matrix $[Y] = ([X]^T \times [X]^{-1})$ and F is the significance limit of Student's t-distribution, where P is the probability (P = 0,95) and M – 2m – 5 is the degree of freedom.

In the case I is smaller than 5% of U-value, than the computed U-value is generally very close to the actual value.

3. APPROXIMATION OF HEAT FLUX USING IRT METHOD

Since heat transfer by conduction, in steady state conditions, is equal to the sum of radiative and convective heat transfer it is possible to determine the heat flux that causes transfer of heat from the fluid to the surface and vice versa – equation (8):

$$\begin{aligned} q_{cond} &= q_{conv} + q_{rad} \\ q_{conv} &= h_c \cdot (T_i - T_{si}) \\ q_{rad} &= h_{rad} \cdot (T_i - T_{refl}) \end{aligned} \tag{8}$$

where q_{cond}, q_{conv} and q_{rad} are conductive, convective and radiative heat transfer rate [W/m^2], h_c and h_r are convective and radiative surface heat transfer coefficient [W/(m^2 K)], T_i and T_{si} are inner air temperature and surface temperature [K].

For temperatures which occur in building physics (i.e. -10 °C up to 50 °C), radiative heat transfer is calculated using equation (9).

$$h_r = \varepsilon \cdot \sigma \cdot (T_i^4 - T_{refl}^4)/(T_i - T_{si}) \tag{9}$$

where ε is surface emissivity, σ is Stefan-Boltzmann constant ($\sigma = 5{,}67\times10^{-8}$ W·m^{-2} K^{-4}) and T_{ref} is reflected temperature [K].

On the other hand, the convective heat transfer coefficient is influenced by several factors, such as the geometry of the building element, element surroundings, the position at the building envelope, the building surface roughness, wind speed, wind direction, local air flow patterns and surface to air temperature differences [8–11]. There are different values to determine convective heat transfer coefficient – analytical, numerical and experimental methods. Experimental methods showed like the main source for calculating convective heat transfer coefficient. These experiments lead to empirical formulae that are derived from a wide range of situations where the reference temperature is typically chosen at a position close to the wall or in the middle of the test rom. Surface heat transfer coefficient can be determined by least square curve fitting using equation (10) from experimental data. In the case of natural convection coefficient h_c can be expressed using equation (10) for all surfaces.

$$h_c = C \cdot \Delta T^n \tag{10}$$

where C and n are constants that are used for curve fitting and $\Delta T = T_i - T_{si}$. Table 1 shows various choices for constants C and n together with authors who studied the natural convection and derived the corresponding empirical expressions.

Table 1: The convective heat transfer coefficients in the case of the natural convection [12]

Authors	**h_c [W/(m² K)]**	**Authors**	**h_c [W/(m² K)]**
Awbi et al. [13]	$1{,}49 \times \Delta T^{0{,}345}$	Nusselt [17]	$2{,}56 \times \Delta T^{0{,}250}$
Khalifa et al. [14]	$2{,}07 \times \Delta T^{0{,}230}$	Heilman [18]	$1{,}67 \times \Delta T^{0{,}250}$
Michejev [15]	$1{,}55 \times \Delta T^{0{,}330}$	Wilkers et al. [19]	$3{,}04 \times \Delta T^{0{,}120}$
King [16]	$1{,}51 \times \Delta T^{0{,}330}$	ASHRAE [20]	$1{,}31 \times \Delta T^{0{,}330}$

4. EXPERIMENTAL SETUP

Measurement was carried out at the Faculty of Civil Engineering, University of Zagreb. Examined wall is composed of the following layers: thermal insulating plaster on exterior side, concrete and lime cement mortar on interior side. Figure 2 shows thicknesses and thermal properties of each component built in the wall. Using those values theoretical U-value is determined: $U_t = 1{,}67 - 1{,}76$ W/(m² K). Since properties of the concrete used in the wall are not known, λ is taken in the range from 2,00 for regular concrete to 2,60 for reinforced concrete as shown in Figure 2.

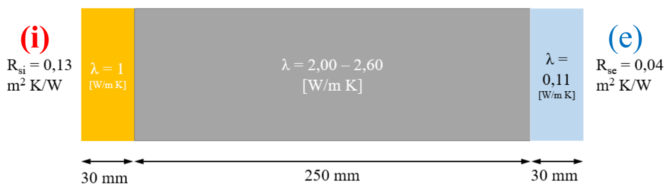

Figure 2: Thicknesses and thermal properties of examined wall

4.1 Measuring procedure

Time step for data collection was set to 10 minutes. Measurement was carried out in the period between 14th of December 2018. and 17th of December 2018. Measurement time duration was 72 hours (433 data points). Heat flux sensor was placed on the same wall with thermocouples for measuring internal and external air temperatures (Figure 3a). Surface temperature was measured using duct tape of known emissivity (ε = 0,95) with Box ROI named "Wall temp." shown in Figure 3b. After extensive background analysis of the influence of the position of Box ROI on the results (U-value, convective coefficients) it was concluded that position of Box ROI was not an important parameter – U-value for different positions varied from around 3 to 5%. Reflected temperature was measured using aluminium foil with Box ROI named "Refl. Temp" shown in Figure 3b. Both surface temperature and reflected temperature were calculated as average temperatures inside of used Box ROI. Analysis was done with both average and dynamic method for both IRT and HFM method. Exterior wall surface is not exposed to outside environmental conditions – rain, direct solar radiation, etc. Camera parameters were set as: reflected temperature 25,0 °C, relative humidity (RH) 60%, atmospheric temperature 22,5 °C and distance of camera from the surface 2,70 m.

a) b)

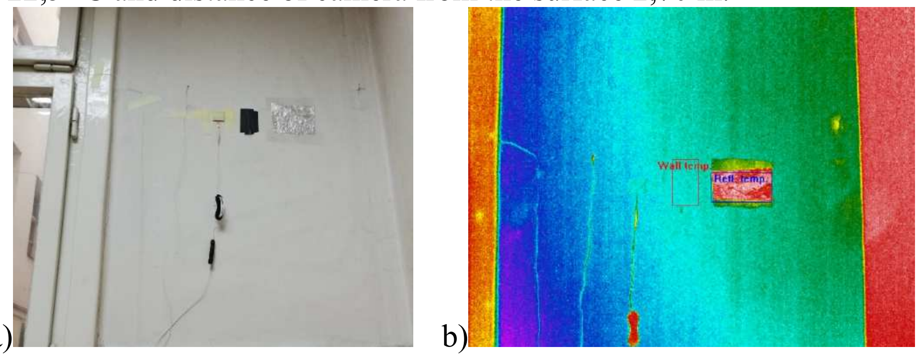

Figure 3: a) Measurement setup (IRT and HFM method); b) One of the thermograms used for analysis in IRT method

5. RESULTS

The collected datasets of 433 readings were used to calculate the U-value and uncertainties using the average method (**U_{avg}**) and the dynamic method (**U_{dyn}**). One time constant was adopted because it gave best confidence interval (from 2,13 to 3,87%).

Figure 4 shows comparison between U-values determined using HFM and IRT method and their comparison to theoretical U-value. U-value determined using IRT method is closer to the theoretical value – maximum error is around 19% at the end of the measuring period.

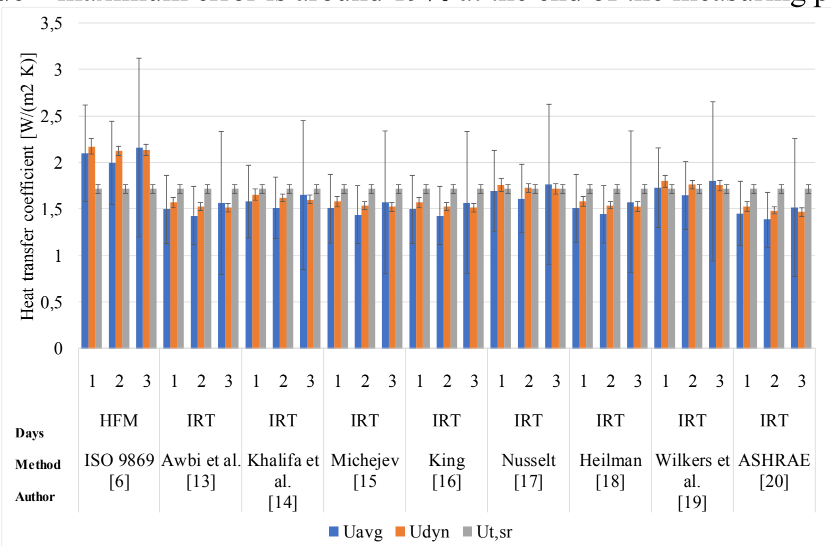

Figure 4: Theoretical U-value and measured thermal transmittance using the average and dynamic methods for HFM and IRT methods

On the other hand, if Wilkers et al. [19] empirical formula is used for determining convective heat transfer coefficient, then difference between theoretical and dynamic U-value is only 0,11%. U-value calculated using HFM method differs from theoretical value by 22 to 30% if measuring period is equal to 3 days (for both Average and Dynamic method). It can be observed in Figure 5 that dynamic method is more stable than average method for any measuring period – difference between U-value calculated after 1 and 2 days is less than 2% of U-value after 3 days. If average method is used maximal difference is around 8%.

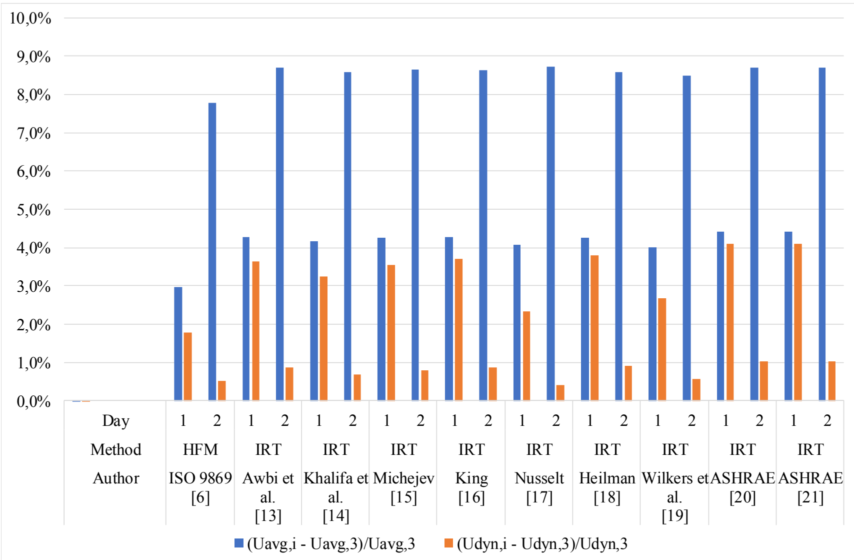

Figure 5: Relative errors between calculated U-values for different measuring period (i = 1,2 days)

6. CONCLUSIONS

This paper shows that there is potential for using IRT for calculation of U-value in real environmental conditions in situ, but firstly case study for different types of building elements and different environmental condition is needed to determine method credibility.

Real environmental conditions were used to determine U-value and even though surface was not ideal (isothermal) it was shown that using IRT method it is possible to determine U-value that is close to the theoretical with difference between 0-19% respectively of the method used to calculate convective heat transfer coefficient. Furthermore, it was shown that dynamic method, in combination with IRT method, could be used for relatively fast and accurate in situ U-value determination.

Determination of U-value by infrared thermography is still under development. To improve the given model, both HFM and IRT methods should be simultaneously used so surface heat transfer coefficient can be determined and correlated for future reference. These measurements will give further insight into why these differences occur and which method is better and under which conditions.

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OPTIMIZING THE HEAT TRANSFER OF ANCHORING COMPONENTS, HERE: BRICKWORK SUPPORT BRACKETS

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Abstract

Raised requirements towards energy efficiency of buildings are stipulated widely, for example in Germany it is the Energie Einspar-Gesetz (EnEG) [1] which is implemented through the EnEV [2]. Affecting a building's energy efficiency, façade constructions play a decisive role.

The here examined façade type is the brickwork façade where the facing layer is supported by special fixing brackets which have to penetrate the insulating layer. A new generation of these brackets was specially designed to minimize the entire heat transfer.

In the design process described here, the Chi-value and the material utilization serve as optimization functions for generating the new shape. It was shown that the minimization of the steel cross-section in the penetration corresponds directly to the reduction of the thermal bridge.

The new shape saves costs and material while improving production with minimized welds, minimized weight, and minimized laser cutting length including a waste reduction. In addition, the load was increased. This not only improves the environmental balance by saving resources, but also by reducing heat losses over many years to come.

This paper gives an overview of the calculation methods and test methods. The design rules are explained, and the results are illustrated.

Keywords: Heat transfer, Advanced building envelope, Low energy buildings

1. INTRODUCTION

For masonry façade systems, ancillary components such as ties, tension straps, hangers and brackets are regulated in [3]. Since anchorages - generally fabricated in stainless steel - need to penetrate the façade construction and especially the insulation layer in order to transfer loads securely, they act as a thermal bridge that needs to be evaluated and minimized.

1.1 Brickwork Support Brackets and their application

Stainless steel Brickwork Support Brackets are an optimal solution for brickwork façades realized as ventilated curtain façades. They are designed for different load classes and for cavity distances of 40 mm to 260 mm. There the insulation is penetrated at regular intervals, resulting in local thermal bridges that negatively affect the heat transfer coefficient of the entire wall.

In contrast to previous versions of the EnEV the additional heat transfer caused by support structures is taken into account for calculating the heat transfer coefficient of the outer wall, if it increases the U-value of the undisturbed structure by more than 3%. That is the case with regular Brickwork Support Brackets.

As part of the new features of [2] there are increasing requirements on the insulation thickness for external components, thus the rise of additional heat transfer through the fixing becomes more and more important. Increasing insulation thicknesses cause increasing withe distances and - due to static needs - often cause in bigger cross sections for anchoring components.

2. HEAT TRANSFER AND OPTIMIZATION

2.1 Topology optimization

The development of a completely new generation of brickwork support brackets should be started completely free, beginning with the basics. The idea is to start from scratch, define only the boundary conditions for the material given and leave the optimization to a software. The software used is an add on to ANSYS.

The use of materials and the shape should follow the flow of force in order to achieve a significant improvement compared to existing designs. While the boundaries are given, the material distribution is left to the optimizing algorithm, searching for the highest stiffness and the lowest heat transfer for the given amount of material supplied. The amount of material supplied, is subsequently reduced from 90% to 10% of the given initial volume.

One question for the target function was to judge the importance between material reduction and minimum heat loss as optimizing priorities. In the end both targets aim in the same direction. The minimum of material is a minimum for the heat loss at the same time. During the topology optimization, therefore, only the outlines or the intended space were specified. Furthermore, the areas for load application and the boundary conditions for wall mounting were defined. The following figures show the volume model for standard load application, see figure 1 to figure 3.

Under the given load, the material distribution was then determined with maximum stiffness for the given material input. The amount of available material was successively reduced.

Figure 1: Volume model with boundary conditions

Figure 2: superposition of 50% and 30% volume reduction

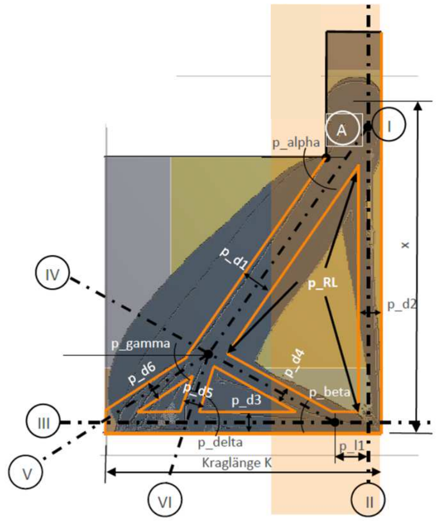

Figure 3: Suggested parametric discretization

Figure 4 shows the optimized material distributions by reducing the material provided from initially 90% to only 10% left.

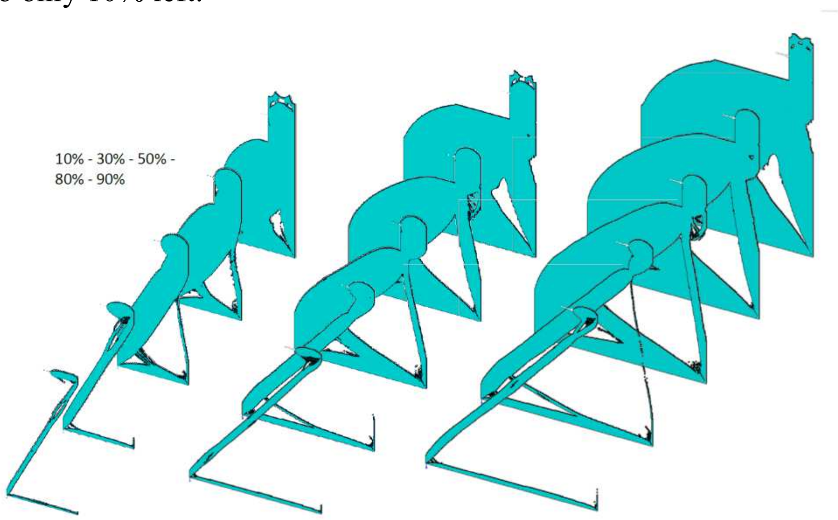

Figure 4: Optimization of Topology, from 90% to 10% material use

It can be shown that a pronounced diagonal tension strut is formed between the load introduction and the upper fixing point. At the same time a horizontal strut is formed from the load introduction to the lower fixing point. The third is a vertical strut between the upper and lower fixing points, which disappears with increasing material savings [4].

2.2 Thermal optimization

During the next step, the basic material distribution was in the focus of more detailed investigations through a parameter study as part of a sensitivity study, optimizing the thermal conductivity, represented by the Chi-value. The study was executed with add on tools to the ANSYS software. Now individual struts were discretized, based on the optimized topology.

The whole bracket is made of stainless steel plates with a constant thickness. The bracket rests against the concrete wall, penetrates the insulation (λ=0,035 W/mK) inside the cavity and supports the facing brick veneer which is resting on a support plate at the tip of the bracket. The 3D calculation of the single point heat loss was done with standard boundary conditions in a 3D model with a sufficient large cutout (see figure 5) comparing the flux with and without a bracket.

The diagonal and horizontal strut of the bracket were presumed to be indispensable. In addition, an optional vertical strut was provided between the upper and lower braces and/or an optional intermediate strut from the lower braces to the diagonal strut, see figure 6.

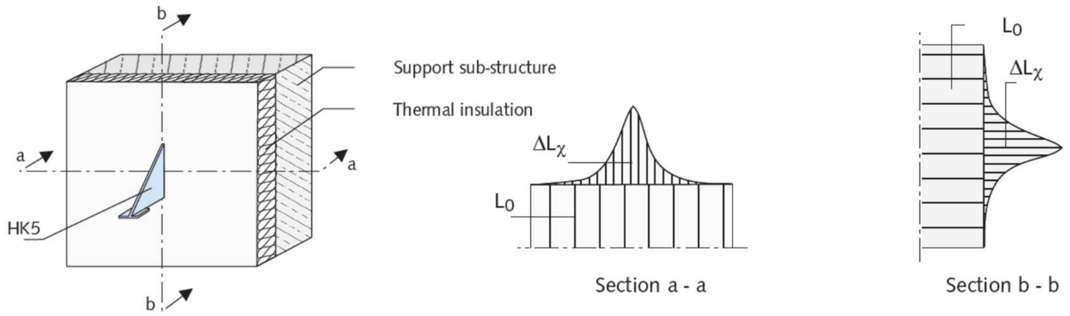

Figure 5: Determination of the thermal bridge loss coefficient X (chi) for Brickwork supports

Input values for the optimization were the geometry of the struts as shown in figure 6 and the optional presence of a sufficient resistance against buckling (“Biegung”) of the horizontal strut. The thermal optimization was the essential part of the objective function and as result the figure 7 shows the relevance of each input parameter on the chi value. A cut out of the calculation model is shown in figure 8.

This was done on the whole scatter of variants producing a scatter of chi values (see figure 9 and 10) depending on the input parameters.

The sensitivity study was carried out to examine the input variables to be considered for the relevant influencing parameters. All input parameters were varied within defined limits. Statistical measures (e.g. Coefficient of Prognosis) were used to explain the relationships and dependencies between the scatter of the input parameters and the resulting scatter of the result variables. Furthermore, the variation range of the result variables shows the relationships between the result variables and their optimization potentials. The target value for the entire optimization was the chi-value.

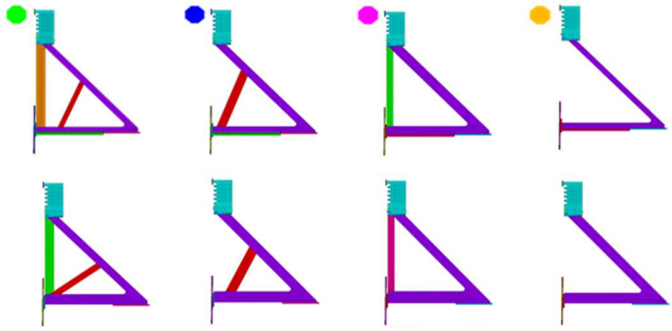

Figure 6: variations of the parametric model with or without extra struts or horizontal legs

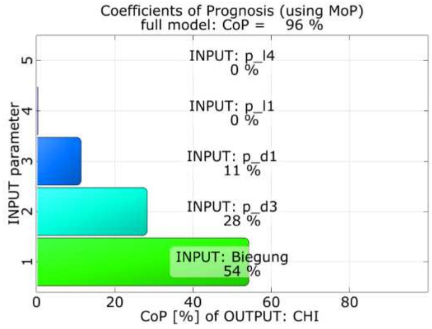

Figure 7: statistical relevance of the input parameter on CHI

The largest influence has the protection against buckling ("Biegung") of the horizontal strut. The height of the horizontal strut (p-d3) and the height of the diagonal (p-d1) had a significant influence on the chi value too. All other parameters were neglectable. The chi value did not benefit from the introduction of any other struts and braces.

As a result, the further struts were discarded. The optimal design simply consists of the diagonal and the horizontal strut. For medium and larger cantilevers, the stability of the horizontal leg benefits from an angled shape.

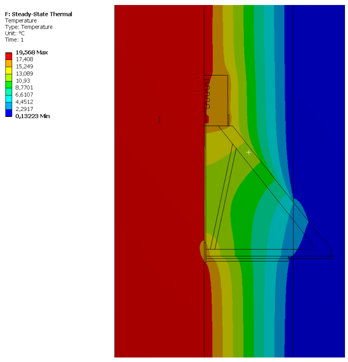

Figure 8: temperature field cut out of the 3D model

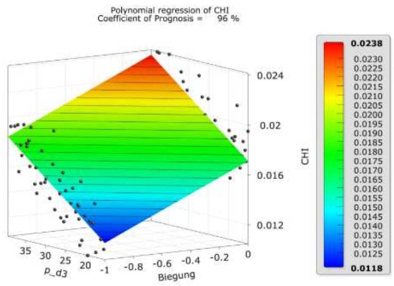

Figure 9: height of the horizontal strut vs. chi and vs. buckling resistance

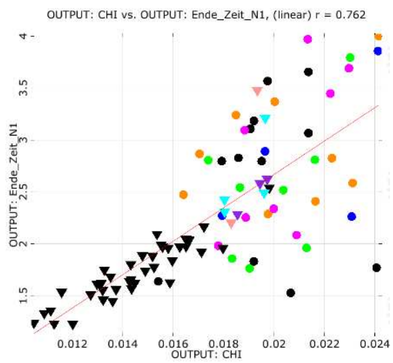

Figure 10: Overview load bearing capacity vs. Chi

Figure 9 shows the chi-value depending on the height of the horizontal strut with and without buckling protection. An overview of the load bearing capacity versus chi value is given in Figure 10. The different colors indicate the type of model according to figure 6.

The thermal optimization results in a theoretical improvement of up to 74% compared to the reference design. The mechanical target properties were controlled by specifying a constraint regarding the end time. The thermal target was defined by minimizing the chi value. The cost target is in turn directly correlated with the thermal target and thus automatically included. This academic approach has to be adapted to constructive border conditions. Production requirements resulting from needs for welding, laser cutting or bending have to be respected and lead to a final design which has to be proven in the following.

3. STATIC RESISTANCE

The load bearing elements of the here examined Brickwork Support Brackets formed from straight steel elements, are to be type tested. For obtaining this type approval, static calculations were provided. The U-shaped bracket which ensures adjustability and is responsible for fastening to the building, is approved by the German Building Authority DIBt Berlin.

3.1 Calculation

Static calculations according to Eurocode 3 [5] were prepared for the web plates, the support plates or support angles and pressure plates or adjusting screws, which were checked by an external institute. This confirmed the stated load capacities. The applicability of the bracket heads is additionally confirmed by a general building authority approval from DIBt. The indicated loads of the bracket heads are verified by component tests. Furthermore, masonry support brackets are covered by the harmonized standard EN 845 [3] and by this they can be CE marked. In addition to the test-related verification of the load capacities, this standard also requires the deflection of the brackets to be stated at 1/3 of the value of the stated load capacity. The tests for measuring the displacements were performed according to EN 846-10 [6], an illustration of the test setup can be seen in figure 11.

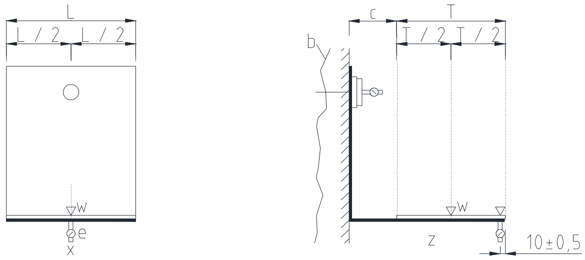

Figure 11: test setup acc. to EN 846-10 [6]

3.2 Load tests

Load tests were implemented to confirm the calculated values of the load-bearing capacity and the serviceability of the here described masonry brackets. Brackets of the different load levels with different cantilever lengths were mounted on steel plates to reduce friction effects.

The horizontal load direction corresponded to a vertical load from the dead weight of the masonry on the real component. The wedge plate was mounted in the lowest position to generate maximum compressive forces in the horizontal strut of the masonry brackets.

The tensile forces were applied continuously with a hydraulic cylinder to the support plate of the masonry bracket, see figure 12. The load was first applied at nominal load. In a second step, the masonry supports were loaded until failure, see figure 13. The failure mode usually was buckling of the compression strut. The applied load and the displacements were measured with calibrated test equipment and recorded on a PC using standard data acquisition software.

Test conditions and results of the load tests are illustrated in table 1 and figure 14.

Figure 12: test setup for load tests

Figure 13: masonry bracket after test

Table 1: Test specimen (load tests) for one specific load class

Specimen	1	2	3	4	5	6	7	8	9	10	11	12
Cantilever [mm]	210	210	210	210	310	310	310	310	350	350	350	350

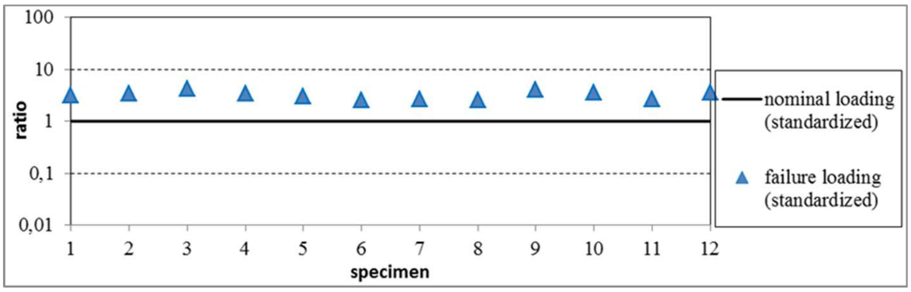

Figure 14: Load test results for one specific load class

3.3 Robustness tests

In addition to the load test of the standard masonry brackets, further robustness tests were carried out due to the filigree shape of the optimized brackets. In these tests, the brackets were specifically preformed or incorrectly installed and then loaded analogously to the load tests.

Pre-deformations e.g were bending of the inclined strut or the horizontal compression strut or even twisting of the bracket. For the simulation of the faulty installation, masonry brackets were installed at an angle so that the pressure plate was not under the head. The aim of these tests was to assess the performance of a masonry brackets which was incorrectly installed or which was deformed manually on the construction site. Regarding to load introduction as well as recording and documentation of the measured values the robustness tests were carried out analogous to the load capacity tests (chapter 3.2). Test conditions and results of the robustness tests are illustrated in table 2 and figure 15.

Table 2: Test specimen (robustness tests), for one specific load class

Specimen	5	6	7	8	9	10	11	12	13
Cantilever [mm]	350	350	350	350	350	350	350	350	350

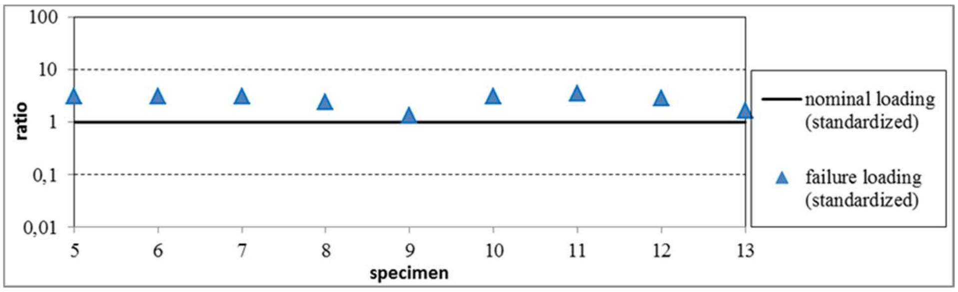

Figure 15: robustness test results for a specific load class

As last step of the optimization the load bearing concept is taken into account and a range of three load classes and 12 projections were optimized with a refined model.

5. CONCLUSION

Support brackets for Brickwork façades always represent a thermal bridge to be considered and should be minimized. In the design process described here, only the boundary conditions of the topology were determined within a finite element model in which the chi value and the material utilization are optimization functions for generating the new shape. It can be shown that the minimization of the steel cross-section corresponds directly with the reduction of the thermal bridge. The objective was a significant reduction of the thermal conductivity compared to existing, already improved brackets. While the thermal bridge is minimized, the load-bearing capacity did not have to be reduced but could even be increased.

The new shape is cost and material saving. Additionally, production benefits can be achieved like minimized weld seams, minimized weight, and minimized laser cutting length including a reduction in waste. Furthermore, the load can be increased. This improves the environmental balance by saving resources and by reducing heat losses over many years.

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WINDOW PLACEMENT AS A THERMAL BRIDGE IN A SUSTAINABLE HEMP-LIME CONSTRUCTION

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Abstract

Thermal bridges are an important issue for buildings built with the use of sustainable materials based on organic components, such as wood and hemp-lime composite. Increased heat losses in construction junctions reduce the temperature of the internal envelope surface, causing moisture condensation and mould growth, especially dangerous in the case of materials susceptible to biological degradation.

Constructions from wood and organic insulating filling are considered sustainable, thanks to the low carbon dioxide emission during the production and building process, possibility of recycling and the opportunity of using locally prepared materials and components. Building partitions presented in the paper consist of a timber frame forming the load bearing structure, filled with a hemp-lime composite acting as the stiffening, thermal insulation and fire protection. Numerical analyses of the window placement in an external wall took into account different thermal conductivity of the composite together with various types of walls and jamb construction. Thermal parameters of hemp-lime composites were obtained from the authors' own research.

Keywords: hemp-lime composites, timber frame construction, thermal bridges, construction junctions, thermal conductivity

1. INTRODUCTION

Despite the use of increasingly energy-efficient constructions, heat losses during the heating season can be significantly influenced by the thermal bridges, constituting "weak points" in the buildings' fabric [1, 2]. Potential thermal bridges in the building structure are usually the partitions' joints: connection of the external wall with the roof, the ceiling, the floor on the ground, the windows and corners. They do not only contribute to the seasonal energy consumption, but also cause local temperature difference.

Temperature reduction on partitions' surfaces is followed by an increased risk of surface condensation as well as interstitial condensation and mould growth in the wintertime, reducing indoor air quality and causing the emission of allergens, irritants, or even toxic substances

[3, 4]. These phenomena are especially dangerous in the case of walls made of material based on plant ingredients, as they are particularly susceptible to biological corrosion.

2. HEMP-LIME COMPOSITE

Hemp-lime composite is a relatively new material, and in many countries only the first buildings using this material have been built. This technology is most developed in France and in the UK. The composite has been tested in many aspects, such as mechanical properties [5, 6], thermal properties [7, 8] and moisture transport [9, 10].

Hemp-lime composite is prepared from a binder based on lime (hydrated or hydraulic with additives), hemp shives obtained from the wooden core of industrial hemp stalks, and water. It is characterized by low bulk density, ranging from 350 to 630 kg/m^3, and relatively high thermal insulating properties thanks to its high porosity in the range of 75 ÷ 80% [11]. Due to the cellulose content, the composite has a high heat capacity of about 1300 J/(kg·K), positively influencing the thermal stability of the partitions [8]. These properties make it an interesting alternative for traditional insulations, especially in the area of sustainable constructions.

2.1 Authors' research on composites and their thermal properties

For the preparation of the composites hemp shives from the industrial hemp of the "Białobrzeskie" variety were used. This is a Polish variety, adapted to local climatic and soil conditions, bred by the Institute of Natural Fibres and Medicinal Plants in 1967. The binder consisted of hydrated lime CL90s class (75% by weight), gypsum (15%) and pozzolan (10%). Gypsum was used in order to accelerate the setting process, and pozzolan helped to achieve greater resistance to the moisture. Two recipes of hemp-lime composites were worked out, differing in the binder to filler ratio, as set out in the Table 1.

Table 1: Recipes of the hemp-lime composites

No.	Composite symbol	Binder : hemp shives ratio (by weight)	Binder : water (by weight)
1.	HLC1	1.4 : 1	1 : 1.45
2.	HLC2	1.6 : 1	1 : 1.45

Thermal conductivity was measured in a FOX314 plate apparatus consisting of a cooling and a heating plate with a heat flux sensor in accordance with the ISO 8302 method [12]. The thermal conductivity tests were carried out on the six specimens with dimensions of 50×300×300 mm. The heat flux passing through the specimens was perpendicular to the compaction direction of the material, as in the external walls (Figure 1). The temperature set on the heating plate was 25°C, while on the cooling plate it was 0°C. The specimens were tested after 28 days of maturation in laboratory conditions (air temperature 20°C ± 2°C, relative humidity 55% ± 5%).

Table 2: Thermal conductivity of tested composites averaged for six specimens

No.	Composite Symbol	Thermal conductivity coefficient [W/(m·K)]	Standard deviation [W/(m·K)]
1.	HLC1	0.080	±0.002
2.	HLC2	0.088	±0.003

The thermal conductivity coefficient depends on the material density, which, in turn, is related to the binder-to-filler ratio (Table 2). As the binder content increases (recipe HLC2), the insulating properties of the material deteriorate [11, 13]. The test results were used in further computer analyses of thermal bridges as limit values for the thermal conductivity coefficient. In addition, indirect values from the 0.080 ÷ 0.088 W/(m·K) interval, namely 0.082 W/(m·K), 0.084 W/(m·K) and 0.086 W/(m·K), which are likely to be achieved with a binder to filler ratio between 1.4:1 and 1.6:1, are used to illustrate the relationship between the thermal quality of a joint and the thermal conductivity of a wall material.

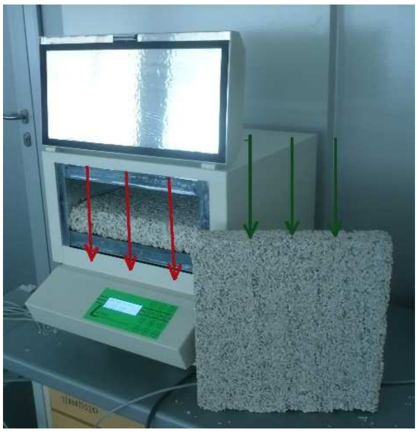

Figure 1: The specimen placed in the plate apparatus. Red arrows – direction of the heat flux during the test, green arrows – direction of the specimen compaction

2.2 Hemp-lime composite as an insulation filling

The composite can be used as a filling (insulation) of partitions with a wooden frame construction. The timber frame is usually hidden in a layer of the composite or aligned with the surface of the partition. To ensure proper insulating properties of the external walls, the thickness of the composite layer is in the range of 300 to 400 mm, depending on the national requirements regarding thermal insulation.

The structure of the walls comprises studs placed in a spacing of 400 to 600 mm, depending on the load. The studs are set on the sole plate and topped by a wall plate. The hemp-lime mixture is placed and compacted in the formwork (temporary or permanent), attached to both sides of the wall structure. There are two typical methods of constructing walls, differing in the location of the load-bearing frame [14, 15]. In the first case the timber construction is placed centrally in relation to the wall thickness, ensuring the uniform distribution of the loads. Timber elements of the frame are surrounded by hemp-lime composite, providing protection against wood pests and biological corrosion (because of the alkalinity of lime). In the second case the load-bearing frame is located on the inner side of the external wall (aligned with the inner surface). This solution simplifies the shuttering works and also allows the installation of permanent shuttering, e.g. wood fibre board.

The window frame is attached to the timber studs with an increased cross section (two studs of 50×150 mm located next to each other). The jamb can be formed with or without the reveal (Figure. 2). It is possible to place the window frame in different positions relative to the wall thickness using an additional timber stud marked as "4" (with different cross-sections). Several situations were taken into account in the analyses: the window frame placed in the centre and at the outer edge of the main timber construction frame (locations “0” and “1”), and extended toward the outside surface of the wall by 50, 100, 150 and 200 mm (locations “2” and further). Two thicknesses of hemp-lime composite layer were taken into account: 350 mm and 400 mm.

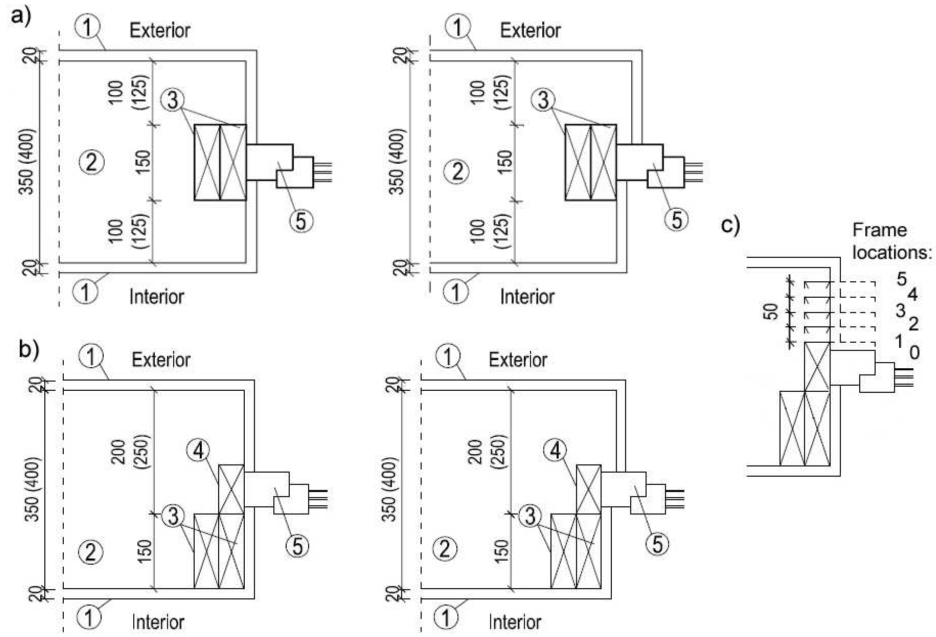

Figure 2: Window placement in the wall: a) centered timber construction (without or with the reveal), b) timber construction in the inner part of the wall (without or with the reveal), c) analysed frame locations. 1 – lime plaster, 2 – hemp-lime composite, 3 – timber stud 50x150 mm, 4 – timber stud 50x100 mm , 5 – window frame.

4. THERMAL BRIDGES MODELLING

Temperature distribution in the described construction joints was calculated with the Therm 6.3 software [16], commonly used in the thermal evaluation of two-dimensional heat transfer in building partitions and construction joints [17, 18]. The modelling process consists of the following stages [19]:

- model definition (including geometry definition, assignment of material properties and boundary conditions)
- mesh generation
- calculation of temperature and heat fluxes by the Finite Element Analysis Solver
- reporting of the post-processed results for the element.

The linear thermal transmittance coefficient ψ is calculated according to [20] as:

$$\psi = L^{2D} - \sum_{i=1}^{j} U_i \cdot l_i \tag{1}$$

where L^{2D} is the thermal coupling coefficient obtained from the 2D analysis of the modelled element [W/(m·K)], U_i is the thermal transmittance coefficient of the i-th component of the modelled element [W/(m^2·K)], l_i is the length assigned to the U_i value [m].

Thermal properties of materials and elements used in modelling together with boundary conditions are compiled in the Tables 3 and 4. The estimated error energy norm (related to the gradient of heat flux) of the results did not exceed 5% in all of the cases.

Table 3: Thermal properties of main materials and elements

No.	Building material/element	Thermal properties
1.	Hemp-lime filling	$\lambda = 0.080 \div 0.088$ W/(m·K)
2.	Wooden construction element	$\lambda = 0.16$ W/(m·K)
3.	Lime plaster	$\lambda = 0.70$ W/(m·K)
4.	Window frame	$U_f = 1.00$ W/(m^2·K)
5.	Glazing	$U_g = 1.00$ W/(m^2·K)
6.	Window – total	$U_w = 1.10$ W/(m^2·K)

Table 4: Boundary conditions used in the calculations

No.	Surface	Temperature	Surface resistance	Description
1.	Internal	+21ºC	0.13 (m^2·K)/W	Heat flow horizontal, simplified*
2.	Internal	+21ºC	0.10 (m^2·K)/W	Heat flow upwards, simplified*
3.	Internal	+21ºC	0.17 (m^2·K)/W	Heat flow downwards, simplified*
4.	External	-18ºC	0.04 (m^2·K)/W	Simplified*
5.	Cut-off planes	–	–	Adiabatic

* simplified heat transfer means that the radiative and convective heat exchange is described by one common surface resistance.

4.1 Results and discussion

The simplest solution is placing the window jamb in the centre of the strengthened (double) timber stud. The window can also be moved to the outer edge of the stud or mounted outside the main load-bearing structure with the use of an additional wooden frame. As different construction options would have an important influence on the heat flow patterns, this joint was analysed in several versions. In addition to basic window placement (in the middle or at the outer edge of the construction frame – locations "0" and "1", respectively), the window was moved by 50 mm to the outer edge of the wall (locations "2" and further). Along the window perimeter the jamb was insulated or not, doubling the number of the types of joints taken into account. Exemplary layout of the isotherms is shown in the Figure 3.

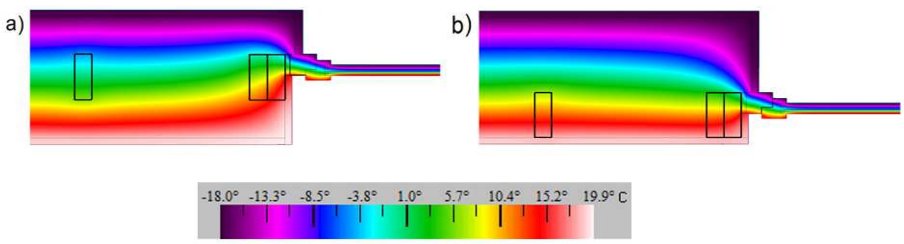

Figure 3: Isotherms in the jamb in the two cases of timber frame location: a) central, b) aligned with the inner plane. Wall thickness: 400 mm, hemp-lime conductivity: 0.080 W/(m·K), window frame location – position "1", case with a reveal

The linear thermal transmittance coefficients do not depend significantly on the hemp-line conductivity, and the graphs remain almost constant for a given type of joint (Figure 4). The joint construction, however, has a very important influence on the heat flow and the thermal quality of the connection. To show this relationship, ψ values were plotted against the location of the window frame in the wall's cross-section (Figure 5). For a clearer presentation, the graph in the Figure 5 was made for the smallest hemp-lime conductivity ($\lambda = 0.080$ W/(m·K)).

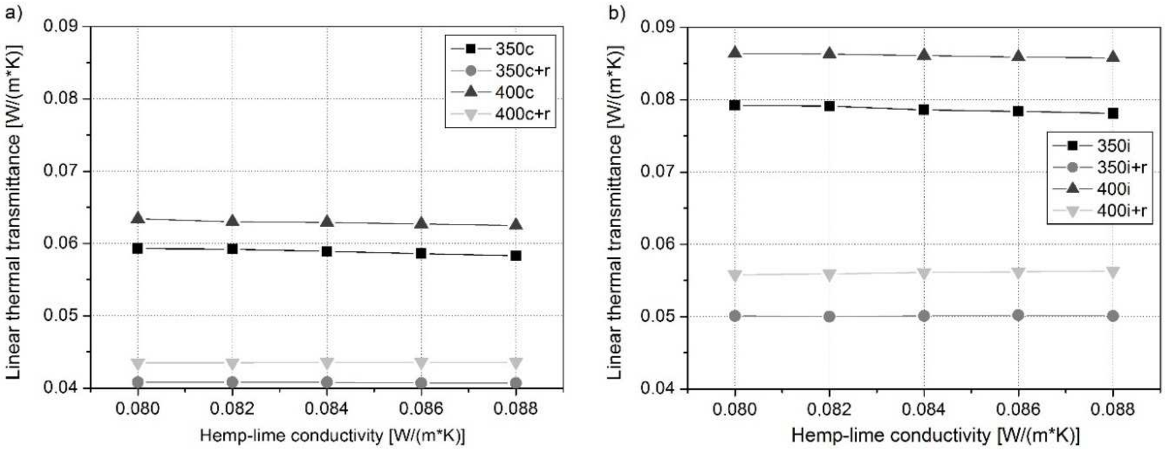

Figure 4: Linear thermal transmittance coefficients vs hemp-lime conductivity: a) centered timber construction (frame location "0"), b) timber construction at the inner part of the wall (frame location "0"). Number in the legend denotes the wall thickness, c – central location of the timber frame, i – internal location of the timber frame, r – reveal

When considering the wall with the load-bearing construction in the middle, the location of the window frame in the area of the timber studs is the most favourable (Figure 5.a). For the uninsulated perimeter, the best option is placing the jamb closest to the studs' outer edge – this can reduce the linear thermal transmittance by approximately 3% to 6% compared with the window's central position. If the window perimeter is insulated, the central position reduces the thermal bridge the most, giving the lowest ψ values of 0.0408 W/(m·K) and 0.0435 W/(m·K) for the walls 350 mm and 400 mm wide, respectively. Moving the windows to the outside increases the heat transfer in the joint, and the effect is more pronounced if the window perimeter is insulated.

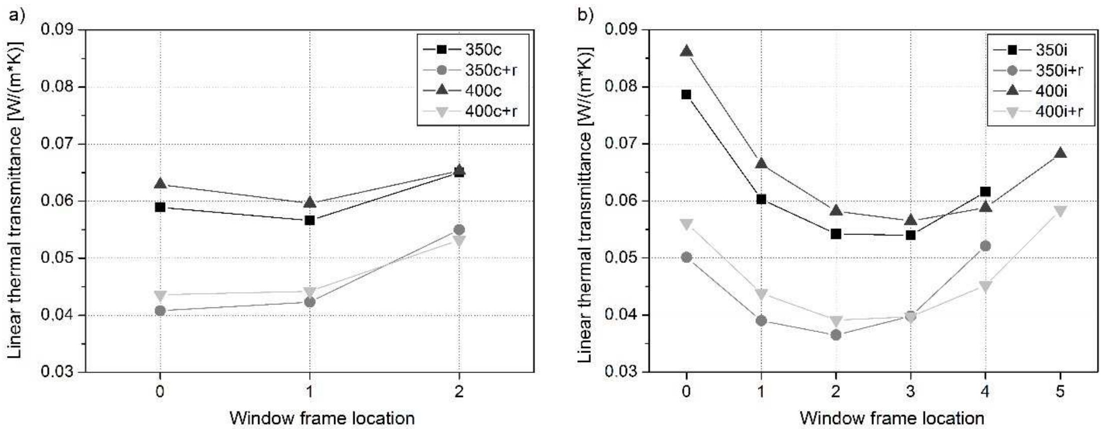

Figure 5: Linear thermal transmittance coefficients vs window location: a) centered timber construction, b) timber construction at the inner part of the wall. Number in the legend denotes the wall thickness, c – central location of the timber frame, i – internal location of the timber frame, r – reveal

For the wall with the load-bearing construction in its inner part, the results are different. Here, placing the window centrally over the timber studs is the worst case, giving the highest values of linear thermal transmittance (Figure 5.b). While moving the window frame to the outside, the ψ values gradually decrease and increase, reaching the minimum for the location extended by 100 mm from the outer edge of the studs (uninsulated perimeter) or by 50 mm (insulated perimeter). The outermost jamb placement is not the best solution because of the deeper penetration of the supporting timber structure into the insulating material. The benefits of proper window placement reach on average a 30% reduction of the linear thermal transmittance. It is worth noting that the lowest ψ values obtained for this type of construction are smaller than in the previous case (0.0365 W/(m·K) and 0.0391 W/(m·K) for the walls 350 and 400 mm wide, respectively).

Regardless of the wall type, the insulation of the frame perimeter decreases the heat losses by approximately 15% to 37%, and the effect is strongest if the joints are of a poor thermal quality.

5. CONCLUSIONS

Despite relatively good insulating properties, timber elements have a noticeable influence on the local increase of the heat transfer in hemp-lime composite structures, forming thermal bridges in the construction nodes.

The window placement turned out to be a very specific construction detail, where a lot depends on the shaping of the wooden reinforcement and the reveal. The linear thermal transmittance coefficients varied from approximately 0.035 to 0.090 W/(m·K), and this can be regarded as a good result, proving the usefulness of this type of construction in energy-efficient and sustainable buildings. The wall with an internal timber frame seems to be the partition type having a bigger potential for minimizing heat losses, making it possible to achieve the lowest linear thermal transmittance coefficients.

Generally, it can be concluded that despite the occurrence of thermal bridges, hemp-lime building structures can be sufficiently protected from excessive heat losses thanks to proper design decisions. The final assessment of the influence of thermal bridges should be connected with the whole building energy analyses, as the heat losses through the envelope depend not only on the linear thermal transmittance, but also on the length of the specific joints in the building's structure.

ACKNOWLEDGEMENTS

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IMPACT OF THE USE OF FLEXIBLE JOINTS TO IMPROVE THE ENERGY OF NEARLY ZERO ENERGY BUILDINGS

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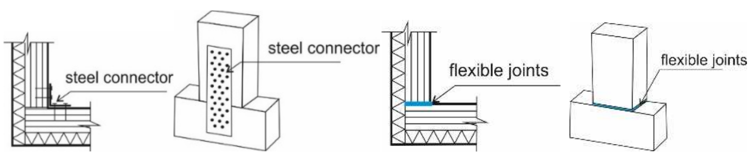
Abstract

Development of nearly zero-energy building is very rapid in recent years. The Directive on the energy performance of buildings 2010/31/EU introduced an obligation for all member states to implement almost zero-energy buildings (NZEB). NZE buildings will have to be designed from as early as 2021. Introduction of such stringent thermal protection requirements for buildings has resulted in the need to search for new innovative material and technological solutions that would improve energy efficiency. In the article, Authors present a new, innovative solution for solving structural knots in wooden frame technology. The solution is based on a flexible joint. Authors carried out laboratory tests of thermal parameters of the materials used to build a new technology. The test results were the basis for the analysis of selected construction nodes of the developed technology. The aim of the research and analysis was to show that the applied flexible joint, in comparison to the standard solution based on mechanical connectors, improves thermal insulation of nodes.

Keywords: NZEB, energy efficiency, flexible joints, wooden constructions.

1. INTRODUCTION

The Directive of the European Parliament and the Council of Europe on the energy performance of buildings was published (recast version, the so-called Recast) on 13 April 2010 [1]. Article 9 of the Directive requires from the Member States to introduce a standard of nearly zero energy buildings from 1 January 2021. A building with almost zero energy consumption means a building with very high energy efficiency. The almost zero or very low amount of energy required should come to a very high extent from energy from renewable sources, including them produced on-site or nearby [1]. Each of the EU member states sets the minimum requirements, based on the analyses of economically justified solutions [2, 3, 4]. In Poland, the minimum requirements for NZE buildings are included in the technical and construction Conditions [5]. The stringent requirements for thermal protection of NZE buildings encourage looking for material and technological solutions that will be better than the existing ones and will improve the energy efficiency of buildings [6, 7, 8]. Manufacturers of materials and technologies are trying to innovate their solutions to increase the energy efficiency of buildings. In addition to the development of modern brick and concrete technologies, the development of wooden house technologies [9], is also noticeable. A trend can be observed that people nowadays more often choose to live in individual houses and pay more attention to ecology, comfort and natural resources [10]. These are the factors favourable for the development of technology of wooden houses. Wood-based technologies are characterized by lower costs compared to masonry technologies [11]. Buildings made in technology of both skeleton and cross laminated timber (CLT) provide high thermal and acoustic insulation, high energy efficiency and tightness of the building. Wood is also an important modern building material that can absorb carbon dioxide. Wood acts as a carbon dioxide absorber by converting CO_2 to biomass in the process of bio-sequestration through photosynthesis [12]. Such wood properties mean that constructions based on a natural component positively affect the environment and are part of the concept of a "sustainable city" and a "residence-friendly city" [12]. An important aspect for investors is the time and cost of erecting a building. In turn, the article [11] presents the calculation of the costs of constructing a clay brick wall and in the Canadian system (wooden frame structure). The most economical was the wooden frame system with straw bale filling. An important aspect is also the assessment of energy efficiency of buildings. The assessment of buildings, according to the assumptions of sustainable development, should take into account the whole life cycle, starting from obtaining raw materials, designing, exploitation to recycling and reusing materials (closed cycle) [15, 16, 17]). In the paper [18] it is presented the possibility of using cross-laminated wood (CLT) as an alternative solution for concrete by life cycle assessment. The results of this article show that using wood construction to replace conventional material with a high carbon content would reduce energy consumption by more than 30% and reduce CO_2 emissions by more than 40%. In the articles [19, 20] the author shows wood constructions as an alternative to reinforced concrete structures. In article [19] the results show that the estimated energy consumption and CO_2 emissions for CLT buildings are 9.9% and 13.2% lower than for reinforced concrete buildings in the context of life cycle assessment. Research teams are looking for the best wooden construction solutions, characterized by high strength, deformability, and shock resistance. In the article [21] presented experimental analyses and tests for massive timber walls. Studies of wooden structures in respect of seismic resistance were also described in [22, 23, 24]. These studies have shown that the wood construction is characterized by high strength and stiffness. The seismic strength of wood construction buildings is mainly related to the possibilities of connections which should be flexible and cooperate with the wooden structure, since wooden elements have limited deformation ability [25]. Timber wood constructions are normally connected by metal connectors such as anchors, angles or flat bars. (Fig. 1 a,b). In the article [26] it is presented the concept of an innovative connection to wood panels. The solution proposed by the author allows to improve the plasticity of connections and energy dissipation. Increased seismic properties of shear walls result from the optimized shape of the steel bracket X.



a b c d

Figure.1 Steel connector in CLT construction (a), steel connector in timber frame construction (b), innovative flexible joint developed by the authors (c,d).

In this article, Authors presented an innovation based on the introduction of wood technology to structural nodes - a flexible joint in place of traditional engineering connectors (Fig. 1c,d). The use of flexible joints in wooden constructions gives the possibility of reduction of concentration peaks, safe transfer of loads, resistance to moisture, new quality of wooden constructions and extension of exploitation possibilities beyond the existing limitations. Flexible joints allow to eliminate steel joints, thus improving cooperation with the structure in places where loads are transferred. In the developed innovative flexible joint, the proportions and type of polymers have been selected by the research team in such a way as to ensure the best possible operation of the wooden construction as well as very good thermal insulation properties of the structure. The research question posed by the authors is «whether replacing traditional engineering connections such as steel joints by gluing with flexible joints in construction nodes improves thermal insulation of timber construction». The research task is to determine the real thermal conductivity coefficients of materials used in structural nodes of innovative technology from wood (wood, thermal insulation, flexible joint). The next step of the research was to conduct a thermal numerical analysis of the wood construction node with the engineering connectors used and a comparison with the proposed innovative connection with the flexible joint. The aim of the analyzes and tests was to confirm better thermal properties when using a flexible connector.

2. MATERIALS AND METHODS

2.1 Materials

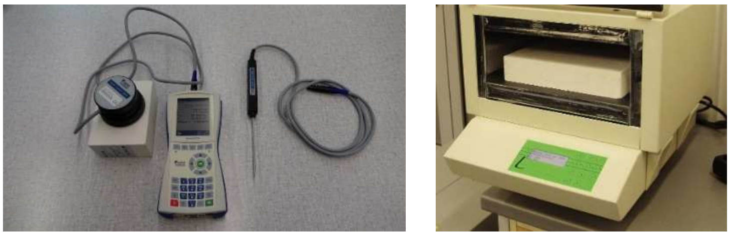
In order to determine the actual thermal parameters of materials used in the construction node, laboratory tests were carried out. The tests were carried out on material samples made of wood, flexible joint, thermal insulation material and on a hard and soft flexible joint. Wood samples were 140 x 140 x 25 mm. Thermal insulation samples had the following dimensions: 300 x 300 x 80 mm in the case of wood wool, 300 x 300 x 150 in the case of stone wool. Samples of flexible joints in the case of soft PM polymer -160 x 160 x 10.02, in the case of hard PT polymer 160 x 160 x 9.63.

2.2 Methods

In order to determine the actual thermal parameters of materials used in the nodes of the developed technology, the thermal conductivity coefficient λ [W/(mK)] and the volume thermal capacity Cv [J/(m^{3}K)] were measured. The tests were carried out for samples of materials from which a connection will be made at the node. Knowledge of thermal coefficient of material allows for precise calculation of thermal insulation properties of partitions or construction details. This approach also allows for adjusting the thickness of individual layers to the heat protection requirements in a given location or time, or to individual investor's expectations. The thermal capacity tested allows for the calculation of dynamic (non-stationary) thermal fields. The tests are compliant with PN-EN ISO 8301:1998 [27], PN-EN 12667:2002 [28], ASTM C518-91 [29]. The samples were seasoned prior to testing. A constant weight was determined for the conditions: average air temperature 21.3 +/- 0.5^{0}C, relative air humidity 23%.

2.3 Test equipment used

Due to the small size of the delivered wood samples, the thermal conductivity test was carried out in an ISOMET 2114 apparatus from Applied Precision Ltd In the test apparatus, thermal conductivity was measured using the non-stationary method. The same apparatus was used to test the thermal capacity of material samples. A surface probe (contact) IPS 1105 was used for both studies. In the thermal conductivity measuring range 0.015 to 0.70 [W/(mK)], the accuracy is 5% of reading +0.001 [W/(mK)]. The accuracy of the device, in the case of heat capacity measurement, in the measuring range 4.0.104 - 3.0.106 [J/(m^3K)] is 15% of reading +1.103 [J/(m^3K)]. The thermal conductivity test of thermal insulation samples (wood wool and stone wool) was carried out using the stationary heat transfer method in the FOX 314 plate apparatus from LaserComp USA. The measuring range of the thermal conductivity coefficient is 0.01 to 0.2 [W/(mK)], measuring accuracy 1%. Testing in a plate apparatus is based on the method of measuring thermal resistance using heat flux sensors in stationary conditions.



a) b)

Figure 2: ISOMET 2114 (a), FOX 314 (b)

3. RESULTS

3.1 Results of laboratory tests of material features of structural elements.

A test for thermal conductivity and thermal capacity was carried out on all material samples described in section 2.1. All construction materials tested form structural nodes in the developed innovative technology. The parameters examined are summarized in Table 1. The measured parameters were used for numerical analysis of construction nodes in two variants.

Table 1: Parameters of material samples tested in the laboratory.

Material samples	Thermal conductivity coefficient λ [W/(mK)]	The volume heat capacity x 10^3 C_v [kJ/(m^3K)]
Wood	0.1157	1.3595
Wood wool	0.0379	0.1369
Stone wool	0.0345	0.1217
PM soft polymer	0.1013	0.7418
PT hard polymer	0.1224	1.0172

3.2 Numerical simulation of heat transfer through construction nodes in two variants

<u>Theory and FEM formulation for the heat transfer phenomenon through the walls of the building</u>

The phenomenon of heat transfer in the building walls can be described by the Fourier-Kirchhoff heat transfer equation [30]-

$$div(\lambda \cdot gradT) - c \cdot \rho \cdot \frac{\partial T}{\partial t} = 0 \tag{1}$$

Equation (1), assuming the homogeneity and isotropy of materials and the thermal conductivity λ independent of temperature, takes the general form (2). The heat transfer equation (2) is simplified to the Laplace equation, (3) when a specific case of heat transfer is analyzed - steady state. Equation (4) is called the first Fourier's Law of Conduction [30].

$$\lambda \cdot \nabla^2 T - \rho \cdot c \cdot \frac{\partial T}{\partial t} = 0 \tag{2}$$

$$\nabla^2 T = 0 \tag{3}$$

$$q_n = -\lambda \cdot \frac{dT}{dn} \tag{4}$$

Boundary conditions can be assumed as boundary conditions of the third type (5).

$$\left(\frac{\partial T}{\partial n}\right)_w = -\frac{\alpha}{\lambda}\left(T_w - T_f\right) \qquad T_w > T_f \tag{5}$$

Where:

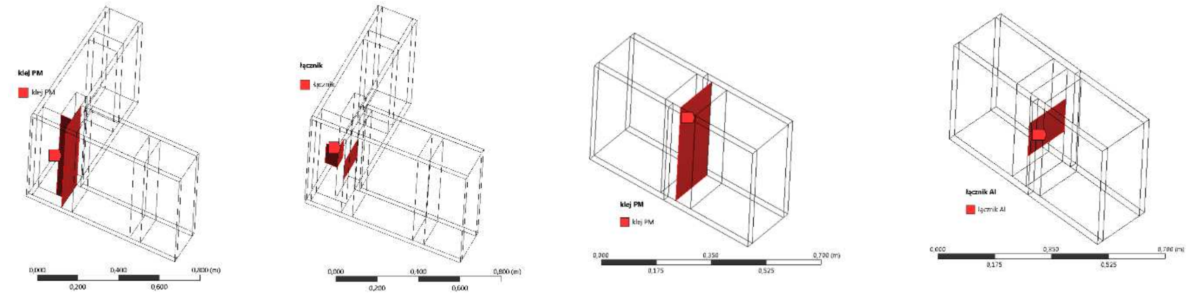
∇ - Laplace operator, ρ - mass density [kg/m^3], c - specific heat capacity [J/kg·°C], t - time [s], λ - thermal conductivity [W/m·°C], n – surface normal, T – temperature [°C], T_f – ambient temperature, T_w – surface temperature [°C], q - heat flux [W/m^2], α – convective film coefficient [W/m^2·°C]. The problem of heat transfer through building walls described by equation (3) was solved using the Finite Element Method. The general formulation of the FEM issues (for equation (3)) is as follows [31].

$$[K_{th}] \cdot \{T\} = -\{Q\} \tag{6}$$

where:
$[K_{th}]$ – conductivity matrix [W/°C],
{T} - vector of nodal temperatures [°C],
{Q} - vector of nodal heat flows [W].

3.3 3-D Finite Element Modeling of wall construction nodes.

The subject of the analysis was the phenomenon of heat transport in two construction nodes of a wooden building with a frame structure. In the analyzed nodes, two connection methods were used. The first variant implemented the joint using metal connectors at the axial distance of 65 cm, the second variant with the PM polymer glue spread over the entire column height. Geometric models adopted for analysis are shown in Figure 3. The material data needed for numerical analyzes is given in Table 1.



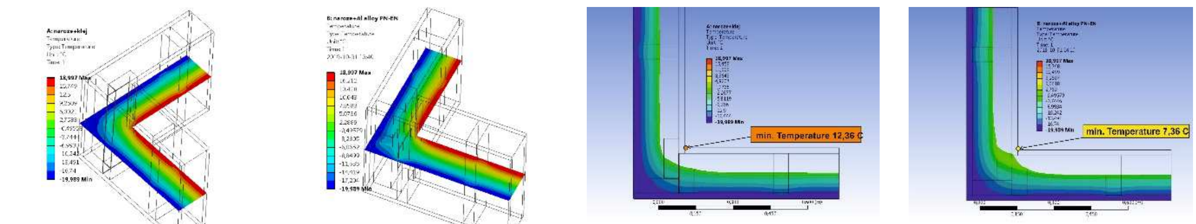
a) flexible joint with polymer glue | b) traditional joint with metal connector | c) flexible joint with polymer glue | d) traditional joint with metal connector

Figure 3: Geometry of construction node in the outer wall corner (a,b), Construction node geometry of the face connection in the outer wall (c,d)

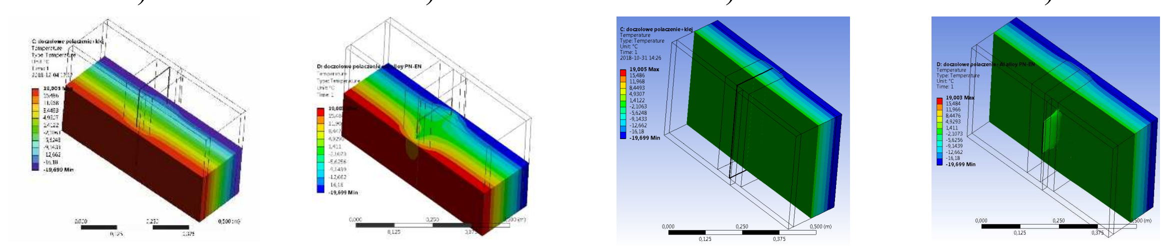
The material data from Table 1 were accepted for numerical analysis. The heat transfer coefficient of the metal connector (aluminum) was adopted in accordance with [32] λ = 200 [W/(mK)]. The analysis was carried out for boundary temperature conditions in accordance with [33]: R_{si} = 0,13 [(m^{2}K)/W], R_{se} = 0,04 [(m^{2}K)/W], T_i = +20[^{0}C], T_e = -20[^{0}C]. Thermal analyzes were carried out in the ANSYS system in the Multiphysics module. In the 3D model 20-node elements SOLID 90, 4-node elements SHELL131, 8-node elements SURF152 and 8-node contact elements CONTA174 were used [31]. The analysis was carried out in a steady state.

3.4 Results of the FEM analysis

Selected results obtained using FEM analysis in the form of colour maps are shown in Figures 4a-h. Minimal internal surface temperatures in the wall corner in the case flexible joint is 12.36 [^{0}C] (Fig.4c), in the case traditional joint is 7.36 [^{0}C] (fig. 4d).



a) b) c) d)



e) f) g) h)

Figure 4 Temperature distribution for a construction node with polymer glue (a, e), for a construction node with metal connectors (b, f), distribution of only the negative temperature for the construction node with polymer glue (c, g), for the construction node with metal connectors (d, h).

4. CONCLUSIONS

The technologies of building houses based on wood, have been very popular recently. In comparison with traditional technologies in Poland, wood technologies are ecological, more economically efficient, faster in construction. It is worth considering introducing in the construction nodes wooden technologies of the flexible joint, instead of standard connections using aluminum connectors. The use of flexible joints in wooden constructions gives the possibility of reducing peak concentrations, safe load transfer, resistance to moisture. The authors showed that joining structural elements improves thermal insulation of construction nodes. The results of FEM simulation show that thermal insulation has more construction nodes using polymer glue as a connector. The heat consumption per day for the assumed air temperatures inside and outside the building and the adopted model geometry (wall fragment) is:

- 800 kJ for the construction node in the corner of the outer wall with metal connectors and is about 5.5% higher than the glued connection method (758.6 kJ).
- 267 kJ for a construction node of a face outer wall with metal connectors and is approx. 17% higher than a connection with the use of glue (226.9 kJ).

ACKNOWLEDGMENTS

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MULTIDIMENSIONAL HYGROTHERMAL ANALYSIS OF COMPLEX BUILDING CONSTRUCTIONS

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Abstract

In accordance with nowadays building energy performance requirements, building constructions developed significantly in the past few years due to new construction materials and building elements, because of the need for increased thermal insulation layers and the development of new building technology solutions. However thermal performance requirements are tightening, there are no moisture performance requirements connected to them, therefore in most cases, building construction design, if at all, only include simplified vapour transfer calculations. This paper presents a comparative analysis of multidimensional conjugated heat- and moisture transport numerical FEM simulations of modern building construction joints. For comparison reference, thermal simulations were made, neglecting the hygrothermal aspects. In the paper, besides the detailed wall section, a wall corner joint is presented, both built in 2D from complex building elements, such as insulation filled masonry blocks and were tested using different fillers (aerogel, expanded perlite, expanded polystyrene, mineral wool and PUR foam), respectively. The hygrothermal material properties of the insulation filled masonry blocks were measured in laboratory. The evaluation of the numerical simulation results shows that there are significant differences between thermal and hygrothermal approach and well insulated construction joints behave differently against heat and moisture using different thermal insulation fillers in the masonry blocks.

Keywords: Thermal Insulation Filled Masonry, Heat and Moisture Transfer, Building Construction, Thermal Bridges, Moisture Bridges

1. INTRODUCTION

In accordance with nowadays building energy performance requirements [1] building constructions developed significantly in the past few years. Material producers also started to develop new products to prepare for even tighter requirements in the near future [2], when nearly-zero energy buildings (NZEB) will be the standard to be built. To achieve significant reduction in the heat loss of the buildings, the demand is increased for particularly thermal insulation layers and the development of new building technology solutions. Masonry producers created thermal insulation filled blocks to achieve lower thermal transmittance without the need for applying additional insulation (produced by other companies). In the past few years researchers also started investigating the thermal and hygrothermal behaviour of hollow and filled ceramic masonry blocks with different fillers and geometries [3-8]. In this research, building construction joints made using filled masonry blocks were examined. Due to limitations, in this paper only the horizontal wall and wall corner sections will be presented.

2. COMPOSITION OF THE MULTIDIMENSIONAL GEOMETRY MODELS

Scaled 2D geometry models of the evaluated building constructions are shown in Fig. 1.

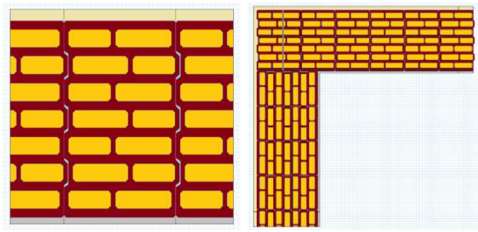

Figure 1: Building construction joints, wall (left) and wall corner (right)

The multidimensional geometry models were constructed bearing in mind the technical guidance of the industry leading masonry block producer in Hungary [9]. As observable in Fig. 1, horizontal sections of a masonry wall and wall corner made from the same blocks were modelled. For the constructions, 24.9 cm x 23.8 cm x 44 cm thermal insulation filled masonry blocks were used. The internal structure of the blocks was modelled according to the most common design of such blocks. Between the blocks in the horizontal joints mortar were used while the vertical joints were connected to each other with tongue and groove connection. 1.5 cm thick gypsum plaster were applied to the internal side and 2 cm thick layer of insulating plaster on the outside surface. In the wall corner that is presented in this paper, the corner masonry block element is constructed using a 2/3 and 1/2 cut masonry block and mortared together.

3. MATERIALS AND METHODS

In the research, monthly based steady-state conjugated heat and moisture transfer (HAM) simulations were carried out based on Künzel [10]. The partial differential equation (PDE) of steady-state heat transfer is shown in Eq. 1.:

$$\nabla q=\nabla[\lambda_{eff}\cdot\nabla T+L_v\cdot\delta_p\cdot\nabla(\phi\cdot p_{sat})]=0 \tag{1}$$

where ∇ is nabla vectorial differential operator $(\frac{\partial}{\partial x},\frac{\partial}{\partial y})$, q is heat flux [W/m^2], λ_{eff} is temperature and moisture dependent effective thermal conductivity [W/mK] according to ISO 10456 [11], T is temperature [K], L_v is latent heat of evaporation of water [J/kg], δ_p is vapour permeability [g/msPa], ϕ is relative humidity [1] and p_{sat} is the saturation pressure of water vapour [Pa]. The PDE of steady-state moisture transfer is defined in Eq. 2.

$$\nabla g=\nabla[\xi\cdot D_w\cdot\nabla\phi+\delta_p\cdot\nabla(\phi\cdot p_{sat})]=0 \tag{2}$$

where g is moisture flux [kg/m^2s], ξ is differential moisture capacity [kg/m^3] according to the hygroscopic sorption isotherms of the materials and D_w liquid transport coefficient [m^2/s] , respectively. Steady-state simulation was chosen instead of performing time dependent hourly based simulations because the main goal of the research is to compare temperature factors and linear thermal- and moisture transmittances of the building constructions considering monthly design conditions to each other, and also to evaluate the effect of neglecting the moisture transfer. The partial differential equations shown in Eq. 1 and 2 were implemented in COMSOL [12], where parametric (changing boundary conditions) and material sweep (changing insulation fillers) were used too. Due to monthly evaluation, only temperature and relative humidity was taken into account as boundary condition. Monthly averaged external data sets of Budapest were obtained from Meteonorm 7 and shown in Table 1. Internal conditions of air, and heat transfer coefficient and the equivalent vapour diffusion thickness of boundary layer were set according to EN 15026 [13]. The effect solar radiation and driving rain were neglected, because these are highly dynamic parameters and monthly averages do not return their variability and behaviour.

Table 1: Monthly internal and external temperature [°C] and relative humidity [1] in Budapest

Month	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.
Ext. temperature	0.9	2.8	7.0	13.3	18.4	21.4	23.1	22.8	17.4	12.5	7.2	1.7
Ext. rel. humidity	0.73	0.68	0.61	0.52	0.53	0.54	0.54	0.54	0.62	0.69	0.73	0.74
Int. temperature	20.0	20.0	20.0	21.7	24.2	25.0	25.0	25.0	23.7	21.3	20.0	20.0
Int. rel. humidity	0.41	0.43	0.47	0.53	0.58	0.60	0.60	0.60	0.57	0.53	0.47	0.42

In the numerical simulations, the hollow masonry blocks were filled with 5 different thermal insulations, such as aerogel (A), polyurethane foam (PUR), mineral wool (MW), expanded polystyrene (EPS) and expanded perlite (EXP). Material properties of the thermal insulations, fired clay (FC), internal plaster (IP) and external plaster (EP) are listed in Table 2 and were measured in laboratory, such as $\lambda_{10,dry}$ thermal conductivity [W/mK] with addition of f_T temperature and f_ψ moisture dependent conversion factors from ISO 10456 [11] and $\mu_{dry/wet}$ water vapour resistance factor [1]. The hygroscopic sorption isotherm of materials were also measured, and moisture storage curves obtained (see Fig. 2). Laboratory measured material properties were compared to similar materials from WUFI database [15], the differences in the values and trends of the hygrothermal material properties were not prominent.

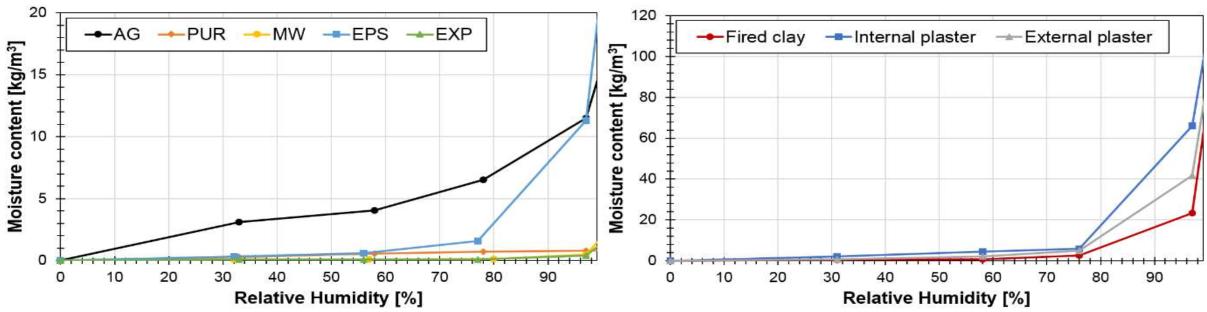

Figure 2: Moisture storage curve of thermal insulations (left) and other materials (right)

Table 2: Main hygrothermal material properties of the steady-state simulations

Material	A	PUR	MW	EPS	EXP	FC	IP	EP
$\lambda_{10,dry}$ [W/mK]	0.012	0.024	0.031	0.037	0.05	0.35	0.4	0.09
f_T [1/K]	0.0015	0.0055	0.0045	0.0035	0.0035	0.001	0.001	0.001
f_ψ [m³/m³]	3	6	4	4	3	10	3	8
$\mu_{dry/wet}$ [1]	4.5	80/70	1.3	70/30	2	15/10	8.1	8.3

4. RESULTS

4.1 Monthly variation of thermal conductivity of insulating materials in wall sections

Effective thermal conductivity of every domain and material were retrieved from each numerical simulation. The most interesting among them is the insulation filler. The monthly value effective thermal conductivity depends on the hygrothermal properties of the filler material. Increasing temperature and relative humidity increase the λ_{eff} of materials, but different magnitude. In Fig. 3. λ_{eff} of the outermost layer of MW in the masonry remain always lower than the innermost layer, because MW seems to react more sensitive to temperature than relative humidity. However EPS filled blocks show that in winter, the outermost layer has the higher effective thermal conductivity, therefore it seems to react more to RH than temperature.

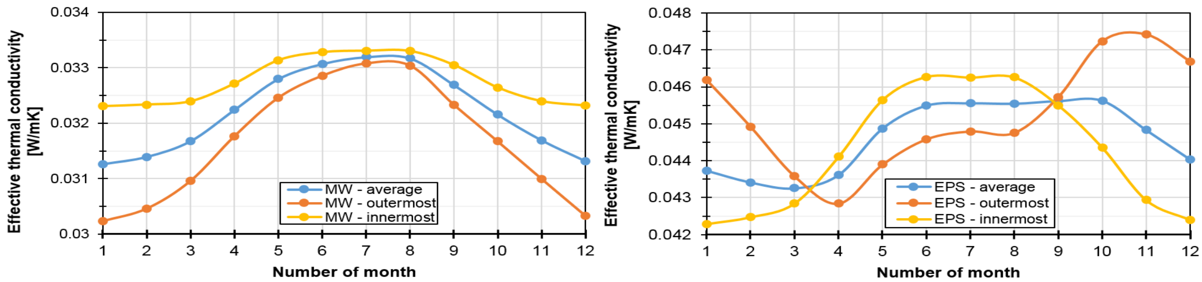

Figure 3: Monthly variation of the effective thermal conductivity of two insulation fillers

4.2 Differences in thermal transmittance obtained from thermal or HAM simulations

Evaluating data shown in Table 3, the trend is clearly visible that U value difference is increasing, when the filler material's $\lambda_{10,dry}$ is lower or it is more sensitive to moisture (EPS). Taking into account the above presented phenomena, likely that it does not worth to use better insulation than MW to fill in masonry blocks, because in contrast to nowadays used standards and catalogue values, in real life applications moisture is always present in constructions.

Table 3: Thermal transmittances from thermal or HAM simulation, in heating season, Budapest

Thermal insulation filler	A	PUR	MW	EPS	EXP
U value, Thermal simulation [W/m²K]	0.141	0.170	0.186	0.200	0.227
U value, HAM simulation [W/m²K]	0.150	0.179	0.196	0.218	0.236
Difference [%]	6.2	4.6	4.8	8.6	3.8

4.3 Temperature and relative humidity in horizontal wall sections

January month steady-state simulation results of temperature and relative humidity field in horizontal wall sections made from insulation filled masonry blocks are shown in Fig. 4.

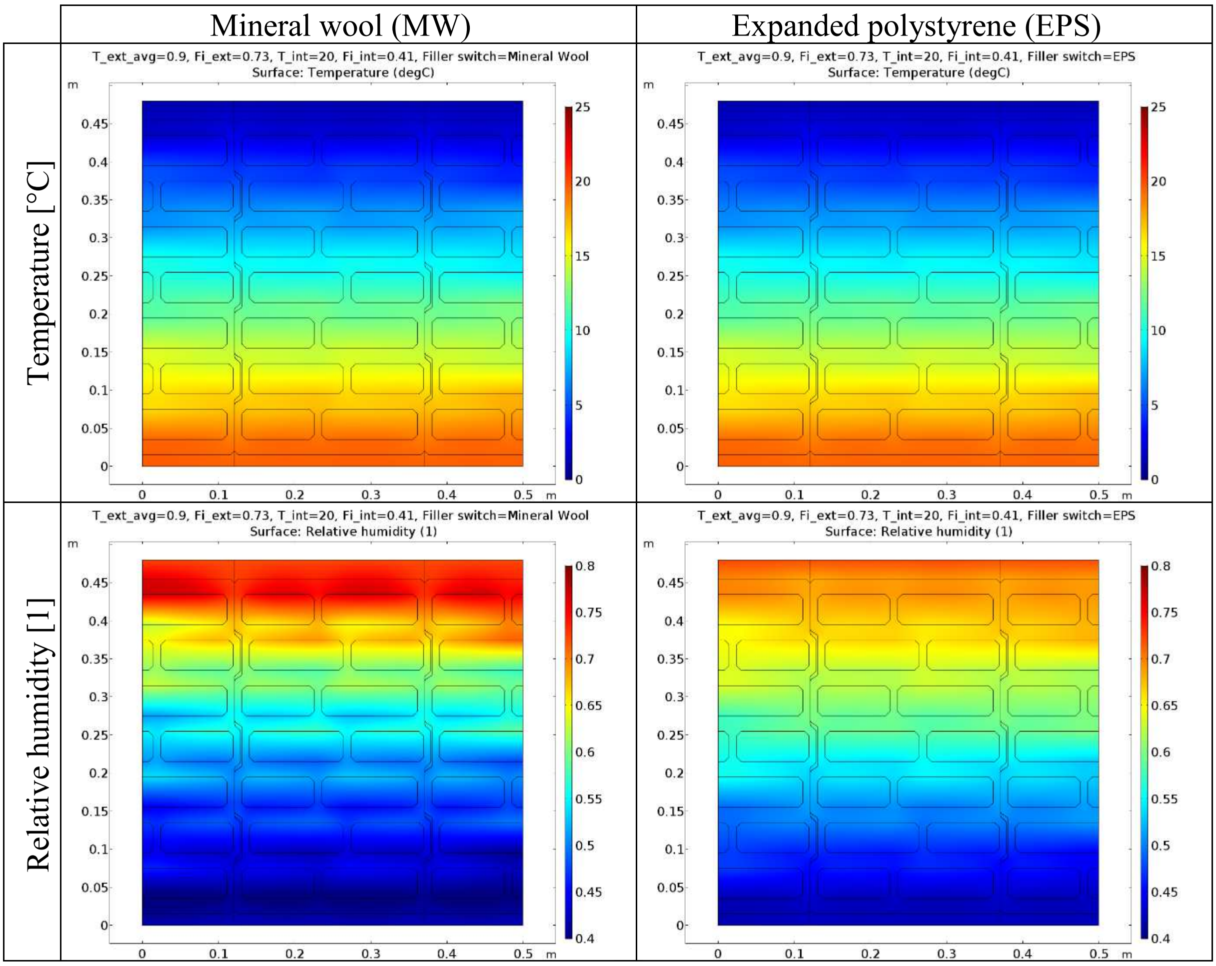

Figure 4: Temperature and RH across horizontal section of masonry walls in January

As the monthly internal and external air conditions in Table 1. indicates, the temperature and relative humidity difference in the masonry blocks are significantly higher in winter than in summer, when there is almost no temperature or RH difference in the section. Also, from autumn to spring, RH increases from the inside to outside, while in summer months, RH is higher the internal side of the wall section. It is observable, that relative humidity increases in the insulation fillers next to the fired clay walls perpendicular to moisture flux. In winter months, therefore there could be higher RH in the outermost insulation layer, than in the external air. This phenomenon happens because of the fired clay's higher μ value, which blocks the flow.

4.4 Thermal and moisture bridges in wall corners

It is observable that both heat and moisture flux magnitudes show increased values in the internal corners (Fig. 5). Heat flux magnitudes are higher in the fired clay internal structures parallel to heat flow direction, while the increase of moisture flux magnitude depends on the moisture transfer properties of the filler. Increased amount of heat flux results in lower temperature, while higher moisture flux and lower temperature results higher relative humidity. It can be stated, that while heat fluxes are similar to constructions with filled either low or high vapour diffusion resistance fillers, moisture flux strongly depends on the filler moisture transport properties. Increasing RH in materials contributes to increasing heat losses and possible moisture or durability problems.

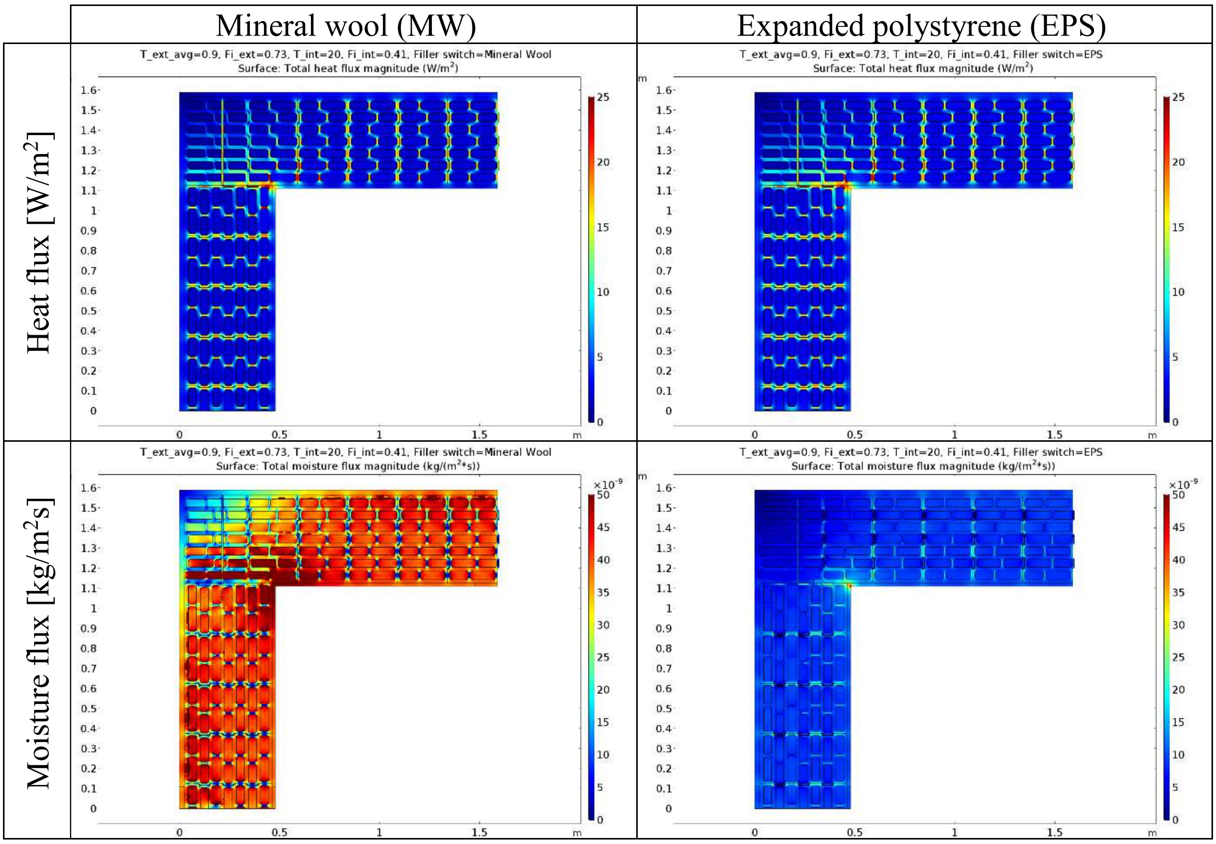

Figure 5: Heat and moisture flux magnitudes in two wall corners in January

4.5 Internal surface temperatures of wall corners by thermal or HAM simulations

The moisture transfer's effect is also slightly visible on the minimum internal surface temperature of corners, when thermal and HAM simulations were compared (Fig. 8). Differences in the surface temperatures are greater in winter depending on the insulation filler, and considering only thermal simulation is a negligible mistake against accuracy in this case.

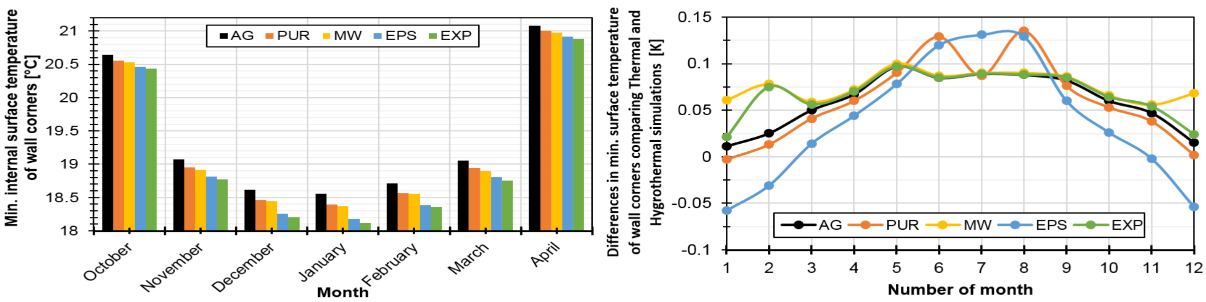

Figure 6: Min. internal surface temperature of wall corners (left) and differences (right)

4.6 Monthly linear thermal and moisture transmittance of the wall corner joints

Left side of Fig. 7. shows the average U values of walls with different fillers. The differences in the values compared month to month to each other are changing due to changes in temperature and relative humidity across the wall and corner sections. From the difference of the walls' and wall corners' U values, the ψ linear thermal transmittances [W/mK] of wall corners can be calculated (see Fig. 7, right side). For the calculation, internal dimensions of the construction joint were considered according to ISO 13789 [16] and ISO 10211 [17]. In winter, both masonry blocks has positive ψ values independently from the type of filler indicating that in the construction, additional heat loss occurs due to thermal bridging.

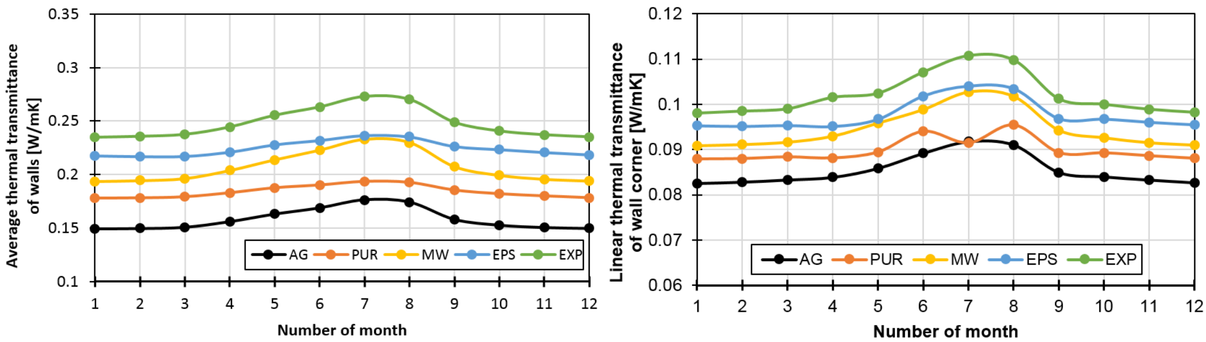

Figure 7: Thermal transmittance of walls (left) and linear thermal transmittance of wall corner joints (right)

Moisture transmittance can be calculated similarly to thermal transmittance but instead of using heat flux and temperature difference, in this case moisture flux and vapour pressure differences of internal and external air should be included in the calculation. Linear moisture transmittances in Fig. 8 shows the additional moisture transported due to moisture bridging effect in wall corner joints. These values are all positive, indicating that moisture is always flowing from inside to outside, although their magnitude rises greatly in summer months compared to winter.

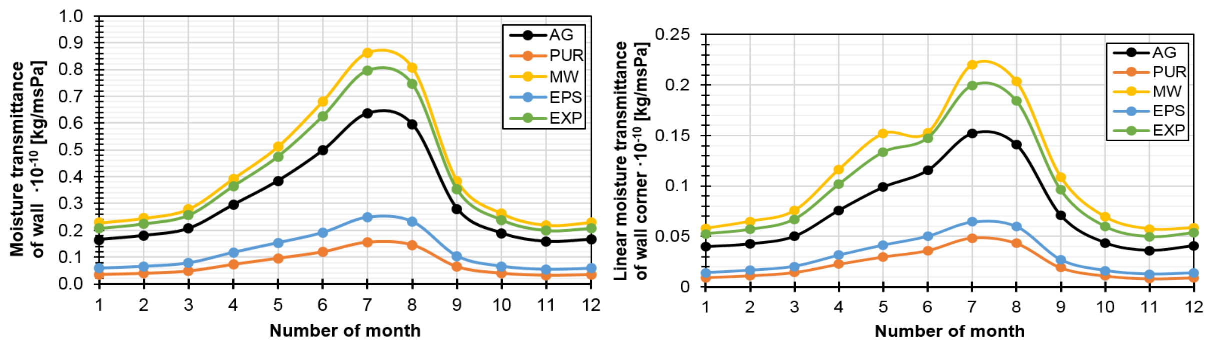

Figure 8: Moisture transmittance of walls (left) and linear moisture transmittance of wall corner joints (right)

5. CONCLUSIONS

– In the case of building constructions made out of thermal insulation filled masonry blocks, the hygrothermal behaviour of materials drastically affect the energy performance.

Thermal transmittance of the examined constructions increased between 3.8% – 8.6% in the heating season, when moisture transport is added.

- The moisture transfer capability of the thermal insulation fillers are key properties when considered in masonry blocks, and significantly contributes to thermal and moisture bridging effect in wall corners. In real life applications, when not only heat transfer is considered, the complex hygrothermal behaviour is more important, than low $\lambda_{10,dry}$ value.
- Comparing HAM to thermal simulations, there are only slightly noticeable differences is the internal minimum surface temperatures in the wall corners.
- Results also shows that there are visible differences in the linear thermal and moisture transmittance of the construction joints using different fillers, especially in summer.

ACKNOWLEDGEMENTS

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EFFECT OF ADSORPTION/DESORPTION MATERIAL HYSTERESIS ON THE HYGROTHERMAL PERFORMANCE OF BUILDING STRUCTURES

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Abstract

Heat and moisture models do not usually account for adsorption/desorption hysteresis while calculating the hygrothermal performance of structures. Most models assume that the materials sorption behavior is properly described by the average curve between adsorption and desorption. As indicated in the literature, this may result in an under-estimation of the moisture-related damage risk. Here, we evaluate this assumption and the necessity to account for sorption hysteresis to accurately describe heat and moisture transport in wall assemblies. Pederson's hysteresis model is mainly considered in this study. Materials with storage dominant over transport at longer time scales (6 months) are targeted, and therefore, two types of assemblies are studied: 1) an oriented strand board-based lightweight construction and 2) a massive concrete-based wall. Two climates are taken into account: Tokyo (Japan) and Seoul (South Korea). Based on the simulations, the hysteresis does not appear to have a major impact on either construction. However, a comparison of experimental scanning curves with Pedersen's model at high relative humidity should also be performed to ensure model accuracy.

Keywords: heat and moisture simulations, adsorption/desorption hysteresis, hygrothermal performance.

1. INTRODUCTION

Several studies from the literature focus on the impact of sorption hysteresis on the hygrothermal behavior of materials and buildings structures [1-9]. Most of these studies consider sorption hysteresis only at the scale of a single material [1-6], and only a few study the impact of hysteresis on multi-layered building assemblies [7, 8, 10].

In particular, references [8] and [10] evaluate the impact of a wood-based layer's hysteresis on the hygrothermal behavior of roof structures, through a numerical and assembly-scale approach. In addition, Kwiatkowski *et al.* [7] evaluate the impact of the hysteresis of gypsum layers on interior climate, and their results suggest that hysteresis is of minor impact. The climate and construction mode combinations that are considered in these studies are local to the research teams and are not specifically chosen as worst case scenarios for the potential impact of hysteresis. In the present study, the impact of hysteresis is evaluated using a numerical and wall-scale approach. Climates and construction modes are carefully chosen so that the impact of hysteresis is maximized. The objective is to revisit the conclusion that the hysteresis impact is of negligible importance through the analysis of extreme cases, and if relevant, to generate conclusions that could be generalized to other climate/construction mode combinations. Herein, Pederson's model [10] is used to describe the hysteresis phenomena.

First, we present our in-house model and reference the heat and mass transport equations. We then justify the selection of the cases of interest. These cases are discussed separately, and we draw conclusions on the impact of adsorption/desorption hysteresis on the hygrothermal performance of the building structures.

2. IN-HOUSE MODEL

Our in-house model solves the classical, transient one-dimensional conservation equations for heat and moisture that are mentioned in H. Kunzel's Ph.D Thesis [11] and implemented in Wufi today. As in Wufi, the heat and moisture transfer equations are solved for an assembly of layers forming a wall and defined by their thermophysical properties. The equations are solved using a finite volume method. The boundary conditions at the exterior and interior surfaces of the wall are derived from climatic exterior files (TMY – typical meteorological year - data) and imposed interior conditions. In the case of a ventilated façade, the air renewal in the cavity is represented through an energy and water mass source dependent on the ACH, the air change rate factor (h^{-1}).

The model employed in this study does not account for rain absorption, which can induce an error in the case of non-ventilated structures with a capillary-active outer layer. However, and as will be seen in the next section, the cases of interest in this study involve a ventilated façade, and thus, the rain absorption limitation is not a concern.

We note that, for the sake of validation, a comparison between our in-house model and Wufi simulations will be shown when presenting the heat and moisture calculations (see section 4).

3. TIME SCALE EFFECT AND HYSTERESIS LITERATURE MODELS

3.1. Fourier number

It may only be important to take the sorption hysteresis into account in situations where moisture storage is dominant over moisture transport. The Fourier number (Fo) compares the mass conduction rate to the mass storage rate and is defined by:

$$\mathrm{Fo} = Dt/L^2, \tag{1}$$

where D is the moisture diffusion coefficient (defined as the ratio of the moisture conductivity and volumetric sorption capacity, and calculated using thermophysical properties from Wufi's database) in $m^2\ s^{-1}$, t is the time in s, and L is the material thickness in m. Fourier number around unity or below indicates that storage is commensurate with or dominant over transport, while large Fourier numbers are indicative of a dominant transport.

The relative importance of water storage with respect to water transport is time scale dependent. Table 1 shows Fourier numbers for several standard construction materials at two different time scales (6 months and 1 day). The thicknesses are common for the chosen materials. It appears that, for the longer time scale, storage is negligible in all cases except for oriented strand board (OSB) and concrete. For the shorter time scale, storage is of significant importance in all cases.

Hence, building physics analysis aiming to evaluate the response of a building assembly to seasonal variations of the climatic conditions may only require a refined treatment of storage effects for wood-based and concrete layers. Shorter time scale analysis, such as analysis of daily moisture buffering effects, may require taking the hysteresis of the buffering layer into account.

Table 1. Fourier numbers for several standard construction materials at two different time scales. Blue shading indicates scenarios where storage is non-negligible. For a six-month time scale, storage is non-negligible for OSB and concrete.

Material	$D\ [\mathrm{m^2 s^{-1}}]$	Thickness [cm]	Fo [-] (t = 6 months)	Fo [-] (t = 1 day)
Glass wool	4.46E-07	8.9	889	5
Gypsum board	1.13E-08	1.3	1100	6
Polyiso board	9.44E-09	5.1	58	0.3
EPS	4.47E-08	5.1	273	1.50
Red cedar	1.16E-08	2.5	283	2
OSB	2.56E-11	1.3	2	0.01
Concrete	1.62E-10	20.0	0.06	0.0003

3.2. Literature models and implementation

The literature reveals numerous sorption hysteresis models. These models have to properly describe the isotherm scanning curves, and, for our purposes, they have to be suitable for a numerical implementation in a homogeneous model based on water mass and energy conservation principles. At least two models from the literature meet these requirements [10, 12]. For the sake of brevity, we only present Pedersen's approach, as it is widely used [7, 13] and is implemented in our in-house model. As shown in Eqs. 2 and 3, the sorption capacity ($\varepsilon_{\mathrm{hys}}$) at any point is a weighted average of the slopes of the adsorption (ε_{a}) and desorption (ε_{d}) curves, at the same relative humidity. The functional relationship is different depending on whether the material is adsorbing ($w_{\mathrm{new}} > w_{\mathrm{old}}$) or desorbing ($w_{\mathrm{new}} \leq w_{\mathrm{old}}$). The sorption capacity is also a function of the water content of the material (w), the water content according to the adsorption isotherm (w_{a}), and the water content according to the desorption isotherm (w_{d}) – each at the same relative humidity.

$$\varepsilon_{\mathrm{hys}} = \frac{0.1(w-w_a)^2\varepsilon_d + (w-w_d)^2\varepsilon_a}{(w_d-w_a)^2} \qquad (w_{\mathrm{new}} > w_{\mathrm{old}}) \tag{2}$$

$$\varepsilon_{\mathrm{hys}} = \frac{(w-w_a)^2\varepsilon_d + 0.1(w-w_d)^2\varepsilon_a}{(w_d-w_a)^2} \qquad (w_{\mathrm{new}} \leq w_{\mathrm{old}}) \tag{3}$$

4. EVALUATION OF THE HYSTERESIS IMPACT IN BUILDING STRUCTURES

A lightweight structure and a concrete wall are considered in Tokyo, Japan and Seoul, South Korea, respectively. Both assemblies are typical of their respective countries. As shown in Fig. 1, the two cities are humid and undergo a significant seasonal temperature variation. As a result, the exterior water vapor partial pressure (Fig. 2) varies significantly over the year, with an amplitude on the order of 3500 Pa. Fig. 2 also presents the yearly evolution of the indoor water vapor partial pressure. The indoor temperature is assumed to be constant and equal to 20 ˚C, while the relative humidity varies periodically with a period of one year between 45% and 60% and a maximum on August 16th at midnight. It appears that the water vapor partial pressure difference between outside and inside is positive during summer time and negative during winter time. The inversion of the moisture flux direction and the strong seasonal dependence of the moisture content of the wooden and concrete layers are of interest for this work.

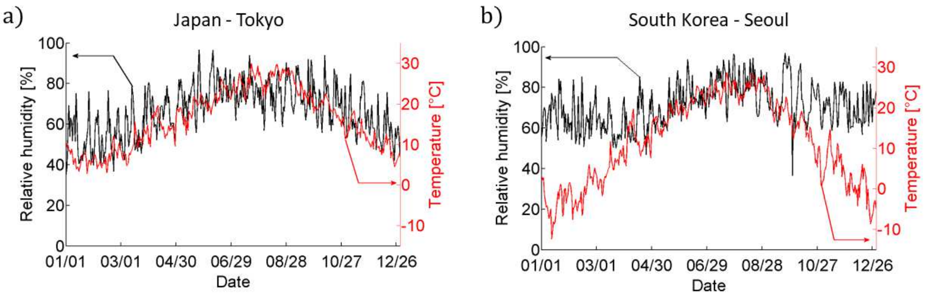


Figure 1. Daily average relative humidity and air temperature in a) Tokyo, Japan and b) Seoul, South Korea. Data from standard TMY files are used.

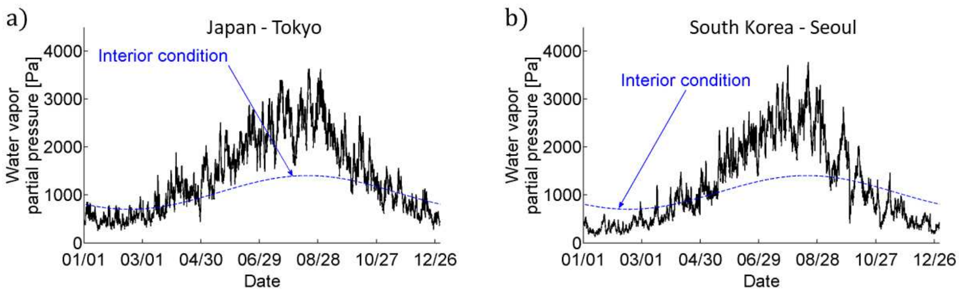


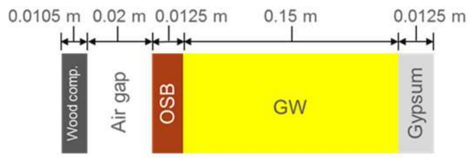
Figure 2. External water vapor partial pressure (black) and internal water vapor partial pressure (blue) for a) Tokyo, Japan and b) Seoul, South Korea. Data from standard TMY files are used.

4.1. Lightweight construction: OSB-based structure

The lightweight wall construction considered for the climate in Tokyo, Japan (Figs. 1.a and 2.a) is shown in Fig. 3.a. From the exterior to the interior, it consists of a composite wood siding, a ventilated air gap (air exchange = 60 h^{-1}), OSB, glass wool, and gypsum board. Based on the components' thicknesses and moisture transport properties (Appendix, Table 1), the corresponding S_d-Values are calculated and shown in Fig. 3.b. The S_d-Values refer to the ability of a material to resist water vapor transport. It is an extrinsic value that corresponds to the equivalent air layer thickness necessary to achieve the same water vapor resistance.

Therefore, the OSB is quite impermeable to water vapor as compared with the other components.

a)



b)

Component	S_d-Value (m)
Wood Siding	0.47
Air Gap	0.01
OSB	3.75
Glass Wool	0.15
Gypsum	0.10

Figure 3. a) Schematic of a typical wall construction in Tokyo, Japan that consists of a wood composite, an air gap, oriented strand board (OSB), glass wool (GW), and gypsum board (left to right; exterior to interior). b) S_d-values for the materials incorporated in the construction in a). Moisture storage and transport properties, as well as thermal properties, for the materials are obtained from the Wufi database (refer to Appendix, Table 1).

Results for the hygroscopic behavior of the lightweight construction in Tokyo, Japan, neglecting the hysteresis of OSB, are shown in Fig. 4. The data are generated using the in-house Matlab code and Wufi and consider a north-oriented wall. The moisture storage and transport properties, as well as thermal parameters, for the various components are extracted from the Wufi database for both types of simulations (Appendix, Table 1). The one exception is that the mean sorption isotherm and dry density for OSB from [4, 14] are employed. This modification is made for the subsequent comparison with the case considering the hysteresis of OSB – the Wufi database does not provide adsorption and desorption isotherms, which are necessary for the calculations considering hysteresis. The initial conditions for the construction are 20 ˚C and 50% RH throughout.

Fig. 4.a shows the variation in the average water content of the OSB. The water content experiences peaks and valleys in the winter and summer times, respectively. This indicates that the OSB is adsorbing moisture during the winter and drying during the summer time. The data support that the model reaches a steady state after approximately one year, and there is good agreement between the in-house Matlab and Wufi simulations. The variation in the relative humidity on either side of the glass wool (Fig. 4.b) throughout the year is illustrative of the general hygroscopic behavior of the wall. During the winter time, the water vapor partial pressure gradient across the wall (Fig. 2.a) results in moisture transport from the interior to the exterior, against the relative humidity gradient. The large S_d-Value of the OSB and the high relative humidity at the interface between the glass wool and the OSB results in an increase in OSB water content. The glass wool is a highly thermally insulating system, and its S_d-Value indicates that it is a relatively open system to water vapor transport. Therefore, a negligible water vapor partial pressure gradient exists across the component, while a significant thermal gradient exists. In turn, this yields a lower relative humidity on the right side of the glass wool during the winter time. Conversely, during the summer time, the OSB is discharging the water that it stored during the winter time to the glass wool and the air gap, and the water vapor partial pressure gradient across the wall (Fig. 2.a) results in moisture transport from the exterior to the interior against the relative humidity gradient. Again, the open nature of the glass wool, coupled with its thermal gradient, give rise to the relative humidity gradient across the component. Similar results are observed for a south-oriented wall neglecting hysteresis (not shown in this document).

a) b)

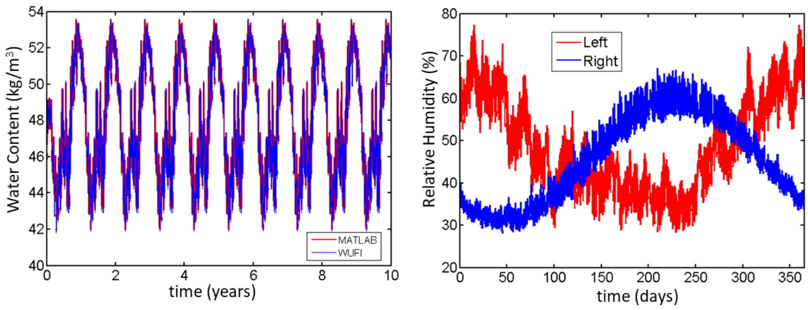


Figure 4. a) Average water content in OSB as a function of time from Matlab (in-house code; red) and Wufi (blue) – neglecting hysteresis. b) Relative humidity at the leftmost (red) and rightmost (blue) nodes of the GW (Fig. 3.a), as calculated from Wufi – neglecting hysteresis. Time equal to zero corresponds to January 1st.

Fig. 5.a shows relative humidity results across OSB for the north-oriented wall considered above in the case that OSB is characterized by hysteresis in its adsorption and desorption isotherms. The adsorption and desorption curves, along with the dry density, for OSB from [4, 14] are used in conjunction with the Pedersen model for hysteresis [10] to perform the simulations with the in-house Matlab code. The remaining simulation parameters are identical to the simulation neglecting hysteresis. The results for the 20th year of simulations in the case of hysteresis are considered. The results are compared with the simulations discussed above in the case that OSB hysteresis is neglected, and it is clear that the consideration of OSB hysteresis is not critical. The residuals between the two scenarios are randomly scattered, which further support that consideration of the OSB hysteresis is not critical.

a) b)

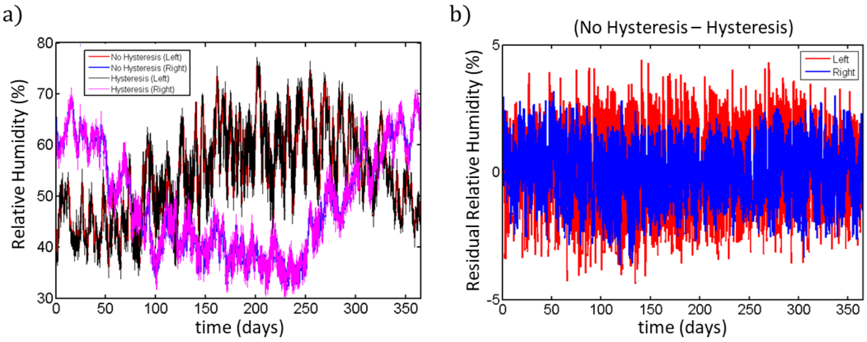


Figure 5. a) Relative humidity at the leftmost and rightmost nodes of OSB (Fig. 3.a) considering and neglecting hysteresis with the in-house Matlab code. b) Residuals between the simulations considering and neglecting hysteresis for the relative humidity on either side of the OSB. Time equal to zero corresponds to January 1st.

Furthermore, the average water content existing in the OSB is similar between the two models, and the difference is less than 5% (Fig. 6.a). The similarities between the two models are rationalized by considering the trajectories of the leftmost node of the OSB in the water content/RH diagram (Fig. 6.b) throughout a typical year (20th simulation year is considered). The relative humidity and water content trajectory for this node are shown alongside the adsorption, desorption, and mean sorption curves for the cases considering and neglecting hysteresis (10th simulation year is considered). In the case of the hysteresis model, it is clear that the trajectory exists quite close to the mean sorption curve that is assumed by the model neglecting hysteresis - hence the close agreement between the two models. Similar conclusions are also obtained for simulations considering a south-oriented wall (not shown in this document).

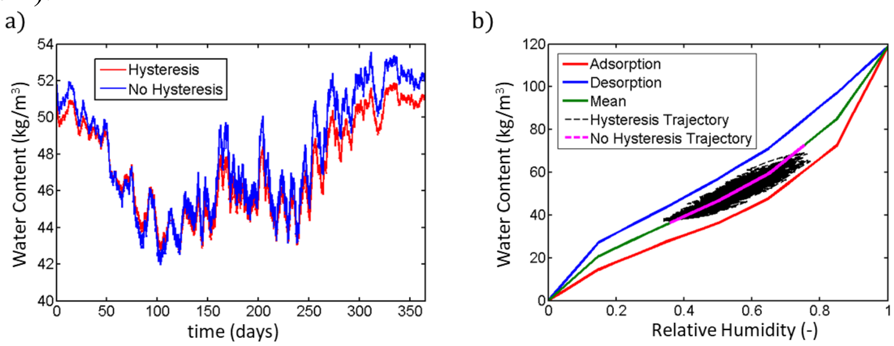
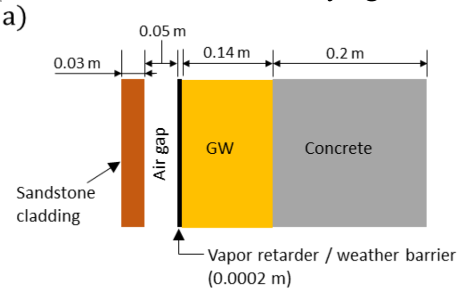


Figure 6. a) Average water content of OSB as a function of time considering (red) and neglecting (blue) hysteresis. The in-house Matlab code was used for both datasets. Time equal to zero corresponds to January 1st. b) Trajectories of the water content and relative humidity for the leftmost node of OSB (Fig. 3.a) over the course of a year considering (black) and neglecting (magenta) hysteresis. The adsorption, desorption, and mean sorption curves are also shown [4, 14].

4.2. Concrete-based structure

The structure shown in Fig. 7.a is simulated in Seoul, South Korea for a Northward orientation. From the exterior to the interior, it consists of a sandstone cladding, a ventilated air gap (air exchange = 40 h^{-1}), a weather barrier, glass wool, and concrete. Fig. 7.b presents the S_d-Value of the different layers. The interested reader can refer to Table 2 of the Appendix that provides the exact name of the different layers in the Wufi database whose properties were used for these simulations, with the exception of the concrete adsorption and desorption isotherm, along with concrete's dry density, that are taken from [1]. The concrete sorption isotherm is shown in Fig. 8. The hysteresis is large and extends over the whole relative humidity range as typically observed for cementitious materials. Fig. 8 also compares experimental scanning curves to the prediction from Pedersen's model (Eqs. 2 and 3). Pedersen's prediction is in satisfactory agreement with its experimental counterpart.

a)



b)

Component	S_d-Value (m)
Sandstone Cladding	0.99
Air Gap	0.02
Weather Barrier	0.2
Glass Wool	0.14
Concrete	49.6

Figure 7. a) Schematic of a typical wall construction in Seoul, South Korea that consists of sandstone cladding, an air gap, a weather barrier, glass wool (GW), and concrete (left to right; exterior to interior). b) S_d-Values for the materials incorporated in the construction in a). Moisture storage and transport properties for the materials are obtained from the Wufi database (refer to Appendix, Table 2).

For the simulations, the construction is initially at 20 ˚C and 50% RH throughout. Fig. 9 presents the time evolution of the concrete water content for the entire simulated physical time (10 years) and of the relative humidity at the weather barrier/glass wool and glass wool/concrete interfaces for the last simulated year, in the case where the hysteresis is neglected. For this case, the mean sorption curve is employed in the models. The structure is in a periodic regime after 6 years. During summer time the water vapor partial pressure distribution across the wall is such that moisture diffuses from the air gap towards the interior against the relative humidity gradient. The concrete S_d-Value is large and the relative humidity at the interface between the glass wool and the concrete is high, which induces an increase of the concrete water content. During winter time, the behavior is reversed: moisture diffuses outwards. The concrete releases the moisture it captured during the summer time, and the risk of condensation is large at the interface between the weather barrier and glass wool.

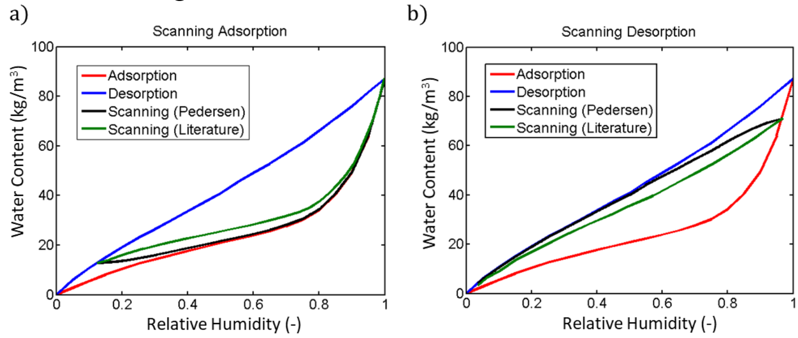


Figure 8. Adsorption (red) and desorption (blue) isotherms from literature are shown with a) scanning adsorption and b) scanning desorption curves (green) from literature [1]. The scanning curves are compared with predictions from the Pedersen's model (black) [10].

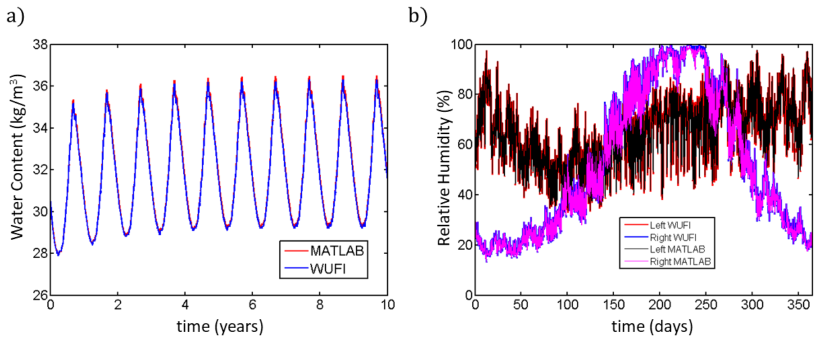


Figure 9. a) Average water content in concrete as a function of time from Matlab (in-house code; red) and Wufi (blue) – neglecting hysteresis. b) Relative humidity at the leftmost (red, black) and rightmost (blue, magenta) nodes of the GW (Fig. 7.a), as calculated from Wufi and Matlab (in-house code) – neglecting hysteresis. Time equal to zero corresponds to January 1st.

Fig. 10.a compares the relative humidity prediction on the left and right-hand side of the glass wool, with and without hysteresis. Fig. 10.b shows the residuals, i.e. the difference between the two approaches. The residuals are small, but not centered around zero. During summer time, the hysteresis assumption leads to a higher relative humidity at the glass wool/concrete interface, while this is reversed during the winter time. Fig. 11.a shows the average concrete water content during the last simulated year, and Fig. 11.b presents the

trajectory of the outermost cell of the concrete layer in the relative humidity / water content diagram for the same time period. The amplitude of the concrete moisture content variation is ~15 % lower in the case where the hysteresis is taken into account. The slope of the trajectory in the hysteresis case is consistently lower than that of the mean sorption curve. Therefore, the sorption capacity and moisture effusivity of the hysteretic concrete layer are lower, which explains the higher relative humidity at the glass wool / concrete interface during summer time. The lower effusivity also leads to a smaller water uptake, and hence, to a smaller water vapor release during winter time, which is associated with a lower relative humidity at the weather barrier / glass wool interface.

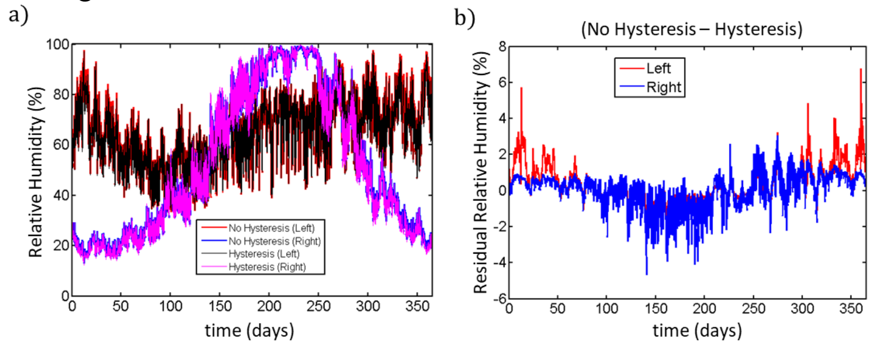


Figure 10. a) Relative humidity at the leftmost and rightmost nodes of GW (Fig. 7.a) considering and neglecting hysteresis with the in-house Matlab code. b) Residuals between the simulations considering and neglecting hysteresis for the relative humidity on either side of the GW. Time equal to zero corresponds to January 1st.

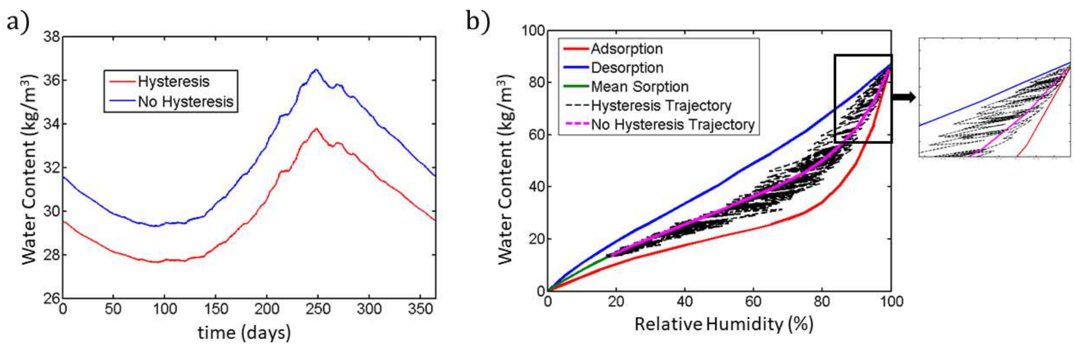


Figure 11. a) Average water content of concrete as a function of time considering (red) and neglecting (blue) hysteresis. The in-house Matlab code was used for both datasets. Time equal to zero corresponds to January 1st. b) Trajectories of the water content and relative humidity for the leftmost node of concrete (Fig. 7.a) over the course of a year considering (black) and neglecting (magenta) hysteresis. The adsorption, desorption, and mean sorption curves are also shown.

Overall, it seems that accounting for hysteresis is not critical, and a similar conclusion is obtained for a Southward orientation (not shown in this document). Additionally, the mold growth analysis, using the VTT approach [15], shows no concern for both models (with or without hysteresis). It would be beneficial to further compare experimental scanning curves at high relative humidity to Pedersen's model prediction and to evaluate the impact of other effects such as the variation of the sorption capacity with temperature [5, 8].

5. CONCLUSIONS

Most of the hygrothermal models from the literature and available in commercial software packages neglect the sorption hysteresis effect. If any, the impact of this assumption may be greater in situations where moisture storage is dominant over moisture transport. A dimensionless analysis revealed that for long time scales (yearly analyses) storage dominates for wood and concrete layers. Pedersen's hysteresis model [10] was implemented in an in-house hygrothermal model. The impact of the hysteresis was evaluated for a lightweight construction and a concrete wall, in climates favoring large moisture content fluctuations. The analysis showed that neglecting the hysteresis and taking into account the average curve between adsorption and desorption is a reasonable assumption. The accuracy of the scanning curves description at high relative humidity by Pedersen's model should also be investigated. Finally, further effects such as the impact of the temperature on the sorption capacity should be evaluated.

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APPENDIX

Table 1. Japan. Note that OSB results were modified based on [4, 14].

Schematic Name	Wufi Name	Wufi Database
Wood Siding	Composite Wood Siding	North America Database
Air Gap	Air Layer 20 mm	Generic Materials
OSB	Oriented Strand Board	North America Database
Glass Wool	Isover GW Integra ZKF-032	Fraunhofer-IBP
Gypsum	Gypsum Board	Fraunhofer-IBP

Table 2. South Korea. Note that concrete results were modified based on [1].

Schematic Name	Wufi Name	Wufi Database
Sandstone Cladding	Sander Sandstone	Fraunhofer-IBP
Air Gap	Air Layer 50 mm	Generic Materials
Weather Barrier	Spun Bonded Polyolefin Membrane	North America Database
Glass Wool	Isover GW Integra ZKF-032	Fraunhofer-IBP
Concrete	Concrete, C35/45	Fraunhofer-IBP

VENTILATED SANDWICH WALL PANEL FROM RECYCLED AGGREGATE CONCRETE: HYGROTHERMAL CHARACTERIZATON

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Abstract

Construction and demolition waste can be used as a new resource for producing building materials, e.g. recycled aggregate concrete (RAC). Currently there is a lack of research that assess RAC's hygrothermal properties at materials and component level. This paper presents an experimental characterization of basic hygrothermal properties of two different types of RAC: one with recycled concrete as aggregate and the other one with recycled brick as aggregate. Replacing 50% of natural aggregate with recycled has resulted with lower thermal conductivity and water vapour diffusion values, respectively. Both RACs exhibited similar adsorption behaviour in hygroscopic range, while in over-hygroscopic range RAC with recycled brick showed increased moisture retention capacity. DVS method for measuring sorption isotherms showed to be questionable for concrete specimens. At component level, innovative ventilated RAC sandwich wall panel was analyzed for different air ventilation rates and climates. The analysis was done using hygrothermal tool WUFI Pro 5.2. Proper water-repellent protection should be used for RAC envelopes. In winter period, air ventilation enhances drying out, but it does not outperform non-ventilated façade in summer period (from the aspect of moisture behavior). High thermal mass of ventilated RAC sandwich wall panel can reduce buildings heating and cooling energy demand, but this is strongly depended on systems operating mode and climate.

Keywords: construction and demolition waste, recycled aggregate concrete, ventilated façade, sandwich wall panel, heavyweight building

1. INTRODUCTION

Construction sector is identified as one of the biggest waste generator as well as energy and natural resources consumer [1]. Enormous amount of waste, referred as construction and demolition waste (CDW), that is generated during all stages of buildings life cycle can be transformed into “new resource”. One possibility is to sort, crush and distribute CDW by the size of particles, which results with material called recycled aggregate. Using recycled aggregate for production of e.g. new concrete and new high-quality construction products and thus reducing natural resources excavation could provide added value to CDW. Furthermore, thermal and hygric optimization of those new products could result with more resilient, moisture-safe and energy high-performing buildings.

Different types of recycled aggregate can be used for concrete production, so-called recycled aggregate concrete (RAC). Considering the fact that aggregate accounts for 60 – 80 % of the volume, concrete can serve as material bank by incorporating recycled aggregate. While mechanical and durability behaviour of RAC with different types of recycled aggregate has already been widely acknowledged by many researchers [2–4], opposite to that, its hygrothermal behaviour is generally neglected.

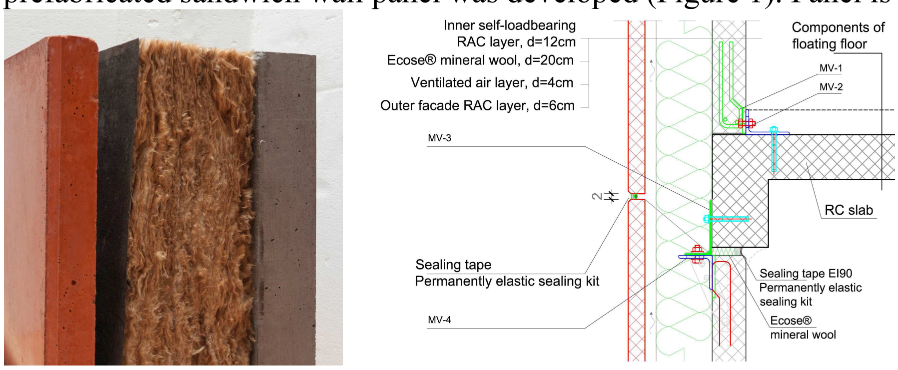
Building’s behaviour when exposed to heat, air and moisture loads from the indoor and outdoor environment – so-called hygrothermal behaviour, is an important aspect of building’s overall performance. Service life, energy needs, indoor comfort and air quality, together with the health of occupants are directly related to the hygrothermal behaviour of buildings. The material’s hygrothermal properties of interest are primarily: moisture sorption isotherm curve, water vapour permeability and thermal conductivity.

There are only few available researches on thermal and hygric properties of RAC [5–8]. Regarding the hygric properties of RAC, there are even more limited research [6]. To the best of authors knowledge, currently there are no available studies related to experimental determination of moisture sorption isotherms of RACs.

The significance of hygrothermal research (at material and component level), specially lies in RAC’s promising contribution towards the sustainable development of built environment.

2. VENTILATED SANDWICH WALL PANEL FROM RECYCLED AGGREAGTE CONCRETE

With aim to tackle CDW in a way that could also contribute to reducing building energy consumption, ventilated prefabricated sandwich wall panel was developed (Figure 1). Panel is suitable for constructing very low-energy buildings. Inner and outer concrete layers are produced using recycled aggregate – recycled concrete aggregate for inner RAC layer and recycled brick for outer RAC façade layer. Innovation of this panel lies in utilizing recycled



a) b)

Figure 1: Ventilated prefabricated wall panel from RAC: a) model, b) technical detail

waste in high replacement ratio (50%) and cavity with naturally ventilated air (which is usually not common in concrete sandwich wall panels). Due to high surface mass (458 kg/m^2), building envelope constructed with presented panels can be classified as heavyweight.

3. HYGROTHERMAL CHARACTERIZATION AT MATERIAL SCALE

This section focuses on the experimental characterization of the main hygrothermal properties of RACs used for production of above presented ventilated wall panel.

3.1 Concrete mixes and basic properties in hardened state

Max size of aggregate in both mixtures was 16 mm. It should be noted that recycled aggregate has replaced only natural coarse aggregate in RAC-C (concrete with recycled concrete aggregate) and RAC-B (concrete with recycled brick aggregate), respectively. Both concrete mixtures were produced with cement CEM II 42.5/R.

Table 1. Properties of hardened RACs

Mixture	Dry density [kg/m^3]	Open porosity [%]	Compressive strength [MPa]	
			Cylinder	Cube
RAC-C	2204.96	16.67	38.38	43.3
RAC-B	1948.22	19.27	32.97	38.73

3.2 Thermal conductivity

Thermal conductivity measurements were carried up by means of guarded hot plate according to HRN ISO 8302 standard [9]. Regression functions derived from measurement results are:

$$\lambda_{dry,RAC-C} = -0.000881 \cdot T_{mean} + 0.95270 \left[W/(mK)\right] \tag{1}$$

$$\lambda_{dry,RAC-B} = 0.000259 \cdot T_{mean} + 0.74234 \left[W/(mK)\right] \tag{2}$$

Dry thermal conductivity at +10°C, $\lambda_{dry,+10°C}$, of RAC-C is 0.944 W/(mK) and RAC-B 0.745 W/(mK), respectively. Conventional concrete made completely with natural aggregates with a density of 2300 kg/m^3 has the $\lambda_{dry,+10°C}$ value of approx. 1.7 W/(mK) [10]. Having in mind that suitable replacement ratio of recycled aggregate has significant influence on density of concrete and its thermal conductivity, more energy efficient building design can be achieved.

3.3 Water vapour diffusion

Water vapour diffusion measurements were conducted in compliance with the standard HRN EN ISO 12572 [11], according to ''wet cup'' method. The average results of water vapour resistance factor μ for RAC-C is 41 and for RAC-B 28, respectively.

The literature suggests to use a water vapour resistance factor μ-value for normal concrete as a constant value of 150 [12]. It can be seen that the water vapour resistance factors for RAC-C and RAC-B concretes from this study are up to 80% lower compared to value suggested in literature for normal concrete. Resistance to water vapour diffusion together with sorption isotherm, i.e. moisture storage capacity, effects on moisture exchange capacity of material, so-called moisture buffering capacity.

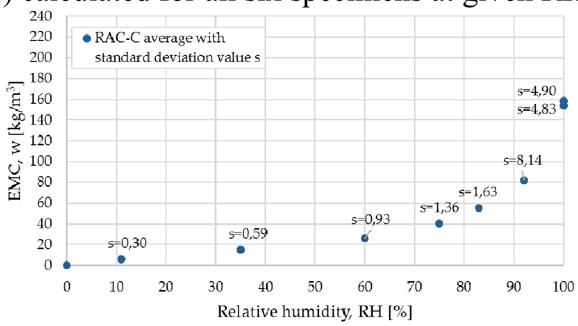
3.4 Sorption isotherm

Sorption curve is the basic and one of the most important data for the design performance of the thermal and hygroscopic moisture properties of porous building materials [13,14] and indispensable for the analysis of buildings' hygrothermal behaviour [15].

Sorption curve can be measured by static gravimetric method or dynamic vapour sorption (DVS) method. DVS has been developed to reduce the running time of measurement, but it can be used with small specimens only. Static gravimetric method is the most commonly applied for the determination of sorption curves. For the purpose of this study, both methods were used. Difference in specimen size is demonstrated in Figure 2.

Figure 2: Sorption isotherm specimens for RAC-C and RAC-B

Small cubic specimens (1×1×1 cm) were prepared for DVS. For static gravimetric method standard doesn't explicitly prescribe specimen size. It was determined in a way to minimize potential influence of aggregate size and not to completely disturb interfacial transition zones (ITZ) of recycled concrete aggregate. Based on that, nominal dimensions of 10×10×2 cm were defined. The adsorption isotherm testing, including the determination of capillary moisture content and maximum moisture content, lasted around 11 months for static gravimetric method. Figure 3 and Figure 4 outline the results of adsorption isotherm measurements at 23±2°C (including hygroscopic and over-hygroscopic range) in terms of RH as a function of the moisture content per unit volume *w* [kg/m^3], tested according to static gravimetric method. Values of standard deviation (*s*) calculated for all six specimens at given RH are also indicated.



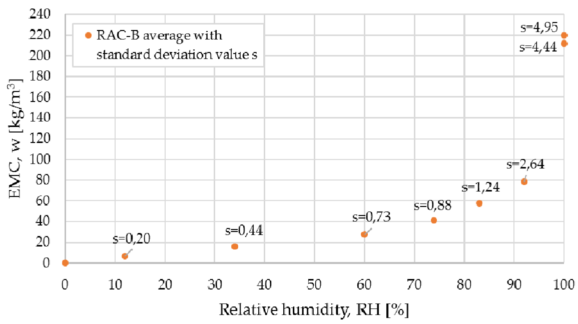


Figure 3. Adsorption isotherm of the RAC-C specimens (with over-hygroscopic range)

Figure 4. Adsorption isotherm of the RAC-B specimens (with over-hygroscopic range)

Experimentally obtained sorption isotherms are represented with discrete points, i.e. the exact value of material's Equilibrium Moisture Content (EMC) when exposed to a given RH is known. To describe RAC sorption curves, different models for curve fitting were evaluated, such as Künzel, Kumaran, Burch, GAB, Cubic, Oswin, Peleg, Giarma, Feng et al., MOIST. Evaluation of suitability, i.e. the goodness of the fitted curves, is based on statistical tools, primarily on the coefficient of determination (R^2) and residual sum of square. If the minimum required goodness of fit, as a function of R^2, is set to 0.99 then it has been seen that besides

Kumaran, Burch and GAB models, for RAC-C Oswin and MOIST models fulfill the requirement, while for the RAC-B those are Cubic and Feng et al. models. Figure 5 clearly shows that RAC-C and RAC-B have similar sorption capacity in the hygroscopic range but RAC-B has higher water retention capacity in the over-hygroscopic range. This behaviour pattern is directly related to the sorption behavior of materials that are used as recycled aggregate. The higher the value of EMC at RH=100 %, the worse fitting with Kumaran model is present.

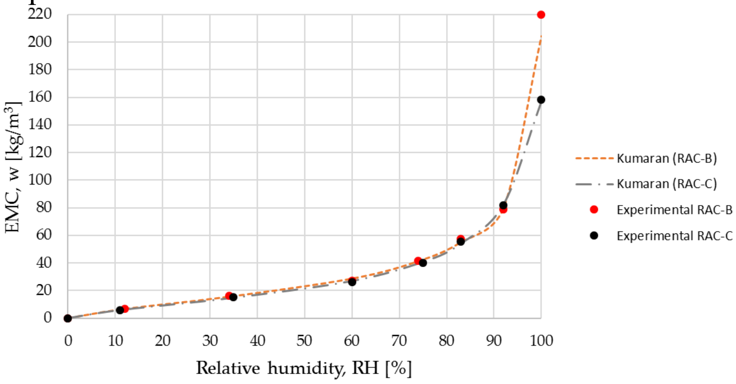


Figure 5. Moisture storage capacity of RAC-C and RAC-B in over-hygroscopic range

Even with such a small specimen size, DVS measurements lasted 42 days (2 cycles of adsorption and desorption per each specimen). For both RAC-C and RAC-B, significant deviation of results is present which is most likely caused by specimen size being not representative of concrete with max aggregate size 16 mm and ITZ. Due to page limitation, results of only RAC-B three specimens are shown in Figure 6.

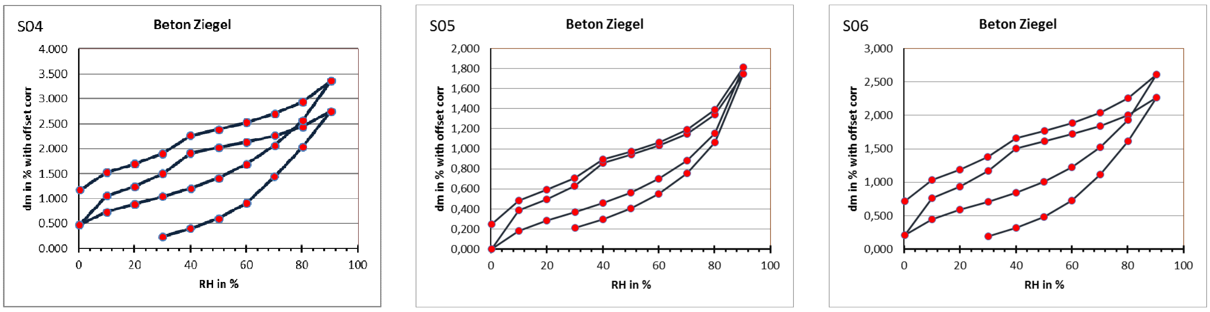


Figure 6: Sorption isotherms of three RAC-B specimens based on DVS measurement

Because of inconsistency of DVS results, adsorption curves obtained by static gravimetric method were used in further section for hygrothermal simulations at component level.

4. HYGROTHERMAL CHARACTERIZATION AT LARGE SCALE

This section investigates transient hygrothermal behavior of ventilated RAC wall panel using WUFI Pro 5.2 hygrothermal tool. Influence of wall's thermal mass on buildings energy performance was also analyzed.

4.1 Influence of adequate material data

The first step was validation of ventilated RAC wall panel model with real material values obtained experimentally, i.e. laboratory values. Total water content was compared with ventilated wall model with default values from WUFI library for concrete with similar bulk density, i.e. database values (Figure 7). Significant discrepancy occurs in behaviour when laboratory and default material values are used. Application of water-repellent layer on outer

RAC façade layer has reduced and smoothed total water content peaks almost 50% compared to model with real material values. For all three cases presented (Figure 7), the same conditions were assumed: ACH 5 1/h, location Zagreb and north oriented façade (the highest amount of wind—driven rain). The quality of prediction of the hygrothermal behaviour of building materials and elements is highly dependent on the used material data in the simulation. In further analysis, ventilated RAC wall panel was modelled with real material data and applied water-repellent protection.

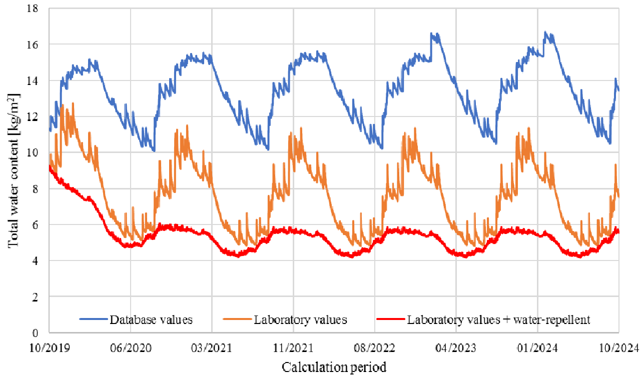
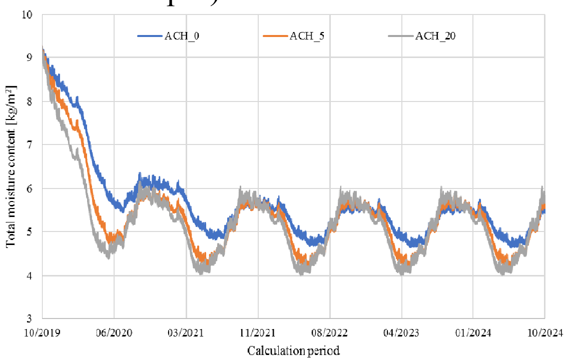


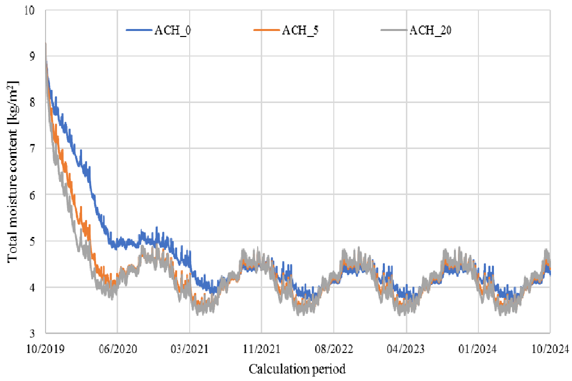
Figure 7: Model validation

4.2 Influence of air ventilation

Five different ventilation rate cases (ACH=0; 5; 20; 50; 100) were observed for continental climate (Zagreb) and littoral climate (Split). Practically the same hygrothermal behaviour was detected for ACH=20; 50 and 100, respectively; in both climates. It can be concluded that, in Zagreb and Split climate, increasing air ventilation rate above 20 1/h doesn't have significant influence on panel's hygrothermal behaviour. Therefore, all results are shown only for non-ventilated cases and cases with ACH=5 and 20, respectively. 5-year calculation period for wall orientation with the highest amount of wind-driven rain was observed (North for Zagreb and East for Split).



a)



b)

Figure 8: Total water content for different air ventilation rates: a) Zagreb, b) Split

In period from July/August – November/December ventilated cases exhibited practically the same hygrothermal behavior as non-ventilated case (ACH_0), while during the rest of the year air ventilation enhanced drying out of RAC wall panel. This positive influence of air ventilation is more pronounced in continental climate (Figure 8). Effect of air ventilation was also evaluated in terms of RH levels in the middle of thermal insulation layer. Dynamic equilibrium was achieved after approximately two years, and for the remaining three years average RH for each month was calculated. In that way, relative humidity within MW was compared for non-ventilated case and ventilated cases (Figure 9 and Figure 10). In both climates, certain period of year non-ventilated case has outperformed ventilated case (mostly summer period), while during winter period ventilation has decreased relative humidity level within MW. This positive effect of ventilation is more pronounced for higher ACH (Figure 10).

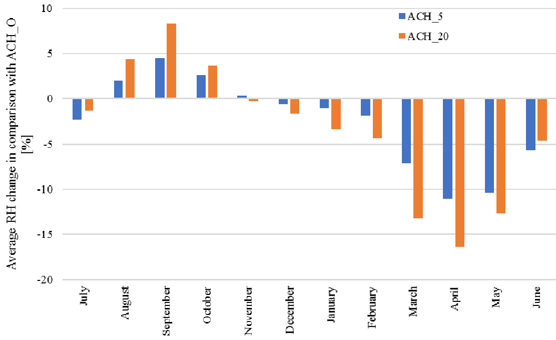


Figure 9: Influence of air ventilation on RH within mineral wool layer in Zagreb

4.3 Influence of thermal mass

Heavyweight building constructed with ventilated RAC panels can be beneficial from energy needs aspect. However, this should be analyzed in correlation with systems operating mode and climate. Following analysis was performed according to calculation procedure from EN ISO 13790 standard [16]. Exemplary building without transparent openings was modelled. Ventilation losses, thermal bridges and internal gains were also excluded from calculation. Figure 11 shows specific heating and cooling energy demand for different climates and different effective thermal capacity class of building.

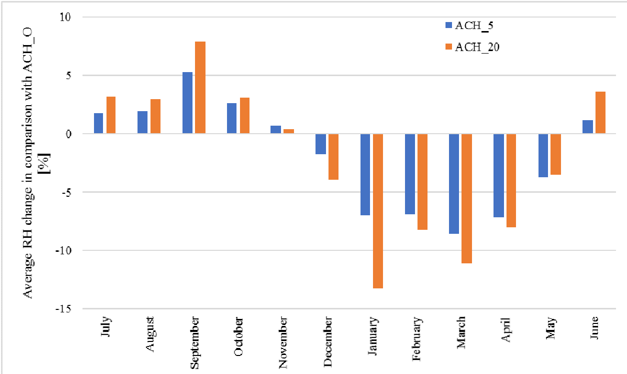
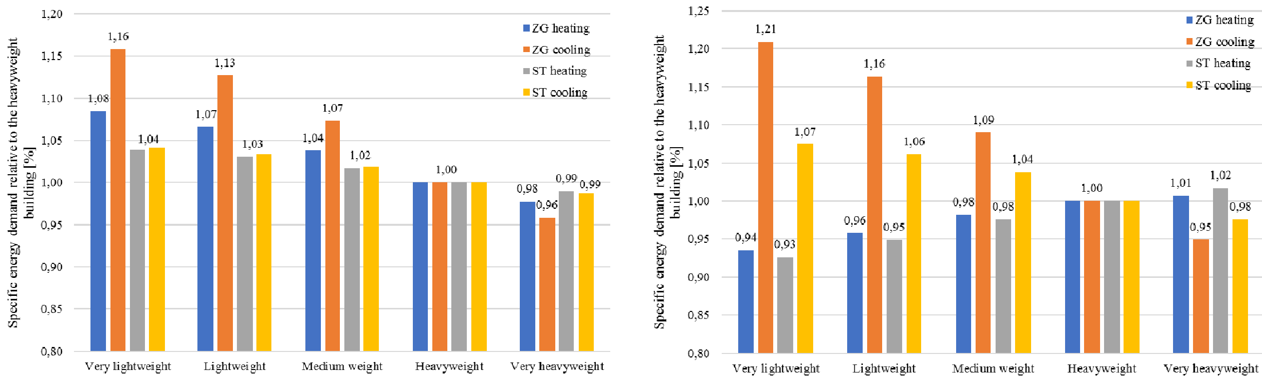


Figure 10: Influence of air ventilation on RH within mineral wool layer in Split



a) b)

Figure 11: Influence of thermal mass on building energy demand: a) continuous operating mode (00:00-24:00h), b) intermittent operating mode (08:00-23:00h)

For continuous mode, heavyweight building will consume somewhat less heating and cooling energy, and that applies for both climates. Contrary to that, for intermittent mode, heavyweight building can consume up to 6% more heating energy compared to very lightweight building, but it will still require less cooling energy (up to 21%), respectively.

5. FUTURE WORK

Ventilated RAC wall panels were used for constructing family house (Figure 12) with very low energy needs. In-situ monitoring of temperature and RH within all characteristic layers of 3 differently oriented panels is in progress. Dynamic hygrothermal behaviour under real environmental conditions will be analyzed as “proof-of-concept” od RAC’s suitability for constructing moisture-safe and energy high-performing buildings.

Figure 12: Monitored building from ventilated RAC panels

6. CONCLUSIONS

In this study, hygrothermal characterization of recycled aggregate concrete (RAC), as sustainable alternative to conventional concrete, was performed at material and component level. For high replacement ratio (50%), concrete with recycled concrete aggregate (RAC-C) and concrete with recycled brick aggregate (RAC-B), exhibited lower thermal conductivity and water vapour diffusion compared to conventional concrete. Also, sorption isotherm curves were established for both types of RAC. DVS method showed to be questionable for concrete due to small specimen size, but further research is needed to confirm that. Static gravimetric method with larger specimen size was extremely time-demanding. Moisture adsorption behaviour is quite similar and comparable for both types of RAC in hygroscopic range. By reaching the over-hygroscopic range, moisture retention capacity of concrete with recycled brick is significantly increased compared to concrete with recycled concrete aggregate. From the hygroscopic tests, the best-fitting curves based on analytical functions have been obtained. By comparing experimental results with ten different fitting models, goodness of fit for each model was evaluated. It is shown that the Kumaran, Burch and GAB models are suitable to reproduce the actual hygroscopic behavior of both types of RAC.

Hygrothermal characterization at component level included hygrothermal simulations of innovative ventilated RAC wall panel, where reliable input data from laboratory testing showed to be crucial for correct prediction of hygrothermal behaviour. Moreover, water-repellent protection significantly reduced peaks of total water content. It has been demonstrated that ventilated façade will not always outperform non-ventilated façade from the aspect of moisture behaviour.

Building envelope built with ventilated RAC wall panels can be classified as a heavyweight. Thermal mass has diverse impact on heating and cooling energy need, depending on climate conditions of location (continental or littoral climate) and operating mode of systems (continuous or intermittent).

Finally, quantitative data on hygrothermal behaviour, at both material and component level, would certainly enable deployment of RAC at large scale.

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EXPERIMENTAL STUDY OF THERMAL PERFORMANCE OF HOUSE MODELS BUILT WITH CONVENTIONAL OR HYBRID WALL PANELS

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Abstract

This article investigates experimentally the heat and moisture behaviour of scale-down houses built using a new hybrid wall)UWall(system and traditional walls. To achieve this, five scale-down houses)1.5×1.5×2.4 m(were built in Samutprakan province)Thailand(using walls made of conventional or composite materials: specimen H1 with mon block walls, specimen H2 with brick block, specimen H3 with lightweight block, specimen H4 with a composite infill wall, and specimen H5 with the new hybrid U-Wall. This study shows initial results from temperature and relative humidity outside and inside the walls as continuously measured for 48 hours using high precision resistant thermal detector)RTD(during the hot season in Thailand. Based on the present study, it is found that the new hybrid UWall shows a good thermal performance compared to the conventional solutions. The temperature difference between outside and inside was approximately 3-5°C for hybrid wall which exhibits the good performance among the walls used in this study.

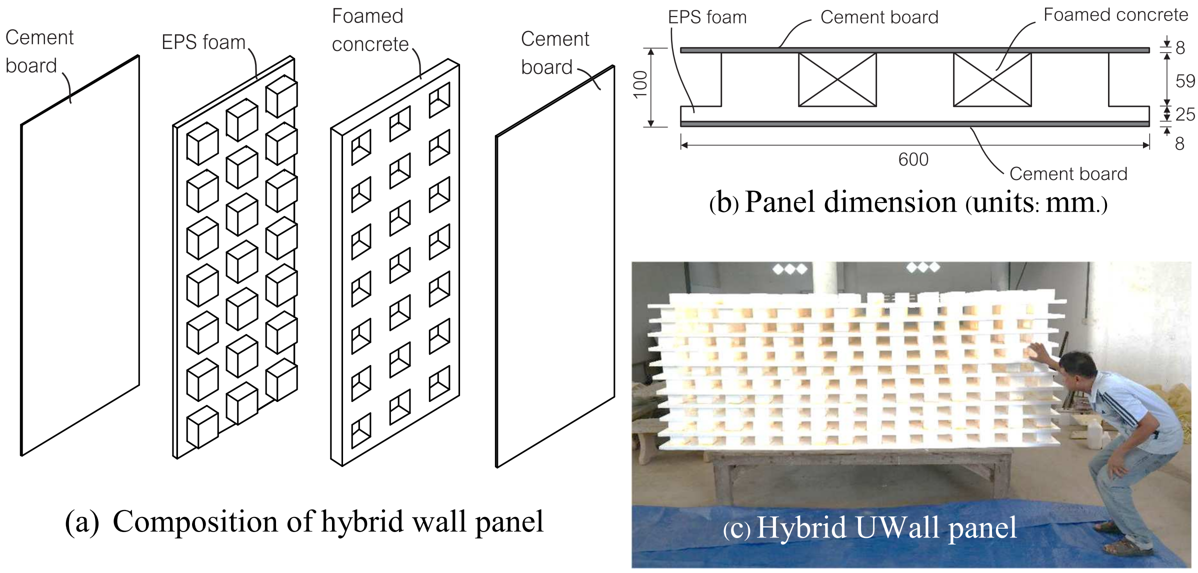
Keywords: Composite wall; Hybrid Walls, Infill Wall; Temperatures; Humidity

1. INTRODUCTION

The construction industry in Thailand is growing fast due to a demand for private and government housing. The hot-humid climate in Thailand also requires highly innovative thermal performance construction solutions to reduce electricity consumption as much as possible. As a result of these challenges, construction companies in Thailand rely heavily on pre-fabricated structural insulated composite panels (SIPs) and infill walls [1,2]. Although SIPs have been used worldwide and proved successfully by many research work on their performance [3], they required waterproof membrane sheet for exterior uses, which increases their cost and their applications in the hot-humid climate in Thailand and still requires a long term durability studies [1]. A recently developed infill wall system overcomes this issue by using plasterboard/cement board for exterior uses [2]. The new hybrid infill wall panel (UWall) consists of two water-proof cement boards with layers of expansive polyethylene (EPS) foam and foamed concrete in the core layer (

Figure 1a). The hybrid wall materials and dimensions (

Figure 1b) make them particularly suitable for rapid construction. However, to date the wall system has not been tested under real environmental conditions in Thailand.



(a) Composition of hybrid wall panel

(b) Panel dimension (units: mm.)

(c) Hybrid UWall panel

Figure 1: Hybrid composite UWall panels

Limited research has been done in Thailand to address the needs of the construction industry while addressing the challenging tropical weather in the country [4,5]. Moreover, limited research has studied the heat transfer of traditional wall systems and composite wall systems using model houses exposed to real environmental conditions [5-8]. Consequently, this paper aims to investigate experimentally the thermal response behaviour of scale-down houses built with the UWall system. To achieve this, five model houses were built using different materials typically used in building construction in Thailand, and one house was built with the new hybrid composite UWall panels. Based on the performance of the five houses, conclusions are drawn that can help improve the thermal performance of the wall construction practices in Thailand.

2. EXPERIMENTAL PROGRAMME

2.1 Description of house models

Five scaled-down houses were built at Kanchanapisek Technical College, Bang Bo District, Samutprakarn Province, Thailand. The model houses had a base of 1.5×1.5 m, and a height of 2.4 m. Different materials were used to build the walls (Figure 2): specimen H1 with mon block walls, specimen H2 with brick block, specimen H3 with lightweight block, specimen H4 with a composite infill wall, and specimen H5 with the new UWall. For the roof, insulating material was used to reduce the heat stickiness from the top. A 0.7×1.8 m PVC door was installed on the east side of the houses, while a glass window of 0.5×0.8 m clear was mounted on the west side of the houses.

(a) Masonry brick (H1) (b) Concrete Block (H2) (c) Light-weight block (H3) (d) Infill wall panel (H4) (e) Hybrid wall panel (H5)

Figure 2: Five scaled-down houses with different wall materials

2.2 Instrumentation and field measurement

Figure 3a) shows the location of the measuring points of temperature, relative humidity, wind speed, and measuring equipment. Heat transfer was measured using a high precision thermal RTD sensor (range -50°C to 330°C) for horizontal and vertical walls. Measurements were recorded every 1 hour for 48 hours in 11-13 March which was the host season in Thailand. Relative Humidity (RH="ratio of actual air vapour to air vapour at saturation at the same temperature") was measured using a digital hygrometer. Ground-level air velocity measurement was monitored with a wind speed monitor at 3 m above the ground.

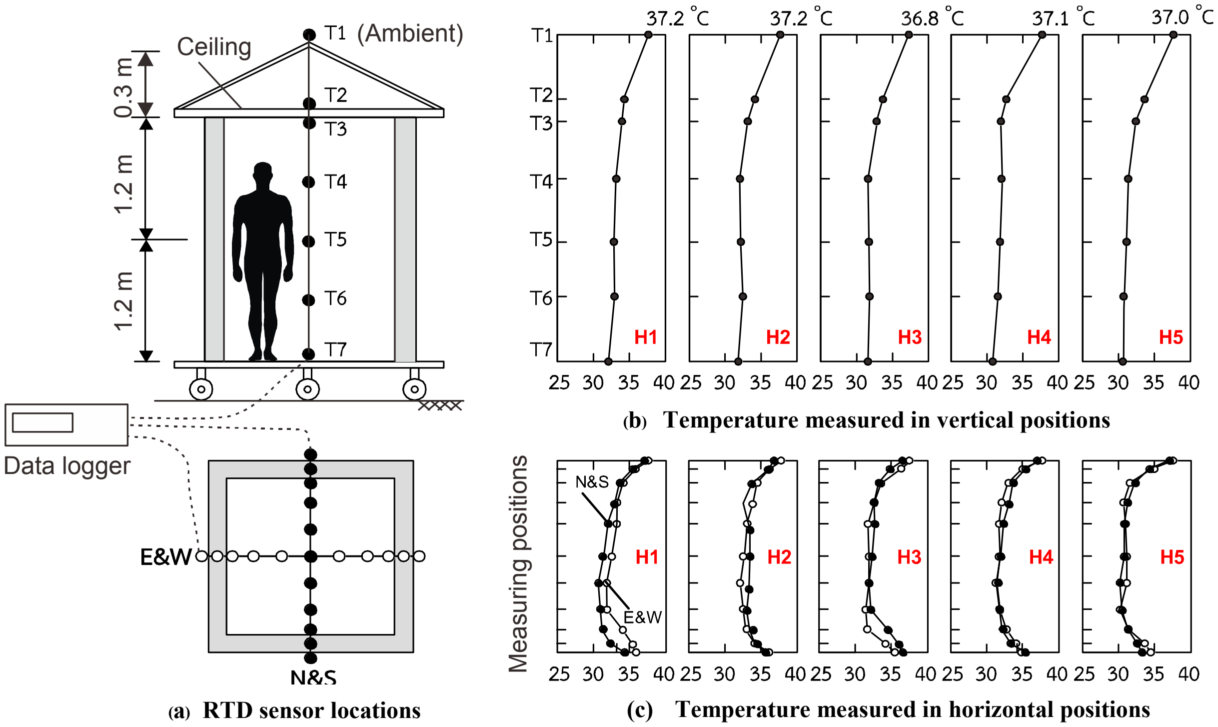


Figure 3: (a) Measuring points, and (b-c) field temperature measurement of 5 house models

3. ANALYSIS OF THE TEST RESULTS

Figure 4 compares the temperature and RH data recorded during the testing time at measuring point T5 (see

Figure 3a). The results are reported with door and window closed or opened. The results in grey-shaded show that the air temperature in the house made of UWalls is lower than traditional wall-built houses for the case of no opening i.e. door and window are closed. The temperature in the composite walls of the UWall (H5) is lower than that of the Infill Wall (H4) by 1 to 3°C. It is also shown that heat accumulation in the bulkhead block (H3) material has a slower heat transfer than the brick wall (H1) and the block brick wall (H2) during night. Based on the results of temperature comparison at the time of study, it was found that the heat-resistant performance of the composite wall-top mats is effective at preventing heat build-up from the outside. Furthermore, it was also found that lightweight block walls were more effective in preventing heat from the outside than bricks and concrete blocks, respectively.

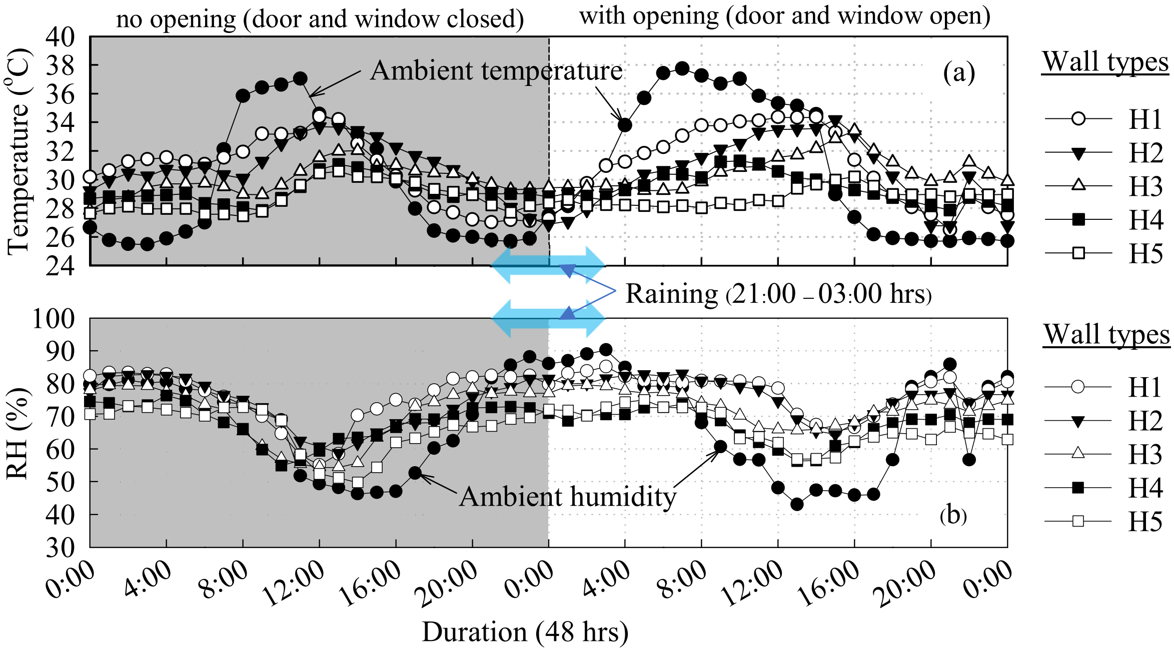


Figure 4: Field temperature and relative humidity data

In the case of model houses with no opening (i.e. door and window are closed), from 0:00 to 7:00 hrs, the RH of the air outside and the humidity of the air inside the five houses were similar and close to 70-80%, then the RH dropped at 8:00 hrs. Then RH gradually increased at 13:00 hrs. In the case of model houses with opening (i.e. door and window are opened), as seen in Figure 4b, the RH (ambient) outside the building at 3:00 pm was 93%. It was found that the moisture content of the air in the model house made of UWalls was 72-75%. Comparatively, walls made of monolith brick (H1) had RH of 85%, concrete block wall (H2) had RH = 80%, light brick wall (H3) had RH=78%, and infill wall (H4) had RH= 71%. Pouring rain occurred during the measuring time (21:00 – 03:00 hrs), and therefore the ambient RH was relatively high during this period (90-93%).

Based on these results, it was found that the RH was characterised by a single increase and decrease and also influenced by the opening during the 48 hours.

5. CONCLUDING REMARKS

This paper investigated experimentally the thermal response behaviour of five scale-down houses built using a new hybrid wall (UWall) system and traditional walls. Based on the 48 hours measurements conducted during the hot season in Thailand (11-13 March), it was found that the model built with the UWall system can reduce outdoor temperature by up to 3-5 °C compared to other wall materials. Overall, houses built using hybrid composite walls had the lowest internal air humidity than houses built with brick walls, mon-concrete blocks, aerated concrete, and Infill Wall walls.

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THERMAL PERFORMANCE OF A FULL-SCALE HOUSE MODEL WITH INNOVATIVE COMPOSITE WALLS IN TROPICAL CLIMATES: A FIELD INVESTIGATION

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Abstract

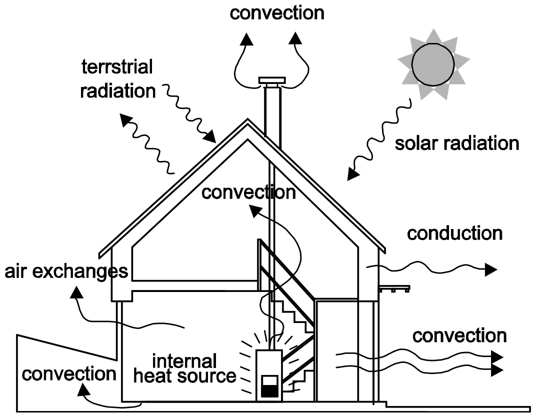
This paper presents initial results of the thermal performance of a full-scale house constructed with composite walls in Thailand. The one-story 10×7 m house was built using an innovative hybrid composite wall as part of a larger experimental programme that is examining comfort in houses using bioclimatic charts. The study reports the initial 48 hours field measurements included temperature, relative humidity and indoor air movement. Based on the results from the bioclimatic chart (that considers field temperature and relative humidity data), it is found that both temperature and humidity inside the house lie outside the comfort zone during daytime. However, when the air movement is taken into an account, the comfort zone enlarges and the house remains within the comfort zone all time. Long-term monitoring is currently underway to investigate the thermal behaviour of the house for 12 months. This paper contributes towards developing more sustainable solutions for the construction industry in Thailand so as to reduce energy consumption in the housing sector.

Keywords: Comfort zone, Hybrid composite wall, UWall, Temperature, Relative humidity.

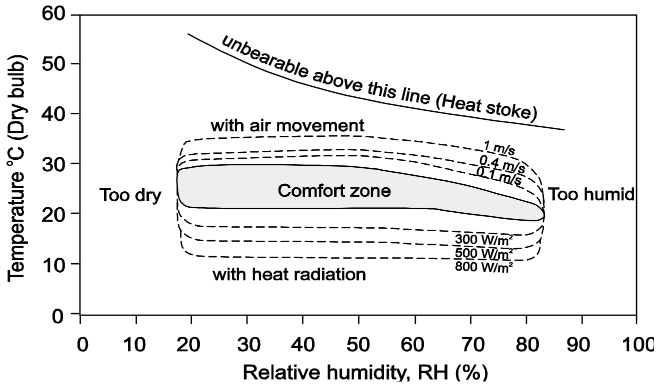
1. INTRODUCTION

Nowadays, buildings consume 40% of the world energy [1]. In Thailand, with a warm and humid tropical weather, the construction industry is being pushed to improve the energy performance of existing and new buildings. In typical buildings, walls have the largest exposed area open to the natural environment. Therefore, the use of highly efficient thermal performance material for the wall construction is expected to improve the energy performance and thus the user's comfort [2].

Ambient temperature, solar radiation, indoor air quality and humidity are the main aspects that affect the indoor's building environment and thus the comfort level (Figure 1a [3-4]). Bioclimatic charts as the one shown in Figure 1b (Olgyay V&A [5]) can be used to assess different comfort zones in buildings. More favourable climatic elements can offer comfort levels to the users, which in turn minimizes the energy consumption for cooling buildings/houses.



(a) Factors influencing comfort level



(b) V. & A. Olgyay Bioclimatic chart

Figure 1: Factors influencing comfort level)a(and comfort zone by bioclimatic chart)b(

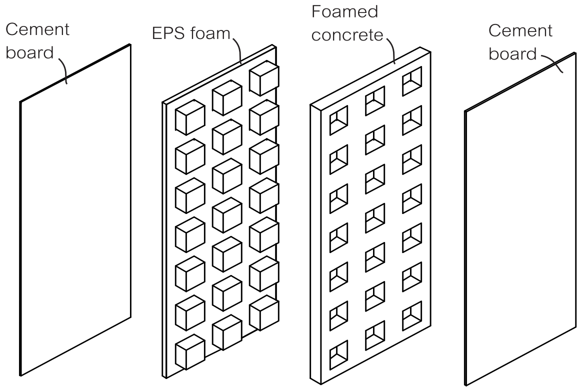
This paper presents initial results of the thermal performance of a full-scale house constructed with composite walls in Thailand. The bioclimatic chart is used to examine the indoor thermal comfort in the house. The results of bioclimatic charts are studied in conjunction with the temperature performance and humidity for 48 hours.

2. A HOUSE MODEL WITH HYBRID COMPOSITE WALL PANELS

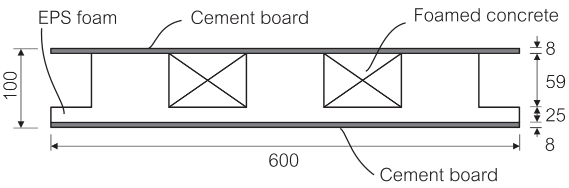
2.1 Design and construction

A house model 10 m long and 7 m wide was built at Chachoengsao province, Thailand. The floor is elevated 0.6 m from the ground (according to local construction practices), whereas the height of the walls is 2.8 m. To investigate the energy performance for long term monitoring, a new hybrid composite wall (UWalls, Figure 2a-c) developed at the Rajamangala University of Technology Tawan-Ok [6] was used as bearing panels (i.e. no beams and columns are provided). Further details of the wall can be found in an accompanying paper [7]. The total area of walls in the house is 112 m^2. The house was designed using local regulations for dead loads (DL) and live loads (LL). Accordingly, the design floor live load is 1.5 kN/m^2 (a typical value for housing in Thailand), while the roof live load is 0.3 kN/m^2. The wind load (5 kN/m^2 for a building of height less than 10 m) was also taken into account in design. Ready mixed concrete of 30 MPa was used to cast two precast slabs (50 mm thick each) to achieve an overall thickness of 100 mm.

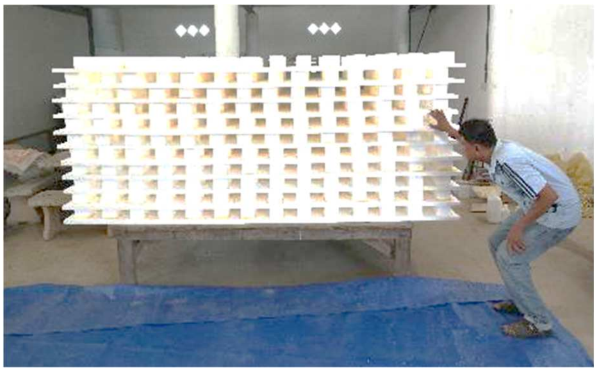
Local workers were trained to install the UWall system and build the house. First, the concrete floor was cast (precast slab with 50 mm topping). Next, the piping and electric works (M&E system) (Figure 2d) and UWall panels were installed (Figure 2e). The wall panels were installed on the floor, and the joints between the panels were connected using cold-form steel channels (C75×45x3 mm). (M&E system) were then installed inside the core of the panel. Doors and windows were fixed after the installation of the panels. Light-weight foamed concrete was then mixed on-site using a concrete mixing machine, and then cast into the walls in layers. The house was carefully designed to optimize the material and labour cost. The mix design and further construction details of the house can be found elsewhere [6,8].



(a) Composition of hybrid wall panel



(b) Panel dimension (unit in mm.)



(c) UWall panels

(d) Installation of M&E system

(e) Installation of panels

(f) House model prior to field monitoring

Figure 2: Construction of a house model with hybrid composite wall panels

2.2 Instrumentation and field measurements

Figure 3 shows the three locations where temperature was measured (reference no. T1, T2 and T3). Relative humidity was also measured (reference no. RH1, RH2 and RH3) in the house (Figure 3). The heat transfer was measure using a high precision thermal RTD sensor (measuring range -50°C to 330°C) for indoor temperature. Readings were taken every hour for 48 hours. The monitoring was set for two conditions; (i) with indoor air movement (having door and window opened), and (ii) no air movement (door and window closed).

Relative Humidity (RH) (defined here as the "ratio of actual air vapour to air vapour at saturation at the same temperature") was measured using a digital hygrometer The HTC-2 (RH range of 10 to 99%). Ground-level outdoor air speed was measured with a AS816 air velocity meter (measuring range = 0.3 - 30 m/s) at 3 m above the ground.

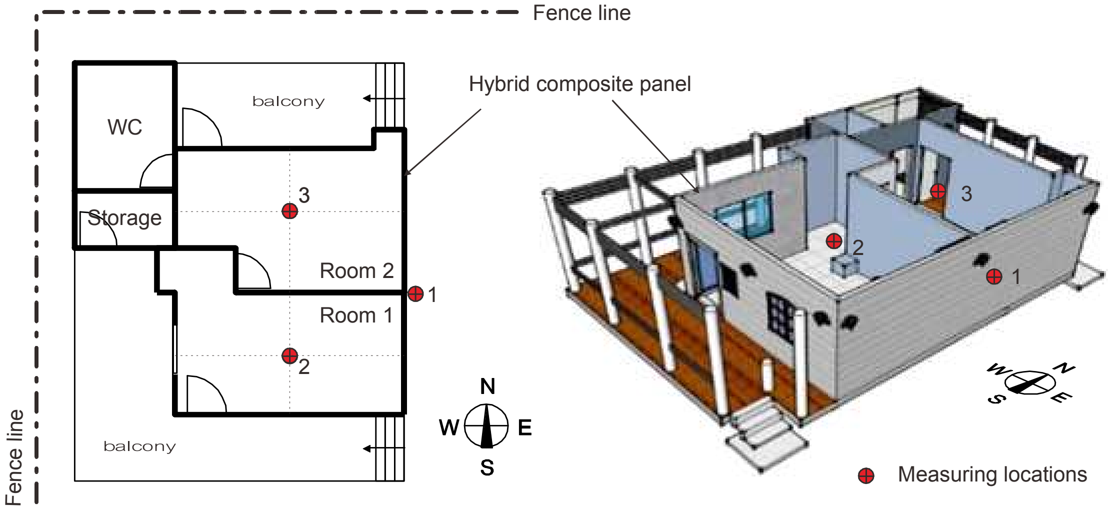


Figure 3: Positions of RTD sensors located inside and outside a house model

3. THERMAL PERFORMANCE AND ANALYSIS OF COMFORT LEVEL

Figure 4 compares the temperature and RH data recorded during the testing time at measuring points 1, 2 and 3 (see Figure 3). The results are reported with door and window closed or opened. The results in the grey-shaded area show that the indoor temperature in the house made of UWall panels is lower for the case of no opening, i.e. when the door and window are closed. However, the indoor temperatures (T2&T3) were higher than the outdoor temperature T1 from 20:00 to 24:00 because the heat collected inside the wall during the day was released at night time. Based on the initial 48 hours field monitoring (11-12 March 2017), the highest outdoor temperature was 37°C at 12:00–13:00 hrs, and the highest indoor temperature was 31°C at 12:00–16:00 hrs. Accordingly, the temperature difference was about 5 and 7°C without air movement and with air movement, respectively. It was also found that the indoor temperature of room 1 was higher than room 2 by up to 1-2°C over the monitoring period because the door and window located in room 1 allowed the heat to pass through these openings. At the night time (21:00-05.00 hrs) it was observed that the outdoor temperature at T1 was slightly higher (about 2°C) than the outdoor temperature at T2&T3. This can be attributed to the hybrid wall releasing heat absorbed during the daytime.

The results also show that the ambient RH was high (90%) at 04:00 hrs, since it rained during that period. However, the indoor RH at 2&3 were lower than the outdoor RH1 by up to 15% (see Figure 4b).

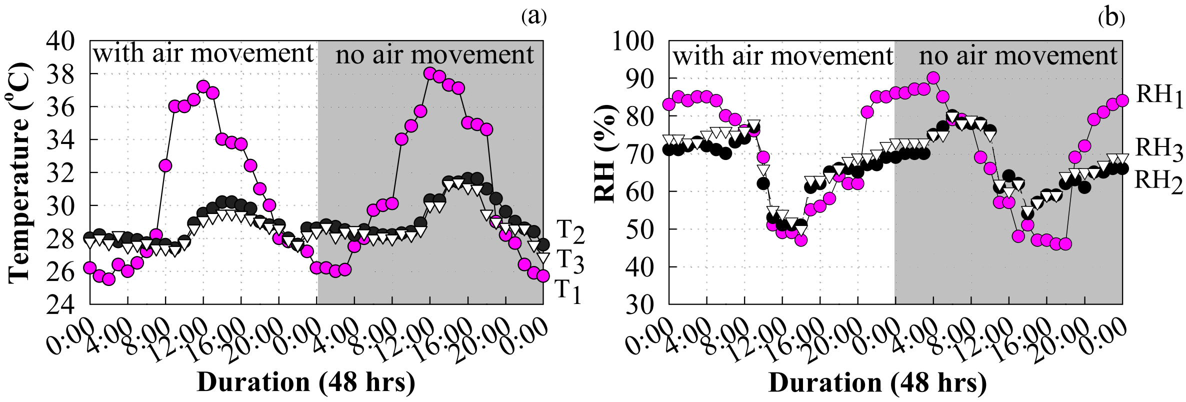


Figure 4: Field temperature (a) and relative humidity (b) recorded for 48 hours

Olgyay V&A. [5] proposed bioclimatic charts for building design. The comfort zone in these charts depends on the air temperature, humidity, mean radiant heat, air movement, solar radiation and cooling by evaporation. The comfort zone is defined between 21°C and 27.5°C and can move slightly downwards (winter) or upwards (summer) (Figure 5a).

According to the meteorological data for Chachoengsao province (see Table 1), the mean daily minimum air temperature ($T_{m,min}$) in December is 15.2°C, whereas the mean daily maximum temperature ($T_{m,max}$) in August is 33.3°C. The difference in temperature during the day and night is about 8–10 °C. The humidity is high during the early morning hours, and lower in the afternoon.

Table 1: Mean daily temperature and relative humidity for each month in Chachoengsao

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$T_{m,max}$	29.2	30.1	35.2	39.3	38.7	35.2	33.4	34.2	32.1	32.0	30.2	28.0
$T_{m,min}$	17.2	18.6	32.0	33.3	32.0	29.2	28.2	25.3	27.9	26.9	24.8	15.2
RH_m *	75.1	80.9	89.2	83.9	75.2	77.0	85.4	91.9	92.4	75.4	85.2	72.3
**	54.1	59.9	61.2	62.9	54.2	56.0	64.4	70.9	71.4	54.4	64.2	51.3

Note: * measured during 08:00 a.m. and ** measured during 14:00 p.m.

In this study, field data in terms of indoor temperature, RH and air movement were record for four measuring periods. Figure 5 shows that the recorded temperature and RH data were slightly outside the comfort zone (highlighted in grey shaded on the left) when no opening. If air movement was allowed (i.e. with openings), the comfort zone required for the air movement of 0.1-0.4 m/s. The average air movement was also recorded and found to be about 0.4 m/s with opening and/or use of the electric fan to improve the quality of indoor air.

Therefore, it was concluded that the house model constructed using UWall lied within the comfort zone when the indoor air movement was 0.4 m/s.

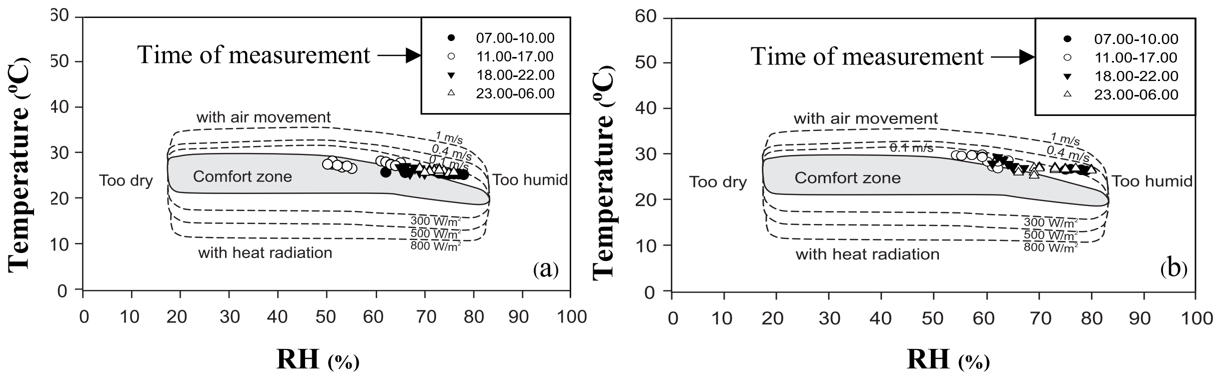


Figure 5: Bioclimatic chart of a house model: (a) without air movement and (b) with air movement

4. CONCLUDING REMARKS

This paper presented initial results of a 48 hours investigation on the thermal performance of a full-scale house constructed with composite walls in Thailand. Based on the results from the bioclimatic chart (that considers field temperature and relative humidity data), it is found that both temperature and humidity inside the house lie outside the comfort zone during daytime with outdoor and indoor temperature difference ranged from 3-5 °C. However, when the air movement is taken into an account, the comfort zone enlarges and the house remains within the comfort zone at all times. Current measurements and research are underway to develop more advanced and specific charts to assess the energy performance of the house.

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ENERGY PLUS SEISMIC RETROFITTING OF EXISTING EU BUILDINGS

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Abstract

In this paper the existing housing stock in EU Member States is considered, especially in seismic active regions with high or medium seismic hazard and possible seismic risk. It is focused on individual energy renovation and seismic retrofitting of RC buildings with infill walls and masonry buildings and how to increase the seismic and thermal properties using innovative new materials. Moreover, it is about the simultaneous energy and seismic renewal of the existing buildings using new composite systems and new materials. At the end, we can envision that in the next years after energy deep renovations building will be sustainable and seismic safe and less vulnerable in potential new earthquakes.

The paper is specifically related to the analysis which are given by the Joint Research Centre (JRC) (2018). JRC is the Commission's science and knowledge service and carry out research in order to provide independent scientific advice and support to EU policy. Due to revised Directive (EPBD) Member States with high and moderate seismic activities must prepare National Energy Efficiency Action Plan and describe the energy efficiency improvement measures for energy deep renovations with seismic retrofitting, which are planned at national level to achieve the target of the Directive.

Keywords: seismic retrofit, energy renovation, simultaneously retrofitting, EU directive revision

1. INTRODUCTION

Safety and sustainability of new and existing buildings must be of interest for all EU Member States. In spite of that today, even during the deep renovations, retrofit, and refurbishment of old buildings, the safety aspects of existing buildings are neglected, and sustainable building may not be the safe building. During recent earthquakes (eg in Italy, [6]), damages of old energy-restored buildings show the vulnerability of structural elements due to poor seismic resistance. Seismic hazard, different than others natural hazards, is sudden, unannounced and not prevented activity.

Sustainability has 3 pillars; environmental, society and economy (UN World Summit, 2015) and the foundation of sustainability pillars must be mechanically resistance, stabile, and safe in case of fire (Regulation (EU) 305/2011, Basic Requirements for construction works) [1].

Since 2011 EU gives financial supports to increase the sustainably of building, in 2014 - 2020 over 5% of budget of the European Regional Development Fund has been allocated to sustainable urban development. This money has been given for increasing energy efficiency, reducing energy bills and for damages related to climate-change (e.g. floods, hurricanes, melting of glaciers). Energy retrofitting value in EU is around 300 billion Euros.

Buildings have a great opportunity for energy saving, and therefore energy renovation was in focus last decade, while seismic risk had been neglected in all existing real estate. Buildings placed in seismic areas remain unsafe and not sufficiently resistant to earthquakes, and consequently not adequate sustainable. Even low intensity earthquake could expose big damages or demolitions of thermal insulating layers (plasters, finishing) and simultaneously big financial cost for repairing. As well, because of inadequate energy renovation a large number of building are unsafe in case of fire.

Energy renovation approach has to be changed. In seismic areas energy renovation shall be combined with seismic retrofit, to prevent damages, possible life losses and expenses for reparations and to prevent duplicating process and costs when doing separately energy and seismic renovation. However, several barriers exist for combined retrofit; technical, financial, duration of retrofitting, technology, historical buildings policy and regulations. Some barriers may be overcome with innovative materials for retrofitting. Old buildings have poor energy performance, big energy consumption and poor resistance to earthquake. JRC target was to explore innovative solutions for possible simultaneously seismic and energy retrofitting of existing buildings and to find the innovative solutions and materials to increase buildings safety and energetic efficiency [7]. Cost, sustainability and durability are challenges for such retrofitting, while socio-economic and environmental impact are expected from research project, and finally safe buildings. At the end, the community has benefit of such new retrofitting's approach.

What is retrofitting? Energy retrofitting means improving existing building energy efficiency, while earthquake retrofitting is the process of strengthening building to improve resistance to earthquake.

What is benefit? Benefit comes from safe and sustainable buildings, from saving money of using new technologies and new product (materials), saving time, and reducing damages and cost in future possible earthquake.

Reconstruction of existing EU buildings is priority and it will be even bigger in coming period, because of policies. Changes in EU regulations, innovative materials and systems, are support for simultaneously retrofitting of existing buildings in near future, in countries with high and moderate earthquake hazard.

2. BUILDING STOCK IN EU

Most of the existing EU buildings are residential buildings (75%), some are public (12%) and others are private buildings (88%), with total values of 116 million. Around 86% of those buildings were built up to 1990, and 62% before 1970.

All existing buildings require high maintenance and reconstruction to meet the today requirements of safety (Eurocodes) and sustainability (for energy efficiency EPBD). 75% of existing building are energy inefficient. In countries with high or medium seismic hazard the amount of seismic unresistant buildings may be the same or even more. Codes started in 70s for seismic resistance and in 80s and 90s for sustainability, mainly for thermal insulation.

In most of the Member States existing buildings are of reinforced concrete (RC) with infill walls or masonry buildings. The highest vulnerability element this type of buildings, both for seismic or energy performance, are external walls. In this paper they will be in focus.

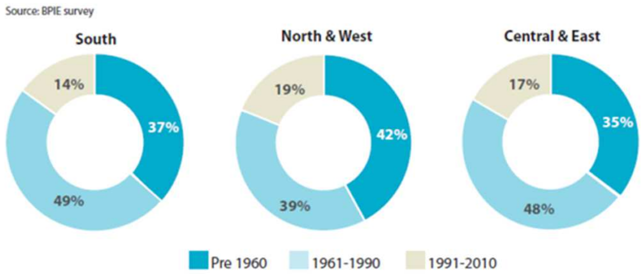

Figure 1 Ages of residential building stock in EU-27 [7]

3. SEISMIC ACTIVITY, HAZARD AND RISK

Seismic hazard is different across EU-27; high in Italy, Romania, Greece, Bulgaria and Balkan region (include Croatia), moderate in Spain and Portugal, and low in others. Earthquakes of the highest intensity were recorded in Euro-Med, in Turkey, Greece, Italy, Spain, Iceland.

Vulnerability and consequently earthquake risk depend on type of structures, materials and state of the building. Seismic hazard map is made for all European countries, while seismic risk map is national and does not exist for all countries. Such as sustainable building shall not mean that the building is safe, such high seismic hazard shall not mean high seismic risk and vice versa.

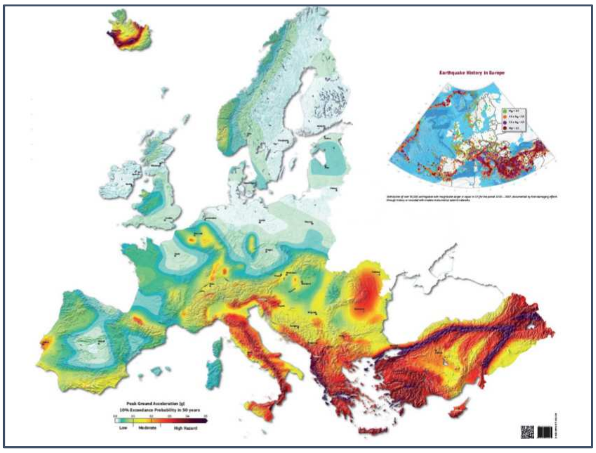

Figure 2 Seismic Hazard Map, edited in 2013, EU-27

25% of the EU-28 building stock is located in seismic zones, that means 1 million building need to be seismic and energy retrofitted annually (for 3% renovation rate scenario).

4. SEISMIC RESISTANCE AND ENERGY EFFICIENCY OF OLD BUILDINGS

4.1 General

As mention before most of existing buildings were built before 1970 and does not fulfil modern requirements for safety and sustainability. Existing buildings have poor seismic resistance and poor energy efficiency. There were built with poor materials, poor workmanship, and were suffering a lot of modifications and reconstructions, most of them decreased resistance, especially when considering earthquake risk.

4.2 Seismic resistance

Damages on AB structures are on columns and infill walls, while on masonry structures are mostly on external walls. Required earthquake retrofitting includes all these elements.

The demands of strengthening of buildings against earthquake have progress and requirements in new standards (eg Eurocode 8 for earthquake resistance structures).

Energy renovation, thermal insulation, on external walls may increase seismic risk, and damages may arise on the external walls during the low intensity earthquakes. That can cause great cost and potential human losses. Damages in the recent earthquakes show vulnerable structural elements [6]. A great amount of money spent on energy renovations may be lost.

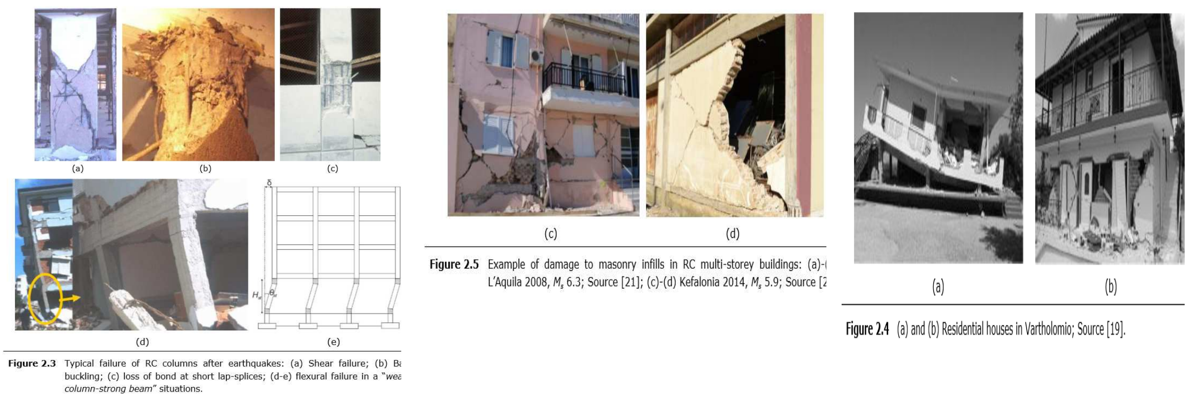

Figure 3 Damages on s structural elements of RC and masonry buildings [7]

A lot of damage occurs on non-structural elements. In latest earthquakes (eg , L'Aquila 2008, Kefalonia 2014) [6]. most of the existing RC multi-storey buildings did not collapse, but great damage was on non-constructive elements. Improvement of seismic performance by strengthening include increase of resistance and deformation capacity.

4.3 Energy efficiency

Most of the buildings were built prior to energy efficiency requirements. After 1980 all EU countries introduced energy codes for reducing the energy consumption of new buildings. 30 years after, the energy efficiency of existing buildings is in the focus.

The building's age profile is a critical factor about which the renovation and technological solutions depends. Energy renovation means a variety of interventions on building; the energy saving, reducing cost for heating, cooling, ventilation and hot water and lights of end users. Minor renovations correspond 0-30%, moderate 30-60% and deep 60-90% of final savings of energy consumptions, while nZEB renovations represent savings beyond 90% (Building Performance Institute Europe).

The energy performance of building is largely determined by the building envelope (external walls, roof, floors, windows and doors). Energy losses through the envelope depends on numerous factor (type of building, orientations, age, climate …).

We consider only the measures of energy renovations connected with external walls which depend on materials. Continuous development of new materials with high thermal performance is needed.

5 SEISMIC RETROFITTING AND ENERGY RENOVATION

5.1 Seismic retrofitting

Seismic retrofitting is based on two main objectives: reduce damage (include human losses) and increase the seismic capacity of building (strength, stiffness and deformations). Fib [10] and FEMA [11] documents provide a guide for seismic assessment and retrofit and give techniques for seismic rehabilitations of existing buildings. Local and global retrofitting measures are possible, only local measures being considered in the paper.

The most conventional materials and techniques are RC jacket or steel jacket. RC jacket increases strength, stiffness and durability, while steel strength and ductility. RC jacketing is suitable for columns, while the steel jacket suitable for increasing walls stiffness while as a diagonal steel beams to increase ductility. Retrofitting with conventional materials require a lot of materials (increase CO2 emissions, and lot of energy in manufacturing) and require a lot of specialist's work and evict of tenants.

Fibre-reinforced polymer (FRP) materials have overcame this disadvantage and replace conventional materials in the last three decades. FRP are thin strips (thickness about 1 mm) made of high strength fibres, usually impregnated with resin. FRP has high strength, resistance to corrosion, offers simple and fast applications and gives minimal geometric changes. FRP deficiency is high costs, bad behaviour at high temperatures or on wet surfaces, and organic resin limits their applicability.

As a solution of problems of conventional and FRP materials new materials are proposed, so called near surface mounted (NSM) materials (for example TRM). Textile-Reinforced Mortar (TRM) is a promising material, recently are use. That is a fabric mesh of long woven, knitted or unwoven fibre roving and at least two directions, impregnated with inorganic binders, such as cement based mortars. TRM is low cost, friendly for workers, fire resistant, applicable on wet surfaces or at low temperatures materials. Probably in short time will replace FRP.

5.2 Energy renovation of envelopes, thermal insulations

Energy renovation improve the energy efficiency of the building by improving the thermal insulation of the envelope (as minimum energy renovations).

Thermal insulations materials are combined materials. When properly applied to wall can retard the rate of the heat flow by conduction, convection and radiations. The choice of heat insulation depends on the thermal conductivity and heat inertia of the selected insulation material. The best result comes when thermal insulations is closest to the surface of heat entry.

Conventional materials; mineral wool, expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PUR), (elements of ETICS). Todays a lot of modern insulation materials are present. Vacuum insulation panels VIP represent an evacuated, open porous material that is enveloped into a multilayer film. Gas-filed panels (GFP) use a combination of thin polymer films and low–conductivity gases to achieve lower thermal conductivity rates. Aerogels are dried gels with a very high porosity that represent one of the most promising thermal insulation materials. NIM technology (thickness of 0,1nm to 10 nm) prevent air and noise penetration. Nano is a homogeneous material (NIM) with a closed or open Nano porous structure. NanoCon is collecting or mixing several different materials with a final product that is not homogeneous. Capillary tubes principally used in interior walls and ceilings now is use into external walls (new heating system).

5.3 Building retrofitting projects, possible scenarios and new composite techniques

Three scenarios of retrofitting may happen, two separately seismic or energy and third combined [9].

Demolitions and reconstruction; suitable for buildings with extremely poor performance. Such retrofitting meets today requirements for energy consumption and structural safety. Possible reuse and recycling of construction materials are conducted. Such reconstruction requires relocations of inhabitants.

Energy renovations; do not ensure structural safety, even small earthquakes could cause damages, requires repair, relocation of inhabitants, or may imposed buildings collapse and human losses.

In previous both cases, some construction materials of demolished building have to be disposed in landfills and may have negative impact on environment.

Energy and structural renovation; mean renovation for improving envelope resistance. Sustainable and seismic safety should be insured, especially in deep energy renovation projects Depend on type of materials for renovations required relocation of inhabitant. The main challenge of seismic plus energy retrofitting is the total cost of such renovations (materials and labour). Technical solutions may be different and may lead to innovations.

All negative influence of conventional materials could be overcome with new inorganic composite materials.

Engineered Cementitious Composite (ECC) is the type of cement mix with a unique composition of low volume fibres, has high ductility, high tensile strength, provides greater resistance to corrosion, suitable for repairs, environmentally sustainable material and resistant to temperature and moisture conditions.

Ultra-High-Performance Fibre Reinforced Concrete (UHPFRC) has high tensile strength, very high compressive strength, high ductility, low permeability, sustainability performance, and the quality required for finishing layer.

Textile reinforced mortars (TRM) combines inorganic binder with textile fibres. Offers durability, high temperature resistance, low price. TRM is the most efficient material in seismic retrofitting of RC and masonry structures (see art. 5.1).

6 SEISMIC AND ENERGY RETROFITTING AND POTENTIAL BENEFITS

Seismic and energy capacity may be changed in an economically sustainable way combining advanced materials and systems. It is necessary to develop integrated solutions, cross-sectoral approaches by combining engineer design, building physics and use of advanced composite material production techniques. The simultaneous structural and energy retrofitting on building envelope are proposed, suitable for RC structures (textile jacket for column), and in infill walls and masonry structures (textile patch and textile anchors). Due to the simplicity of application this environmentally friendly materials are promising. Various retrofitting solutions are possible: TRM + PUR, TRM + VIP, TRM + NIM, TRM + heating system.

The solutions combine high strength lightweight reinforcement for seismic retrofitting (for structural and non-structural elements) and additional insulation materials or heating system integrated to achieve energy retrofitting. This allows simultaneous achieving the required safety and energy performance.

Binding reinforcement on the envelope of the building is realized by an inorganic mortar on the base of the cement, ensuring the durability and resistance to fire on the upgrade. Insulating materials or heating systems are connected to concrete or masonry surfaces by inorganic mortar.

TRM jacket is an effective local strengthening technique for increasing the deformation capacity of column. TRM for seismic retrofitting for infill walls RC frame are suggested as global retrofit measure to increase strength and stiffens of structure. In one intervention together both the security (earthquake) and energy efficiency are increased.

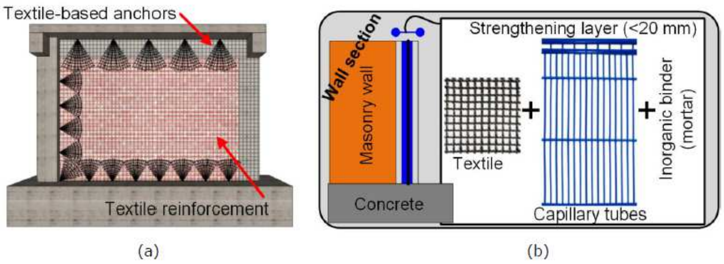

Figure 4.2 (a) Seismic strengthening configuration; (b) Textile reinforcement combined with capillary tubes will be integrated and embedded into a thin mortar layer.

Figure 4: Example: seismic and energy retrofitting [7] [9]

The use of inorganic composites in rehabilitations reduces overall costs. Incredibly reduce labour costs and all that keep the overall cost low. It is presuming, after a lot of investigations and cost analysis, that the overall cost of retrofitting is 30% less. In EU 81 million of RC buildings and 23 million of masonry buildings need energy rehabilitation. 25% of the EU-28 building stock is located in seismic regions and because of that consequently 1 million building need to be seismic and energy retrofitted annually (for 3% renovation rate scenario). Total cost of simultaneously retrofitting could be reduced at least 30% due to labour savings [7, 9] that means 3.5 million Euros are saving in the reconstruction what is big economic impact on the EU building sector.

Finally, the benefits come from the time needed for reconstruction, from the overall cost of retrofitting, from not re-locating tenants, and from final geometric characteristics of the exterior walls that can provide the possibility of renovation historic buildings.

7 POLICIES AND REGULATIONS

EU has a policy relevant to the Built Environment and the Construction Sector, programmes, strategies and blueprints for action, as; The 7th Environment Action Programme of the European Union (EAP), EU Strategy on adaptation to climate change (2013), Thematic Strategy for the Urban environment (2016), The Row Materials Initiative (2011), The Roadmap to a Resource Efficient Europe (2011), and EU action plan for Circular Economy (2015).

EU relevant regulations and directives are: Energy Performance of Buildings Directive (2010), The Energy Efficiency Directive (2012), The Renewable energy Directive (2009), The Construction Products Regulations (2011), The Industrial Emissions Directive (2010) and The Waste Framework Directive (2008). Most important, New (revision of previous), Directive

(EU) 2018/844 [5] introduced safety requirements for energy-renewable buildings due to safety of fire and seismic actions (*In Article 7, the fifth paragraph is replaced by the following:*

'Member States shall encourage, in relation to buildings undergoing major renovation, high-efficiency alternative systems, in so far as this is technically, functionally and economically feasible, and shall address the issues of healthy indoor climate conditions, fire safety and risks related to intense seismic activity.')

8 CONCLUSIONS

New retrofitting approach and new technologies for simultaneous seismic and energy retrofitting in EU Member States with earthquake hazard are needed. Existing buildings have poor earthquake resistance, not adequate thermal insulation, and consequently big energy consumption.

Sustainability and environmental requirements are focusing on the reduction of the operational energy consumption and on the use of low carbon materials without counting on structural deficiencies which could leave the buildings seriously unsafe in the seismic active regions. Recent earthquakes have highlighted this problem, damages on many buildings proved that.

Simultaneous seismic and energy renovation of existing buildings are necessary for increasing sustainability and remaining safety as before renovation (as minimum). National authorities for the seismic and fire safety requirements of existing buildings, because of Directive provision, shall upgrade the national regulations.

Approach of new retrofitting must be implemented for public buildings, as soon as possible, because governments need to give example. Problem are private owners who are not sufficiently motivated to take seismic and energy renovations together, mostly because of insufficient knowledge about earthquake risk and benefits of simultaneous seismic and energy retrofit.

Governments, beside improvement and revision of regulation, should give some additional financial support to private sector for such retrofitting. Many buildings for energy renovation (thermal insulations) use national subsidies and from EU funds.

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NEW LIGHTWEIGHT TEXTILE REINFORCED CONCRETE AND SUSTAINABLE DIATOMITE-BASED INSULATION MATERIAL FOR SANDWICH PANELS

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Abstract

The “Smart PI.QU.E.R.” project, supported by Lombardy Region (Italy), is aimed at developing a sandwich panel for the energy retrofitting of existing residential building. The panel is characterized by external textile reinforced concrete layers and by an eco-friendly inner insulation layer based on inorganic diatomite. The main feature of the panel is that it could be applied on an existing façade through four punctual connectors by means of a crane, without any scaffolder. Basing on the experience gained in the European project “EASEE”, the partners try to overcome some criticisms previously encountered in the EASEE panel, related to the use of expanded polystyrene as insulation material, to the cost of the anchoring system and to aesthetical issues related to the cracking of TRC layers. The main innovations of this panel concern: the development of a new insulation material, based on diatomite (natural source); the optimization of its shape; the optimization of textile reinforced concrete layers; the development of a new anchoring system. This paper is focused on the research developed at material level referring to both external layers and insulating core.

Keywords: sandwich panels; lightweight textile reinforced concrete; sustainable diatomite-based insulation material.

1. INTRODUCTION

Starting from 2002, European Union have introduced energy performances of existing buildings in the directives concerning the mitigation of climate changing [1,2]. The energy efficiency of new buildings is continuously increasing; however, it is necessary to retrofit the existing buildings in order to reduce their impact on the energy consumption due to heating and air-conditioning.

The European building stock is heterogeneous; however, in all the countries residential buildings represent the majority of the floor area (varying from the 60% computed in the Norther and Central European countries to the 85% in the Southern countries) [3]. The age of the existing buildings is a good indicator of their energy efficiency: the higher is the percentage of new buildings, built following the latest Standards, the higher the energy performances. In the EU countries, about 50% of residential buildings has been built before 1970, when the first Standard concerning energy efficiency issue was introduced [3].

In Italy, about 12.2 million residential buildings exist: 56.7% of them have been built before 1970 and 17.4% between 1971 and 1980 [4]. Considering that the first Standard on energy savings in buildings has been introduced in 1976 [5], the energy consumption related to heating and air-conditioning is significant and close to 40% of the total energy consumption [6].

In the 7th Framework Programme promoted by the European Commission, the project EASEE [7] proposed innovative solutions for the energy retrofitting of existing cavity walls in residential buildings acting on the inner side of the wall, on the cavity and on the external façade. Focusing on the outer solution, a sandwich panel was developed: it is characterized by external textile reinforced concrete (TRC) layers, 14 mm thick, and an inner insulation layer in expanded polystyrene (EPS), 100 mm thick. The dimensions of the panels (maximum size 1.5 x 3.3 m) allow fixing them to the beams of the concrete frame through four punctual connectors placed in the corners. The solution has been applied on some demo buildings; in particular, a four-storey building in Cinisello Balsamo (Milano) was completely retrofitted, thus allowing the validation of the solution concerning energy performances [8, 9, 10, 11].

Smart P.I.QU.E.R. ("Pannelli Isolanti per la riQUalificazione di Edifici Residenziali") is a project supported by Lombardy Region (Italy) with the aim of developing sandwich panels for the energy retrofitting of existing residential buildings, basing on the knowledge gained within the EASEE project. The following criticisms of the European project need to be solved: the use of expanded polystyrene as insulation material, the high cost of the anchoring system and the cracking of the TRC layers due to shrinkage and thermal stresses (sun radiation). The choice of EPS was mainly due to its mechanical performances, which were needed to guarantee a good mechanical behaviour of the sandwich; however, it is not an eco-friendly material and it does not guarantee great performances in case of fire. The main innovations of this panel, with respect to that developed in EASEE, are listed in the following. (1) Development of a new insulation material, based on diatomite (natural source), characterized by a high level of sustainability, multiscale porosity, low thermal conductivity, lightness and good mechanical behaviour, even in case of fire. (2) Optimization of the core shape, in order to reduce the global weight of the panel. (3) Optimization of the TRC layers, acting both on the mortar (light sustainable aggregates, reduced shrinkage) and on the fabric (behaviour in case of fire, sustainability). (4) Investigation on the TRC/insulation interface, in order to guarantee a good mechanical behaviour also in the case of high thermal gradient. (5) Development of a new anchoring system, with a lower impact on the panel cost, weight and thermal properties. The thickness of the layers will be the same adopted in the EASEE project.

This paper is focused on the research developed at material level in order to obtain lightweight TRC layers, characterized by good mechanical behaviour in tension, and an inorganic diatomite-based insulation core, characterized by a density close to the target and suitable thermal and mechanical properties. It is worth noting that the lightening of TRC layers, obtained thanks to the use of light aggregate in the mortar, is mandatory as the new insulation material is characterized by a density which is about 7 times the density of EPS and the weight of the panel is aimed at not significantly affect the total load acting on the existing structure.

2. LIGHTWEIGHT TEXTILE REINFORCED CONCRETE

2.1 Mix designs

In the paper, five matrix mix designs are taken into account (see Table 1). The “Reference” mortar was used in the first phase of the EASEE project (e.g. [10]). At that time, cracks due to shrinkage could be observed in the panels produced using this mortar. Hence, shrinkage reducer admixtures were added in the matrix mix design; the panels applied in the EASEE demo-buildings were produced using this “Reference+SRA” mortar. A quartz sand, with a density of 2500 kg/m^3, was used as aggregate; in the textile reinforced concrete specimens, the maximum aggregate size was equal to 1 mm. Concerning vapour diffusivity, “Reference” matrix has been characterized within the EASEE project according to prescriptions of UNI_EN 1015-19 [12], resulting not permeable to vapour.

Table 1. Matrix mix design: reference, reference + SRA, mix 1A, mix 2A and mix 4.

	Reference	Reference + SRA	Mix 1A	Mix 2A	Mix 4
Cement I 52.5 (kg/m^3)	600	600	600	400	600
Slag (kg/m^3)	500	500	500	300	500
Quartz sand 0-1mm (kg/m^3)	886	847	-	519	-
Fillite	-	-	196	196	-
PA	-	-	-	-	382.5
Water (l/m^3)	223	223	280	280	223
Superplasticizer (kg/m3)	31	31	31	31	31
Super Absorbent Polymer (kg/m^3)	-	-	1.8	1.8	-
Shrinkage Reducer Additive 815 (kg/m^3)	-	6	6	6	6
Shrinkage Reducer Additive 150 (kg/m^3)	-	30	30	30	30
w/c	0.37	0.37	0.47	0.70	0.37
w/b	0.20	0.20	0.25	0.40	0.20
ρ (kg/m^3)_estimated	2240	2237	1645	1701	1772
ρ (kg/m^3)_measured	-	2305	-	-	1824

“Mix 1A” (Table 1) has been obtained starting from “Reference+SRA” mortar, keeping the same amount of cement and slag and substituting the sand with a lighter aggregate, the fillite. Fillite is a glass hard, inert, hollow silicate sphere characterized by an apparent density of 400 kg/m^3, a real density of 700 kg/m^3 and an average size of 200-250 µm. The addition of water in the mix is aimed at obtaining the wright workability. Super absorbent polymers (SAP) were also added in the mix in order to reduce the autogenous shrinkage and to further control the plastic shrinkage [13].

“Mix 2A” has been obtained starting from “Mix 1A”, keeping the same amount of fillite and reducing the amount of cement and slag (fine particles) in order to further limit the problems related to shrinkage. In order to fill the volume of missing material, quartz sand was added. The entity of the reduction of cement and slag was based on previous results concerning the investigation of mortar shrinkage on various type of matrixes.

"Mix 4" (Table 1) has been obtained starting from "Reference+SRA" mortar, just substituting the sand with lighter aggregates made of plastic waste (PA) with a maximum size of 5 mm and a measured real density of 1130 kg/m^3. If compared with fillite, which is spherical and regular, PA aggregates are characterised by larger dimensions and irregular shapes. Looking at Table 1, it is worth noting that the density of the light mixes (1A, 2A and 4) is considerably lower than that of reference mixes, thus leading an important reduction of the weight of TRC layers (-20.8÷26.5% with respect to "Reference+SRA" mix). That means that, considering the same thermal conductivity and thickness of the insulation layer and its target density (200 kg/m^3), the increase of the panel weight ranges between 0 and 3.5 kg/m^2.

2.2 Mechanical characterization of the matrixes

A mechanical characterization of the matrixes was performed according to the prescription of EN 196-1 Standard for mortar [14]. In particular, the tensile strength due to bending and the cubic compressive strength were determined.

The results are collected in Tables 2 and 3. The specimens have been cured in air at environmental conditions for at least 28 days before testing.

Table 2. Tensile strength due to bending for reference, reference + SRA, mix 1A, mix 2A and mix 4 matrix.

	Reference	Reference + SRA	Mix 1A	Mix 2A	Mix 4
f_{ctfm} at 28 days [MPa]	11.89	13.47	9.58	9.26	6.56
(number of spec.)	(2)	(10)	(4)	(4)	(2)
STD	-	0.97	1.00	0.56	-
STD%	-	7.20	10.41	6.10	-

Table 3. Compressive strength for reference, reference + SRA, mix 1A and mix 2A matrix.

	Reference	Reference + SRA	Mix 1A	Mix 2A	Mix 4
f_{ccm} at 28 days [MPa]	90.62	96.16	49.75	44.19	37.34
(number of spec.)	(4)	(20)	(8)	(8)	(4)
STD	4.25	8.47	3.96	3.24	7.22
STD%	4.69	8.81	7.97	7.33	19.34

A significant reduction of the compressive strength was recorded in the lightweight mortars with respect to "Reference + SRA" specimens (-48.26%, -54.05% and -61.17% respectively for Mix 1A, Mix 2A and Mix 4), while the influence of lightweight aggregates on the tensile strength due to bending is smaller (-28.87÷-51.30%).

2.3 Alkali-Resistant glass fabric

The geometrical and mechanical characteristics of the alkali-resistant glass fabric used as reinforcement in the TRC specimens are collected in Table 4.

Table 4. Characteristics of the fabric.

Fabrication technique	Leno weave
Material	AR-glass
Coating	SBR*-based water resin
Warp and weft yarn spacing (mm)	10.0 ; 14.3
Warp and weft (Tex)	2 × 2400 ; 2 × 1200
Coating weight (g/m$^2_{fabric}$)	100

Max. tensile load on 70 mm (kN)	12.19 **

* Styrene-Butadine Rubber ** average value of 4 tests tested in warp direction

2.4 Tensile behaviour of textile reinforced concrete

For each mix, 3 textile reinforced concrete specimens were cast. Each specimen has the dimensions of 400 x 70 x 9 mm and is reinforced with one layer of the fabric described above, placed in the middle of the thickness, with the warp aligned in the longitudinal direction. Before testing, specimens were cured in air at environmental conditions for at least 28 days.

Tensile tests were performed using an electro-mechanical press INSTRON 5867 with a maximum bearing capacity of 30 kN. A pressure equal to 2.3÷2.8 MPa (corresponding to a force of 8.1÷9.8 kN) was applied at the specimen edges in order to clamp them in the clamping devices; in order to avoid the local crushing of concrete in the clamping devices, 3 mm thick steel plates were glued at the specimen edges, in the clamping regions. Tests were displacement-controlled and were performed imposing a constant crosshead displacement (δ) rate of 0.02 mm/s. The test set-up is shown in [15].

In Figure 1 the test results are plotted in terms of nominal stress (σ) vs. normalized displacement (δ/l). The nominal stress is computed as the ratio between the load and the area of the specimen cross-section, and the normalized displacement is obtained dividing the applied displacement (δ) for the initial distance between steel plates glued to specimen edges.

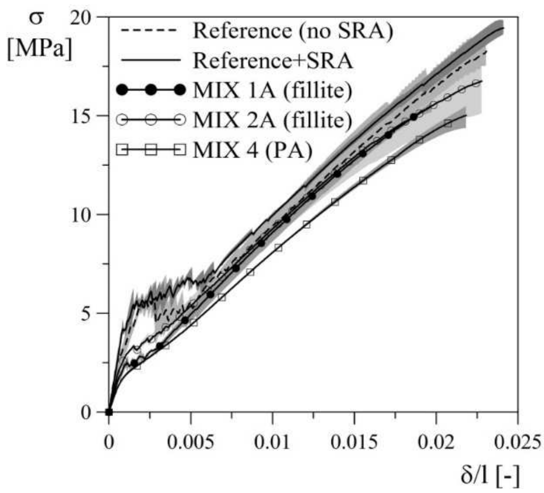

Figure 1: Tensile behaviour of TRC specimens: nominal stress vs. normalized displacement curves for reference, reference+SRA, mix 1A, mix 2A and mix 4 specimens.

Looking at the graph, it is worth noting that each average curve is stopped when the first of the three specimens fails; hence, the maximum stress value reached by the average curve differs from the average peak value. The average peak values are collected in Table 5.

Table 5. Average values of maximum stress reached by reference, reference + SRA, mix 1A, mix 2A and mix 4 TRC specimens.

	Reference	Reference + SRA	Mix 1A	Mix 2A	Mix 4
σ_{max_av} [MPa]	18.62	19.52	16.15	16.98	15.51

The scatter of results is very limited, with the only exception of mix 2A (post-cracking branch). In all the cases, the tri-linear behaviour of TRC is achieved [15].

The addition of shrinkage reducer admixtures in the reference mix involves an increase in the first cracking strength, with a consequent translation of the multi-cracking branch at a higher level of stress. However, the increase is limited.

All the lightweight TRC specimens are characterized by lower performances with respect to the reference mixes. However, a good global behaviour is obtained using both fillite and PA aggregates. The two sets of specimens including fillite are characterized by a comparable behaviour, even if their particle size distribution is completely different.

Concerning the ultimate behaviour, it is possible to compute an Efficiency Factor (Table 5) [15] determined as the ratio between the maximum load achieved by the TRC specimen with respect to the maximum tensile load of the fabric (Table 4). For reference matrixes, EF is close to 1; it is worth to note that, even with weak matrixes, considerably high values of EF are reached, even if lower than the reference case and characterized by larger dispersion of the results.

Table 5. Efficiency Factor for TRC specimens produced with different matrix mixes.

EF	Reference	Reference + SRA	Mix 1A	Mix 2A	Mix 4
Specimen 1	0.98	0.99	0.82	0.84	0.98
Specimen 2	0.96	1.03	0.83	0.93	0.83
Specimen 3	0.99	1.04	0.89	0.98	0.88
	0.98	1.02	0.85	0.91	0.90

3. SUSTAINABLE DIATOMITE-BASED CORE INSULATION MATERIAL

3.1 Core mix design

Lightweight sustainable insulation core was developed and characterized. The insulation core was obtained by using natural source (diatomite) as matrix, suitable amount of Si powder and vegetable surfactant as chemical and physical foaming agent and a polysilicate solution as reactive crosslinker [16].

Furthermore, to improve flexural mechanical properties, the effect of waste synthetic fibres (SFTR) and hemp short fibres was also evaluated; Table 6 collects the details of formulation. The process preparation, at material level, has been optimized in terms of fibre amount and vegetable surfactant in order to improve both thermal insulation and mechanical properties. The foam systems were cured at defined temperature and time and were subsequently characterized by means of thermal conductivity and mechanical characteristics.

Table 6. Core mix design

SAMPLE	Diatomite (wt%)	Polysilicate (wt%)	Si (wt%)	Catalyst (wt%)	Vegetable (wt%)	Waste fiber (wt%)
DHCF	19.57	65.24	0.046	8.39	5.82	/
SFTR-tq-1wt%-c1	19.64	65.46	0.046	8.42	5.85	1
SFTR-tq-1wt%-c2	19.56	65.19	0.046	8.38	5.82	1
Hemp 3 wt% -c1	19.18	63.93	0.046	8.22	5.70	2.91
Hemp 3 wt% -c2	19.19	63.97	0.046	8.22	5.71	2.85

3.2 Hygro-thermal properties and mechanical characterization of the core

According to the ASTM WK50791/WK43689 [17], thermal conductivity (λ) of foams was measured at ambient conditions using the Modified Transient Plane Source (MTPS) technique as well described in [18]. For each foam, three tests were performed. The results highlighted that λ of the foamed samples decreases with increase in the diatomite content. DHCF showed a thermal conductivity value equal to 0.052 W/m·K whereas SFTR_tq_1%wt showed 0.045 W/m·K. and hemp fibres 3 wt% 0.032 W/m·K. λ substantially decreased with the addition of fibres, in particular with content of hemp fibres; this could be correlated to the increase of porosity within the core structure induced by the addition of fibres. In order to investigate the factors that affect the thermal degradation of the core material, the thermo-degradative behaviour up to 1000°C was examined with TGA/DTGA analysis (detailed procedure in [16]). The thermo-degradation of sample showed one main decomposition temperature with maximum value occurring at 100 °C and a weight loss around 5 wt% (in the range 50-200°C) due to the water evaporation deriving from the condensation reaction of sodium silicate polymer [16]. Concerning the water vapour resistance factor (μ), it can be expected to be equal to that of an aerated concrete with a similar density (e.g. μ_{dry_cup}=7.1, ρ=304kg/m^3 [19]).

The same set-up described in [14] was used to test the foam specimens in bending in order to determine the mechanical performances of the core. Results for DHCF including waste and hemp fibres are shown in Figure 2. A ductile behaviour is achieved in both cases; in particular, the use of waste fibre allowed obtaining a hardening behaviour in bending.

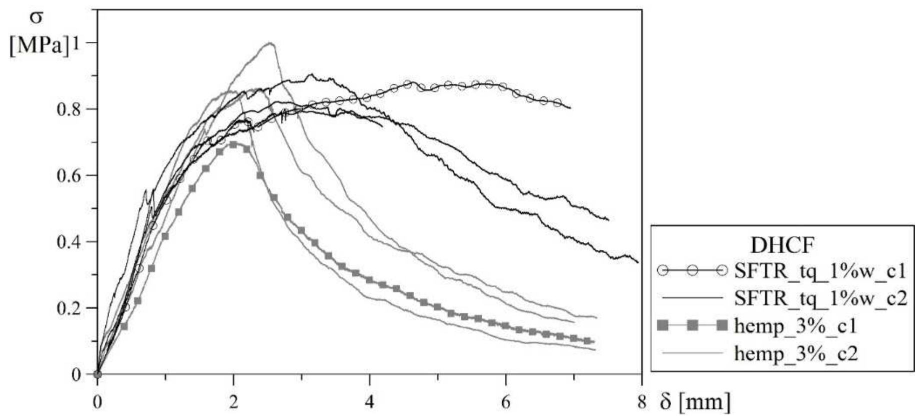

Figure 2: Bending behaviour of DHCF specimens: nominal stress vs. displacement curves for specimens including SFTR and hemp fibres.

4 CONCLUSIONS

Concerning textile reinforced concrete layers, the lightened mixes seem promising for their use in the production of the sandwich panels, even if further investigation are needed for their applicability, especially concerning shrinkage strain. Concerning the core material, it is possible to state that both the proposed solutions are suitable for the application in the panel, as they are both characterized by proper thermal and mechanical properties.

ACKNOWLEDGEMENTS

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ID SiAge: 379284). The authors would like to thank Cascamificio Bergamasco Srl and Fibranova for the supply of waste synthetic and hemp fibres.

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FIBER REINFORCED ALKALI-ACTIVATED SLAG FOAM CONCRETES CONTAINING RECYCLED AGGREGATES PRODUCED USING PETRIT-T: AN APPLICATION OF ACOUSTIC PANELS FOR INDOOR WALLS

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Abstract

This paper presents experimental results regarding the efficiency of using acoustic panels made with fiber reinforced alkali-activated slag foam concretes containing lightweight recycled aggregates produced using an industrial side stream, Petrit-T. Process was developed in a laboratory setting, and its scalability was assessed by an industrial pilot: 50 acoustic panels with dimension 500×500×35 mm were produced using a common concrete production line and used to cover the indoor walls in a reverberation room. The acoustic absorption in diffuse field conditions was measured and the interrupted random noise source method was used to measure the sound pressure decay rate over time.

Since the rate of the drying shrinkage could be high for alkali-activated slag foam concretes and this increased greatly the possibility of crack formation, the rate of the drying shrinkage was also evaluated by using some prismatic beams with dimension 40×40×160 mm. Additionally, the negative effects of high rate of drying shrinkage on the crack formation of acoustic panels were monitored visually.

This investigation demonstrated the production feasibility of the acoustic panels made with fiber reinforced alkali-activated slag foam concretes using a common concrete production line. Furthermore, the experimental results showed that the panels exhibited good acoustic properties to absorb the sound. Moreover, the results indicated that the maximum acoustic absorption coefficients for the panels could be varied in the range of 0.5–0.6 in the high frequency regions (4000-5000 Hz). The rate of the drying shrinkage was limited to 0.25% after 1100 hours and no localized crack was detected on the surface panels.

Keywords: Acoustic panels, alkali activated foam concretes, the sound absorption, drying shrinkage.

1. INTRODUCTION

There is a growing need for more sustainable construction materials. As the world population grows exponentially, construction consumes more and more raw materials. Excessive consumption of raw materials leads to increase of energy consumption, emission of greenhouse gases and dust pollution [1]. One of the main sources of CO_2 is the production of ordinary Portland cement (OPC), which accounts for up to 5% of total CO_2 emission [2-5]. Alkali-activated materials are studied as one alternative to OPC. By alkali activation, many large-scale waste streams can be converted into sustainable construction materials. The sustainable concrete industry is one research area that has been investigated broadly; researchers have specifically focused on how to convert industrial by-products into cement and concrete [6-9]. Therefore, alkali-activated binders have been proposed and have emerged as an alternative to OPC binders, as alkali-activated binders seem to have acceptable mechanical and durability performance in addition to positive environmental impacts.

Recently, these alternative binders received great attentions to be used as foam concretes, which it brings the advantages of both porous concretes and alkali activated binders [10-12]. On the other hand, alkali activated foam binders present lightweight, good thermal and acoustic properties, eco-friendly and cost effective construction materials. Different alkali activated foam binders developed using fly ash, metakaolin, and granulated blast furnace slag. To produce foam concretes, different approaches were employed to introduce air voids in alkali activated binders such as adding chemical agents (Aluminium (Al), Hydrogen peroxide (H_2O_2), Sodium perborate ($NaBO_3 \cdot nH_2O$)), pre-made foaming agents. Using the chemical agents such as aluminum powder has some disadvantages, which this component has high kinetic energy, which this limit the usage of this chemical agent for alkali activated slag binders which themselves have short setting time. Moreover, the porosity production is out of control, however, using this powder has high impact on reduction of density. It is worth stating that there is no experimental data with respect to use of the chemical agents to produce foam in upscaling applications. Since premade foaming approach has been used widely and successfully in generation of OPC based foam concretes.

To the best knowledge of the authors, all studies regarding the development of alkali activated foam binders have being limited to laboratory scales and no one has developed these porous materials for upscaling applications. Therefore, this study was established to assess the feasibility of using normal concrete production lines to produce these lightweight and porous alternative binders. Furthermore, in this paper, a comparative study was conducted between the results obtained from lab scale and large scale of foam concrete castings.

This paper represents the experimental procedures of casting fiber reinforced alkali activated slag foam concretes in upscaling applications. In this study, more than fifty panels with dimension (500×500×35 mm) were cast and tested to obtain hardened state and sound absorption properties. Mechanical properties were addressed in terms of flexural and compressive performances. The efficiency of PVA fibers used on controlling shrinkage was also evaluated. The sound properties were measured in a reverberation room.

2. EXPERIMENTAL PROGRAM

2.1. Materials and mix design

Fiber reinforced alkali activated slag foam concrete was comprised of ground granulated blast furnace slag (GGBFS), recycled aggregates provided granulation of Petrit-T, alkali activated solution (a combination of sodium silicate and sodium hydroxide), PVA fiber, pre-made foam. The proportion of the mix composition listed in Table 1. Recycled aggregates were prepared by mixing pre-wetted Petrit-T, borax, and sodium silicate. Pre-wetting was executed by stirring 10% mass of Petrit-T water with Petrit-T and then, cover it with plastic for 24 hours. Using Petrit-T without pre-wetting process results in production a huge amount of heating during the addition of alkali solution, therefore, using Petrit-T without pre-wetting process is impossible. The Petrit-T was supplied by Höganäs (a Swedish company), which is a stable by-product obtained in the production of sponge iron. More details regarding Petrit-T can be found in [13, 14].

Table 1: The proportion of the foam concrete

Slag	Recycled aggregates/slag	Alkali activator/slag	SS/SH	PVA fiber/slag	Foam/slag
1	1	0.56	2.5	0.024	0.25

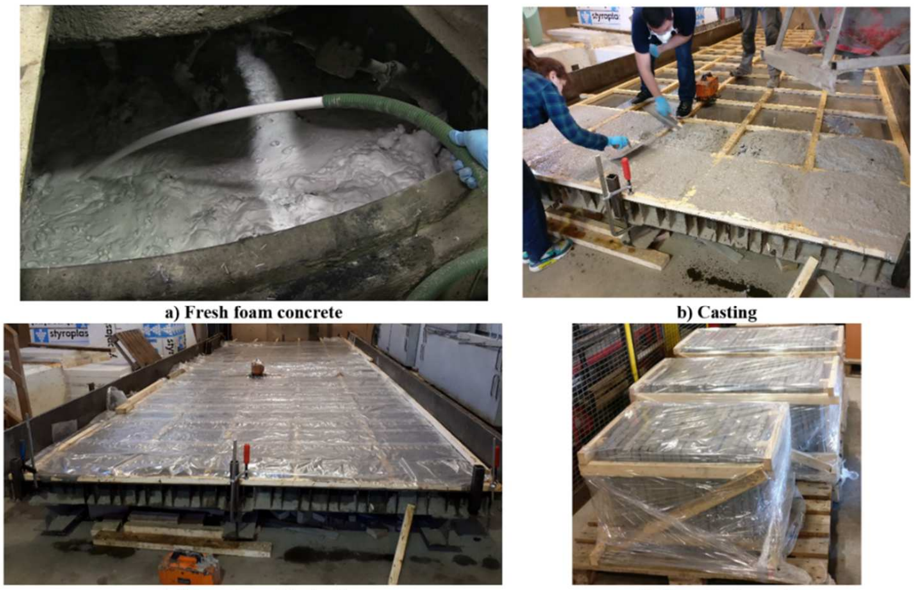
The procedure of recycled aggregate production in small scale has been addressed in [13]. This recipe was also used for producing recycled aggregates in the process of upscaling, however, it did not work and Petrit-T was dry after adding the liquid (a combination of sodium silicate and borax was around 70% mass of Petrit-T). Therefore, a trial-and-error process was used to achieve the minimum content of this liquid to consider both economic and cost efficiencies (Figure 1). According to the results of this procedure, the content of liquid increased to total mass of Petrit-T. Moreover, it was observed that the particle sizes of recycled aggregates varied in higher ranges of 0.2-30 mm, which it may be due to differences in heat generation during the mixing of the materials, differences in speed and frequency of mixer, and differences in volume of materials. After producing the recycled aggregates using the granulation process, aggregates cover with plastic bag for 24 hours. Using coarse recycled aggregates affects hardened state properties and density of the mix composition, therefore, recycled aggregates were sieved to separate coarse aggregates with diameter larger than 10 mm. The results obtained from small scale of casting of fiber reinforced alkali activated slag foam concrete in the lab conditions met the requirement criteria for using this material as the acoustic panels. Thus, all efforts made to have similar results in upscaling pilot compared to the results obtained in the lab.

Figure 1: Granulation of Petrit-T to produce recycled lightweight aggregates

The GGBFS used, which was supplied by Finnsementti (a Finnish company). The d50 value and density of the GGBFS were 10.8 μm and 2.93 g/cm^3, respectively. GGBFS was activated by a combination of sodium hydroxide and sodium silicate as the alkali activator with a ratio of 2. The NaOH solution was prepared by combining NaOH pellets in water with a molar concentration of 12 mol/L and subsequently cooling the solution to room temperature. A sodium silicate solution was used as a liquid sodium silicate with a modulus of 2.5 (molar ratio Ms = SiO_2/Na_2O). The alkali activator-to-binder ratio was equal to 0.56. Moreover, to minimize the negative effects of drying shrinkage, PVA fibers (2.4% of slag mass) were used to reinforce the foam concrete. These fibers (RSC 12 mm) were supplied by Kuraray Company. The physical and mechanical properties of PVA fibers are included: length to diameter ratio of 200, elastic modulus of 41 GPa, tensile strength of 1600 MPa, elongation at break of 6%, and density of 1.3 g/cm^3. A pre-made foam was used to introduce the air voids. The foaming agent was stirred in water to obtain a stiff, white foam with a volume in-crease of 20–25 times and with no foam collapse. The foaming agent, in the form of protein hydrolysate, was supplied by EABASSOC Company. The agent was mixed with water using a weight ratio of 1:33. The created foam was stiff, resembling a shaving foam, with a density of approximately 0.045 g/cm3. The diameter of 75-85% of the bubbles is in the range of 0.3-1.5 mm. An EABASSOC junior foam generator was used to produce pre-made foam for large scale of casting. This machine could have a throughput of foam, typically 150-200 liter/minute, depending on the used air compressor. To have the optimum foam quality, the foam generator was connected to an air pressure machine with the maximum pressure capacity of 10 bar.

2.2 Casting and aging

The mixer used for industrial upscaling had a maximum capacity of 150 liters. In the batching process, the dry ingredients including recycled aggregates and slag were initially stirred for 1 minute. Then, alkali solution was added and materials were mixed for an extra 2 minutes. Afterwards, PVA fibers gradually were introduced to the mix composition during the stirring materials to avoid balling effects. Finally, pre-made foam was added to mix composition and all materials were combined for a further 1 min (Figure 2a). The fresh fiber reinforced alkali activated slag foam concrete was moved by a truck to a place where the oiled molds were prepared there. It is worth stating that it is required to have good workability and enough setting time (more than 40 min) of fresh concrete to transfer the porous material with truck from the mixer to the molds. As indicated in Figure 2b, fresh foam concrete was cast into the oiled molds and the panel surfaces were flatted and then covered with plastic bags (Figure 2c). The molds were kept in an environmental temperature of 22^{0}C and relative humidity 40%. After 48 hours, the specimens were demolded and then again wrapped with plastic for 28 days (Figure 2d).



a) Fresh foam concrete b) Casting
c) Wrapping with plastic d) Demolded panels

Figure 2: Mixing, casting, and curing

3. TEST PROCEDURES

3.1 Density and mechanical strengths

Mechanical characterizations were addressed in terms of the compressive and flexural strengths. Since the fiber orientation and dispersion affect the flexural performance of fiber reinforced composites, six prismatic beams with dimension (350×100×35 mm) were extracted in both longitudinal and transverse directions. The prismatic beams were assessed under a three point bending test by using a displacement control and speed rate of 0.6 mm/min. Moreover, three cubic specimens with the edge of 35 mm were cored from the panels and the compressive loading was imposed by speed rate of 1.8 mm/min.

In addition, hardened state properties of the porous materials obtained from the small and large scales were compared by using the dry densities.

3.2 Shrinkage

Three prismatic beams with dimension 40×40×160 mm were used to cast and two steel pins were installed at both end sides of beams to measure the change length. After 24 hours, beams were demolded and length change of beams was recorded. Moreover, the surfaces of panels made with foam concrete were monitored visually and the crack formation was evaluated.

3.3 Measurement of the sound absorption in a reverberation room

The panels were installed on the floor and their surfaces were upward onto the reverberation chamber floor, as shown in Figure 3. This assessment was carried out in VTT Expert Services Ltd premises. The volume and inner surface area of the reverberation room was 201 m^3 (height of 4.7 m and floor area of 5.95 m × 7.20 m) and 209 m^2, respectively. Moreover, the temperature and relative humidity of the reverberation room were 21^0C and 52%, respectively when measurements were carried out. The sound absorption coefficient was measured according to the standard SFS EN ISO 354 - 2003 [15].

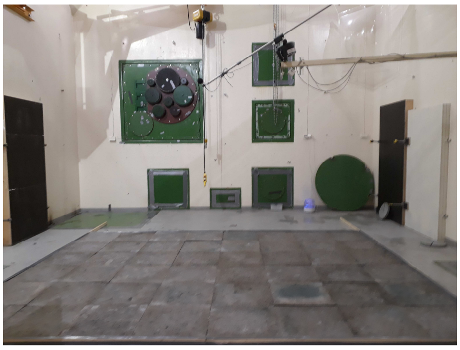


Figure 3: Used reverberation room to measure sound absorption

4. RESULTS AND DISCUSSION

4.1 Density and mechanical characterizations

The density of three panels were also measured and its average was obtained around 0.8 g/cm^3. Similar density was also measured for foam concrete in the lab scale.

As aforesaid, the mechanical characterizations were expressed in terms of the compressive and flexural performances. Regarding the results in Figure 4, a flexural strength equal to 1.35 MPa (σ (standard deviation): 0.22 MPa) and mid-span deflection corresponding to 3.45 mm were recorded for the beams extracted from the transversal direction, while a flexural strength equal to 1.20 MPa (σ: 0.15 MPa) and mid-span deflection corresponding to 3.30 mm were registered for the beams extracted from the longitudinal direction. The results indicate that fiber orientation had no great impact on the flexural performance. It means that fibers almost distributed uniformly. Moreover, a compressive strength equal to 2.75 MPa (σ: 0.2 MPa) was obtained for the cubic specimens. In the lab scale and using cylindrical molds (having a height of 70 mm and a diameter of 50 mm), a compressive strength equal to 4 MPa was measured [13]. This difference could be justified by differences in size and shape of specimens, differences in mixer properties, and fiber distributions.

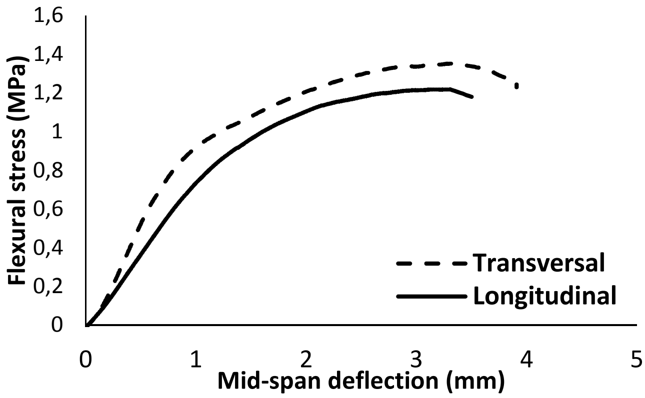
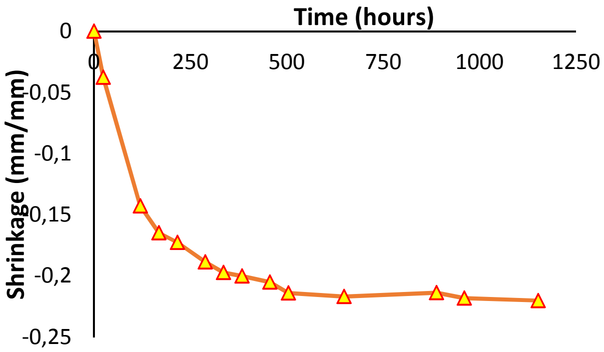


Figure 4: The flexural performance of extracted beams

4.2 Drying shrinkage

Regarding the results in Figure 5, the drying shrinkage is stabilized and almost reached its ultimate value after 500 hours. However, the test was run to be assure that stabilization has been achieved certainly. The results show that drying shrinkage in alkali activated foam binders is limited to 0.25 mm/mm, which it indicates large drying shrinkage compared to alkali activated slag binders [16]. This large drying shrinkage increased significantly the possibility of crack formation, however, it was found that PVA fibers could control successfully the negative effects of large shrinkage. Moreover, no localized or micro-crack (visually) was detected on the panel's surfaces.



a)

b)

Figure 5: a) Shrinkage in fiber reinforced alkali activated slag foams; b) An acoustic panel to observe the crack tendency

4.3 The sound absorption measurements in a reverberation room

The sound absorption coefficient for each third octave band of the panels at different frequencies are indicated in Figure 6. Regarding the results, the sound coefficient reached to 0.55 at the frequency of 5000 Hz. At frequency of 4000 Hz, the green walls developed in [17] and used as the passive acoustic insulation system for buildings showed similar the sound properties as acoustic panels developed in this paper. Moreover, it was detected that the developed panels with fiber reinforced alkali activated slag foam concrete had a similar sound absorption capacity to green walls with 71% greenery coverage density at frequency of 5000 Hz and green walls with fully greenery coverage density indicated lower sound absorption coefficient. According to EN 1793-1 [18], an absorption ($DL_{\alpha} \approx 7$ dB) was measured and it could be categorized as class A2.

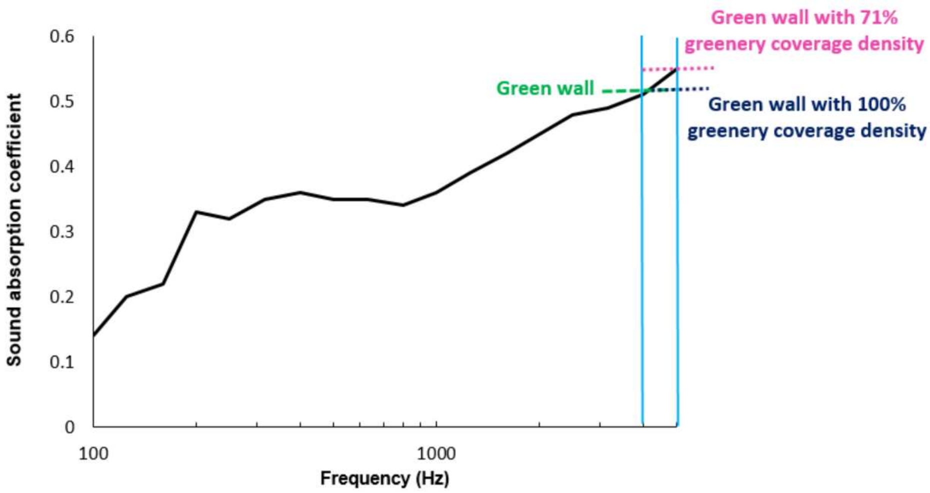


Figure 6: The measured sound absorption in a reverberation room

5. CONCLUSIONS

This paper reports briefly the experimental results regarding the scalability of developing fiber reinforced alkali activated slag foam binders in industrial pilot. Regarding the results, there was a feasibility to produce fiber reinforced alkali activated slag based foam concretes using normal concrete production lines. Similar density was recorded for both large scale and lab scale casting conditions, while mechanical characterizations had some differences due to differences in the size and shape of tested specimens and the properties of mixers. Moreover, PVA fibers could significantly control the negative impacts of shrinkage in the porous material and no micro-crack was detected on the panel's surface. The obtained sound absorption coefficients in reverberation room showed that the panels reached the sound absorption coefficient value of 0.55 at the frequency of 5000Hz. Reached sound absorption is comparable level to green walls used as the passive insulation system for buildings.

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BIO-BASED INSULATION MATERIALS: AN OPPORTUNITY FOR THE RENOVATION OF EUROPEAN BUILDING STOCK

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Abstract

In the next decades, a large share of the European residential building stock (EU-28) is expected to be renovated to keep the increase in the global average temperature to well below 2°C, as requested by the Paris Agreement by 2050. Bio-based materials might be a valuable opportunity to fasten the transition to a zero-carbon society due to the ability to temporary store carbon. The purpose of this paper is to investigate the effect of massively storing carbon in bio-based construction products when used for the renovation of existing facades. Five alternative construction solutions have been compared, three with a large amount of fast-growing biogenic materials, one with wood-based elements, and one with synthetic insulation. A dynamic life cycle assessment has been performed to include timing in the calculation in order to verify the contribution of construction materials in reducing/increasing the carbon emissions over time.

The results show that fast-growing biogenic materials have an increased potential to act as a carbon sink compared to timber. In particular, if they are used as insulation materials, the capacity to uptake carbon from the atmosphere is effective in the short-term, which represents an important mitigation strategy towards the Paris climate Agreement long-term goals.

Keywords: biogenic materials; building retrofitting; carbon storage, zero-carbon society; life cycle assessment.

1. INTRODUCTION

Renovation of dwellings to reduce primary energy consumption is a key strategy for EU-28 Member States to reduce carbon emissions [1]. However, several studies show that even the most optimistic scenarios for reducing energy in buildings are not sufficient to achieve the 2°C objective of the Paris Climate Agreement [2,3]. By 2050, almost 80 million houses in Europe are expected to be renovated and a large amount of additional insulation has to be installed on facades to improve the thermal resistance [4]. The use of wood components and bio-based elements in general can be a valid alternative for improving the energy performance of buildings, the aesthetic of the facades and, particularly, for massively storing carbon. When wood is harvested from the forest and used as timber or insulation material, the biogenic carbon embedded in the mass is fixed for a long time in the product. During this period, the same amount of carbon is absorbed into the forest due to tree regrowth. However, the process of carbon sequestration in the forest typically requires long cycles, about 45-120 years [5], due to the slow growth rate of the trees.

2. METHODOLOGY

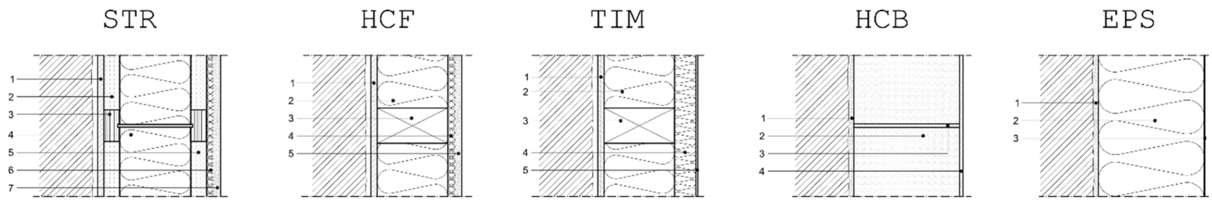
2.1 Reference construction alternatives for the energy requalification of external walls

Five alternative building solutions for the energy requalification of the external walls were considered as a reference in this study. The proposed strategy is recladding by additional insulation, which can be applied externally on existing walls in order to improve their thermal resistance. The functional unit (UF) assumed for the assessment of the impact of materials in the life-cycle the life cycle (LCIA) is identical for all alternatives examined and is defined as follows:

- 1 m^2 of wall;
- identical thermal resistance (R_T);
- non-load-bearing structure;
- identical fire safety;
- expected service life of 60 years.

As shown in Table 1, the first three wall elements are typically prefabricated, while the last two are assembled directly on site.

Table 1. Materials inventory for the five alternatives for exterior walls renovation. Waste treatment categories for each material are taken from BAFU [6] while reference value of life span from SIA 2032/2010 [7].



Cod.	Material	Thickness	Density	Thermal conductivity	Mass	Life span	Waste treatment category
		mm	$kg \cdot m^{-3}$	$W \cdot m^{-1} \cdot K^{-1}$	$kg \cdot m^{-2}$	yr	
01. STR - I-joist frame with pressed straw							
1	OSB	18	650	0.13	12	60	Wood

2	Light clay straw	45	600	0.16	27	60	Recycling potential
3	Timber I-joist	var*	500	0.12	var*	60	Wood
4	Straw chips	var*	100	0.051	var*	60	Fast decomposing
5	Light clay straw	45	600	0.16	27	60	Recycling potential
6	Reed mat	20	145	0.06	3	30	Fast decomposing
7	Lime plaster	20	1800	0.67	36	30	No potential
02. HCF - Preassembled frame with injected hempcrete							
1	OSB	18	650	0.13	12	60	Wood
2	Injected hempcrete	var*	200	0.054	var*	60	Recycling potential
3	Timber frame	var*	500	0.12	var*	60	Wood
4	Reed mat	20	145	0.06	3	30	Fast decomposing
5	Lime plaster	20	1800	0.67	36	30	No potential
03.TIM - Timber frame							
1	OSB	18	650	0.13	12	60	Wood
2	Glass wool	var*	18	0.038	var*	40	No potential
3	Timber frame	var*	500	0.12	var*	60	Wood
4	Wood fibreboard	60	130	0.05	8	40	Wood
5	Cover plaster	6	1800	0.8	11	40	No potential
04. HCB - Hempcrete blocks							
1	Cement mortar	10	1800	0.80	18	60	No potential
2	Hempcrete blocks	var*	330	0.07	var*	60	Recycling potential
3	Light lime mortar	-	500	0.1607143	6	60	Recycling potential
4	Lime plaster	20	1800	0.67	36	40	No potential
05. EPS – Expensed polystyrene for external thermal insulation composite system (ETICS)							
1	Cement mortar	1	1800	0.80	2	60	No potential
2	EPS	var*	16	0.04	var*	40	Combustible
3	Base plaster	2	1800	0.80	4	40	No potential

* "var" means that this layer thickness or quantity changes depending on the insulation requirement.

2.2 Material flow analysis model

The residential building stock in Europe is largely heterogeneous and it is necessary to adopt a characterization method to evaluate the thermal and geometric characteristics in order to simulate large-scale renovation scenarios. Using a simplified "buttom-up" approach, mainly supported by statistical data, the annual flow of materials (input data) was estimated. A Geocluster-based logic was introduced to aggregate data and fill the gaps in case of lack of information at national level [8]. The methodology suggested by Birchall [9], which is based on aggregation by similar climatic conditions, was adopted in this work. Seven different climate-based macro-areas were identified and buildings constructed between 1945 and 1999 were considered, most of which are characterised by envelopes with thermal resistance that do not meet the limits required by current standards. This results in a total share of potentially renovated dwellings representing about 87% of the current residential building stock. In this work, statistical data based on the archetypes collected in the framework of the European project TABULA [10] were used. For each Geocluster, the different building typology identified in the TABULA catalogue were aggregated and divided into two categories: a) single-family houses (SF) and b) multi-family houses (MF). For each building typology an average value of the ratio between the surface area of the exterior walls (S_w) and the floor area of the building (S_f) was evaluated and the results were aggregated on the basis of the two selected categories, as shown in Table 2. In case explicit national data are missing, data from other countries within the same Geocluster were considered as representative.

Table 2. Characterization of the residential building stock per each Geocluster.

		Geocluster						
	Unit	1	2	3	4	5	6	7
Floor area	10^6 m^2	2'406	3'203	3'059	2'979	5'398	1'775	781
Multifamily (MF)	%	58%	69%	33%	15%	35%	40%	40%
	S_w/S_f	1.00	0.98	0.85	0.60	0.64	0.49	0.62
Single family (SF)	%	42%	31%	67%	85%	65%	60%	60%
	S_w/S_f	1.34	1.34	1.38	0.76	1.03	1.00	1.13
Renovation Rate (RR)	%	0.1%	0.8%	2.0%	0.3%	1.4%	0.5%	0.9%
Walls yearly renovated	10^6 m^2/a	2.05	25.57	68.55	6.81	65.21	6.47	5.53
Current U-value of ext. walls	W/m^{2}K	1.90	1.42	1.36	1.60	1.14	1.07	0.44
Min U-value	W/m^{2}K	0.54	0.33	0.35	0.29	0.27	0.29	0.18
U-value target after retrofit	W/m^{2}K	0.38	0.22	0.24	0.18	0.17	0.16	0.15

1: Southern dry (Spain and Portugal);
2: Mediterranean (Italy, Greece, Cyprus and Malta);
3: Southern continental (France, Bulgaria, Croatia and Slovenia);
4: Oceanic (United Kingdom, Ireland and Belgium);
5: Continental (Germany, Netherlands, Austria, Hungary, Czech Republic and Luxembourg);
6: Northern continental (Poland, Denmark, Romania, Slovakia, Lithuania);
7: Nordic (Sweden, Finland, Latvia and Estonia).

2.3 Dynamic LCA model

The lack of time dependence and the treatment of biogenic CO_2 are critical aspects in LCA and carbon footprint calculations. Levasseur proposed a dynamic LCA model (DLCA) [11] that allows to take into account carbon absorption timing and GHG emissions. The model was adopted for this work and implemented taking into account only the global worming effect of CO_2 and methane (CH_4), as it was observed that they contribute for the most part to the impact of radiative forcing due to the high quantities released in the process. A time horizon (TH) of 200 years was considered in order to include short term (2050) and long term (2100) effects in the calculation.

2.4 System boundaries

The LCA model was developed according to EN 15804:2012 [12] and comprises the following phases:

- production and construction (modules A1-5) - extraction, transport, on-site delivery and construction;
- use (modules B1 and B4) - emissions by replacing elements and absorption by using biomass and lime products;
- end-of-life (EoL) (modules C1-4) - demolition of walls, transport to waste treatment, separation of materials and waste treatment, final disposal.

Additional benefits, such as virgin materials avoided by recycling or emissions avoided by energy recovery, are accounted for separately as additional benefits beyond the system boundaries (Module D).

2.5 Calculation model

The ΔR_T required to meet the expected limits of U-value in the future was assessed for each European Member State, as well as the annual area of walls that are expected to be renovated. The two values were aggregated according to the clustering process and then related to the material inventory for the five alternative construction solutions in order to define the incoming material flow. To calculate the inventory of impacts, measured in terms of kg of GHG emitted per year, a life cycle inventory (LCI) from modules A1 to C4 was carried out. In parallel, in module B1 three different carbon absorption resources were modelled and included in the analysis: two biosphere absorption resources (forests and crops) and one from technosphere, which takes into account the carbonation of lime products. On the basis of the required materials, the annual carbon uptake was measured, typically as a function of time, and the resulting carbon removals were related to the GHGs emitted by the renovated stock to define a time matrix that was used as input for the dynamic impact assessment. Finally, the results, expressed as instantaneous and cumulative radiative forcing (GWI), were converted into kg of $CO_{2\text{-eq}}$ according to the IPCC method to measure the global warming potential (GWP).

2.6 End of life

In general, the calculation of GWI using a DLCA is particularly sensitive to end-of-life scenarios. A full understanding of the sensitivity of the results to the decommissioning scenarios (DS) is necessary to succeed in a careful interpretation. Similarly to Pittau et al. [13], five different waste treatments have been assumed for the end of life:

- WT1- inert landfill: considered for materials that do not release hazardous substances after deconstruction of the building;
- WT2 - sanitary landfill: considered as temporary storage for reactive materials such as biogenic products;
- WT3 - composting plant: considered an alternative to WT2, where the whole quantity of methane produced during biological decay is captured and reused as biomethane instead of natural gas;

- WT4 - urban incineration: it consists in the incineration of waste with recu-per of thermal energy;
- WT5 - Recycling: consists of the generation of new products from waste materials.

From the combinations of different waste treatments shown in Figure 1, the following three alternative disposal scenarios have been defined:

- DS1: landfill;
- DS2: energy recovery;
- DS3: material recycling.

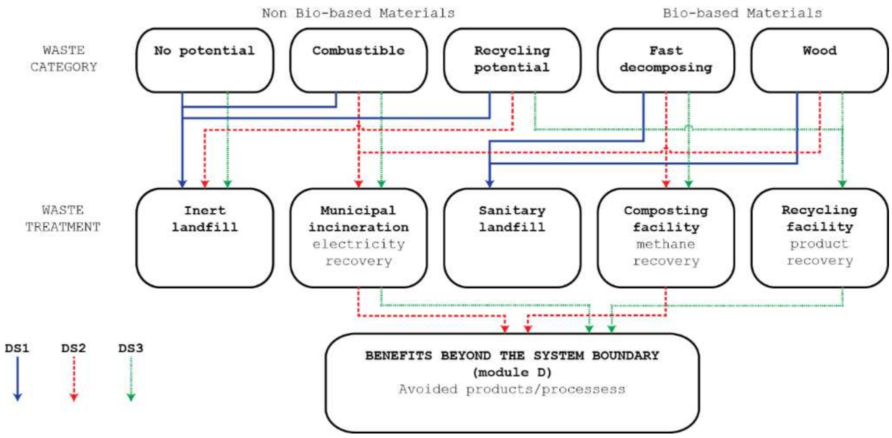


Figure 1. Waste treatments and disposal alternatives for each end of life disposal scenario

3. RESULTS

Instantaneous radiative forcing - which contributes to altering the Earth's radiative balance, affecting temperature growth and decrease - has been calculated for each wall alternative and for the three DSs using the DLCA calculation model. The annual instantaneous radiative forcing values were then added up to show the cumulative effect of the emissions released during the life cycle of the five construction alternatives. Finally, they were converted from GWI_{cum} to GWP according to the IPCC method, in order to dynamically quantify the carbon emissions/removals in terms of $kgCO_{2\text{-eq}}$. The dynamic GWP values for each alternative and for each DS are shown in Figure 2. After an initial positive emission, the GWP of STR decreases rapidly, with a climate neutrality achieved after only 4 years. Then, the effect of removing carbon from the atmosphere continues with the same positive trend. It is expected that by 2050, almost 100 Mt $CO_{2\text{-eq}}$ will be removed from the air due to the massive use of straw. This is roughly equivalent to 27% reduction of carbon emissions from industrial processes and product use in 2015 in the EU-28, or 23% of emissions from agriculture in the same year, or 3% of total carbon emissions in all sectors.

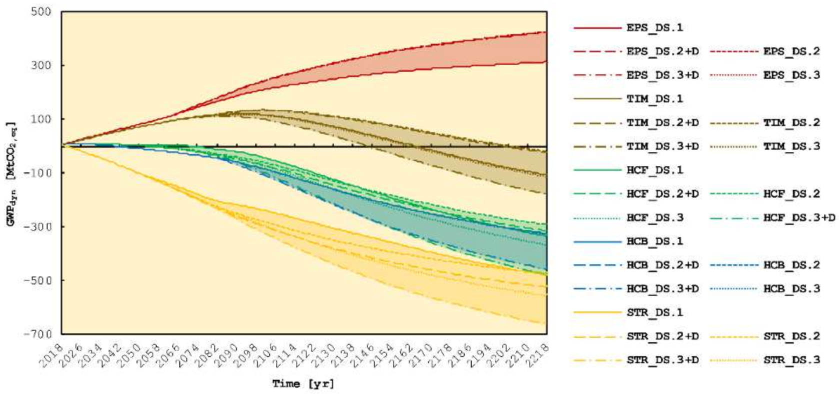


Figure 2. Dynamic GWP for all scenarios. DS1, 2, 3 stand for disposal scenario with landfill, energy recovery and material recycling respectively. DS +D stands for disposal scenario with module D and DS for disposal scenario without module D.

In 2050, the materials needed to renovate the residential building stock with HCF continue to lead to positive emissions, which are expected to be emitted cumulatively from 2018. In 2100, GWP shows a negative value, corresponding to 17% reduction in carbon emissions from industrial processes and the use of products, 15% reduction in agricultural emissions in the same year or 2% reduction in total carbon emissions of all sectors in the EU-28 in 2015. A similar trend can be observed for HCB, although a negative GWP will be reached in 2050 due to the increased amount of carbon sequestered by concrete blocks. For the last two alternatives, no carbon removal is expected by 2100, even if a large amount of biological material is used in TIM.

4. CONCLUSIONS

Fast growing biological materials, such as hemp and straw, have considerable potential for carbon capture and storage when used as thermal insulation for facade renovations in EU-28. Results show that they have greater carbon absorption potential than wood, which is an important strategy for achieving the objectives of the Paris climate agreement. In particular, if straw is used as an insulating material, 3% of the CO2-eq emissions of the whole sector in 2015 can be offset by 2050. Hemp-based alternatives are starting to be slightly negative in terms of carbon emissions after 2050, with a potential for carbon removal in 2100 of around 2% of the emissions of all sectors in the EU-28 in 2015. Therefore, it is clear that EPS, which is now the most widely used and widespread insulation system in Europe for energy retrofitting, reduces additional loads on existing facades, but is not able to actively contribute to decrease the CO2 concentration in the air.

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REUSE AND RECYCLING OF CDW MATERIALS AND STRUCTURES IN ENERGY EFFICIENT PREFABRICATED ELEMENTS FOR BUILDING REFURBISHMENT AND CONSTRUCTION - RE^4

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Abstract

The EU Waste Framework Directive 2008/98/EC states that all member states should take all necessary measures in order to achieve at least 70% re-use, recycling or other recovery of non-hazardous Construction and Demolition Waste (CDW) by 2020. In response, the Horizon 2020 RE^4 project consortium (REuse and REcycling of CDW materials and structures in energy efficient pREfabricated elements for building REfurbishment and construction) consisting of 12 research and industrial partners across Europe, plus a research partner from Taiwan, was set up. For its success, the approach of the project was manifold, developing sorting technologies to first improve upon the quality of recycled aggregate. Simultaneously, CDW streams were assessed for quality and novel applications developed for timber, aggregate, and plastic waste in a variety of products including structural (e.g. beams, columns, slabs) and non-structural (e.g. building blocks, insulation panels, tiles) elements. With all products considered, innovative building concepts have been designed in a bid to improve future recycling of the products by promoting prefabricated construction methods and modular design to ease future recycling and increase value of the construction industry. The developed technologies and products will be put to the test in different test sites in building a 2 storey house containing at least 65% of CDW in the next 6 to 12 months.

Keywords: CDW-derived materials, Prefabricated structures, Recycling, Reuse

1. INTRODUCTION

Construction and Demolition Waste (CDW) constitutes the largest waste stream in the European Union (EU), accounting for more than 350 million tonnes/year excluding excavated soil and dredging spoil [1]. It consists of a heterogeneous mix of materials such as concrete, mortar, bricks, tiles, mineral aggregate, bitumen, ferrous, plastic, wood and organic lightweight particles [2]. The vast amount of CDW is deposited to landfills mainly because most existing buildings were not designed for disassembly and reuse [3]. In addition, most recovered CDW is confined to low value applications (e.g. recycled aggregate used for pipe bedding or subbase and base course in road pavement construction) despite the fact that some of its constituents have a high resource value. However, EU Waste Framework Directive 2008/98/EC [4] requires that all member states should take all necessary measures in order to achieve at least 70% re-use, recycling or other recovery of non-hazardous CDW by 2020. Consequently, the development of reliable strategies and innovative technologies is required in order to:

- Increase the percentage of CDW-derived materials in new residential construction
- Increase the technical and economic value of CDW-derived materials
- Minimise future CDW coming from the next generation of buildings
- Increase building energy efficiency

Prefabricated elements (structural and non-structural) which incorporate large amounts of CDW-derived materials can have a significant effect towards achieving the above objectives.

This paper aims to provide an outline of the efforts of the RE^4 project consortium (CETMA, ACCIONA, RISE, CDE Global Ltd, CREAGH Concrete Products Ltd, FENIX TNT, Queen's University Belfast, ZRS Architekten GmbH, STAM S.R.L., STRESS S.C.AR.L., National Taiwan University of Science & Technology, VORTEX HYDRA S.R.L. and ACR+) [5] in developing prefabricated building components which incorporate at least 65% by weight of CDW-derived materials while describing the challenges that have been faced along the way.

2. MINIMIZING FUTURE CDW FOR FUTURE GENERATIONS

2.1 Case for prefabrication

Prefabricated concrete differs from in-situ concrete as the former is first cast in the premises of precast concrete factories and then delivered to site. This has many added benefits, including better quality control, less waste, improved health and safety, increased speed of manufacturing and reduced cost [6]. Furthermore, precast concrete allows for the building of standardized products, but also bespoke elements to answer the needs of a client.

2.2 Modular design

In parallel to the development of CDW containing building elements, the prefabricated elements are designed to be reused as whole functional units. To achieve this, the designed buildings within the scope of RE^4 are to be modular, where each 'module' (beam, column, slab, façade panel, etc.) can be removed and reused later in its design life. This presents a series of challenges including:

- Ensuring all elements comply with existing building regulations
- Using available mechanical connections to facilitate assembly and disassembly
- Limiting element size for standard lorry transport, saving time and cost

- Life span, ease of repair, maintenance or replacement
- Traceability, specifying information into Building Information Modelling (BIM)

All elements were deemed suitable for modular design with the exception of foundations, as their performance relies on the soil conditions.

3. INCREASING THE % OF REUSED AND RECYCLED CDW

The reuse of CDW recycled aggregates in concrete, for example, is already permitted and standardised. Currently, EN 206:2013+A1:2016 [7] and EN 12620:2013 [8] limit the maximum amount of coarse recycled aggregates up to 50%, depending on exposure conditions. However, this limits the recycling potential of CDW. Raw CDW first needs to be treated in order to become suitable for use as recycled aggregate. This involves removing ‘unwanted’ fractions such as floating particles, clay and soil, ferrous metals, non-floating wood, plastic, rubber and gypsum. However, to increase the recycling rate, the amount of fractions such as ceramics (bricks & tiles) and bitumen present in treated recycled aggregate must also be reduced (Figure 1).

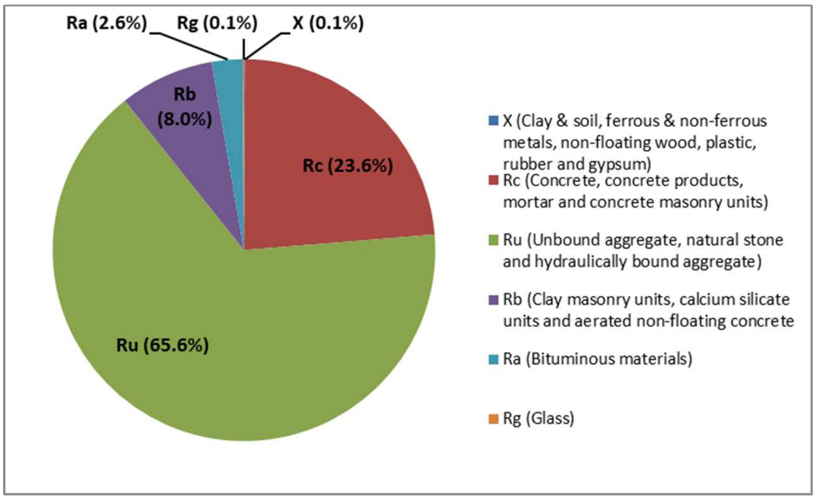


Figure 1: Typical composition of 8-16 mm processed recycled aggregate coming from a recycling plant near Marseille, France.

3.1 Improving the quality of CDW aggregates

To further improve recycling rates, attempts have been made to improve the quality of the CDW aggregates (Figure 2 a-c).

For coarse aggregates (≥ 8 mm), an automated mechanism has been devised to remove the remaining ‘unwanted’ particles. These particles are determined on a real time basis using advanced electronic and optical systems based on the infrared reflectance signature of different types of CDW. The sensing unit determines the reflectance of the particles in different wavelengths (1000 to 1700 nm – near infrared) to differentiate the unwanted particle which is then removed using a robotic arm. Currently, the production rate stands at 100 kg/h.

For fine aggregates removed during treatment, the particles are first scrubbed clean using an attrition cell, after which the fine aggregates are separated based on density. This is done by having the sand flow through a corkscrew shaped gravity column. In passing, the lighter particles migrate towards the outer edge and the heavier particles remain inside of the column. The particles are collected at the bottom and separated by density to the user's requirements.

a) Robotic arm and conveyor belt b) Attrition cell c) Gravity column

Figure 2 (a-c): Examples of new technologies used for improving CDW-derived mineral fractions.

3.2 What to do with the ceramic fraction?

As not to dispose of the ceramics fraction successfully removed from the CDW waste stream, two potential uses were investigated. In a first instance, the ceramic waste was ground to a fine powder to be used as a precursor. It was then activated in the presence of sodium oxide (Na_2O) and sodium silicate (Na_2SiO_3) varying their proportion to maximise strength [9], [10], [11]. The water/binder (w/b) content was fixed at 0.37. Such mixes, depending on the chemistry of the activating solution, reached strengths of up to 30 MPa, when tested on 50 mm mortar cubes.

Ceramics were also reused as floor or wall tiles. This was achieved by blending the ground ceramic fraction in resin and allowed to harden in moulds. The grading of the ceramic powder and the resin to ceramic fraction ratio were investigated to achieve the desired strength and workability properties. Optimal performance was achieved when blending 3 parts of resin to 7 parts of ground ceramic by weight.

4. RECYCLING AND USE OF CDW IN STRUCTURAL ELEMENTS

4.1 Concrete

Concrete is perhaps the focal material due to the breadth of structural and non-structural elements that can be designed within the scope of the project. The project's approach was to design various concrete types and strength grades from which various elements could be designed (beams, columns, slabs, blocks, façades, stairs, etc.). The type of concretes designed are detailed in Table 1 and include 3 types of concrete mixes – vibrated, self-compacted and semi-dry – suitable for the needs of the relevant partners within the project. After carrying out trial mixes, the designed concretes reached the target strength and workability targets set by the manufacturers within the project. Newly quarried aggregate replacement varied from 40% to 100% depending on the source of the recycled aggregate and the type of concrete produced.

Table 1: Different types of concrete incorporating high levels of CDW-derived aggregate

Product	**Strength class**	**Consistency class**	**Virgin aggregate replacement level (%)**
Vibrated concrete	C25/30	S2/S3	100
	C32/40	S3	83
Self-compacting concrete	C40/50	640-770 mm based on slump flow test	40 to 80
Semi-dry mix concrete	7.3 MPa	N/A	70

4.2 Reclaimed timber

A strategy for reusing timber elements from dismantled buildings for structural and non-structural elements has been developed. Different methods for the procurement and characterisation of CDW timber have been applied to generate raw materials that can be strength graded according to existing norms.

As a precondition waste wood must be free from wood preservatives, fungal or insect infestation and serious damage. The absence of wood preservatives has to be verified by an accredited laboratory and appropriate measures have to be taken e.g. cut off of affected areas.

Visual, on-site inspection is sufficient to determine fungal or insect infestation and potential damages. In addition, it enables to define the wood species, its nature and moisture content. The raw density can be estimated through literature data, in case no information about the location of growth of the CDW timber is available. Salvaged sections must then be cleaned from impurities such as metal fittings, paint etc. in order to be assessed with regards to dimensions and location of cracks, branches and slope of grain. Sections are then cut or planed to final cross section, ideally to standardized sizes in order to be classified according to DIN 4074-1:2012 [12] into the relevant sorting classes. This in turn, leads to the respective strength class according to EN 338:2016 [13]. Such procedure enables the effective reuse and recycling of waste wood with minimal loss in performance for reuse as structural elements [14].

Depending on the final strength grade, the nature of the element and its conservation, several strategies can be adopted to reuse the wood, including:

- Complete reuse of the element with minimal processing (Figure 3a)
- Reprocessing into standardized cross sections
- Reprocessing into lamellas for glulam fabrication (Figure 3b)

a) Reclaimed timber sections b) Glulam from reclaimed timber

Figure 3 (a-b): Converting reclaimed timber section into Glulam.

In the case of glulam timber beams, timber strength grade GL24 was targeted, meaning the timber beams reached a target flexural strength of 24 MPa. If the elements were deemed not to be suitable for use as structural elements, the timber could potentially still be reused to prepare non-structural elements, for example in cladding or wood fibre insulation. Because of the varied forms timber can take and the potential for a cascading use, the recycling rate of all wood and timber products remains very high.

5. RECYCLING AND USE OF CDW IN NON-STRUCTURAL ELEMENTS

5.1 Lightweight particles for the preparation of insulating elements

Typical lightweight CDW particles are small in size (≤ 4 mm) and are made of plastics and wood. RE[4] attempted to utilise these fractions in the development of insulation panels having low thermal conductivity. In addition, recycled plastics were used as lightweight aggregates in the development of low density concrete.

Table 2 below highlights the target properties for the development of lightweight Portland Cement (PC) concrete and optimised mixes meeting those targets. Depending on the source, rigid plastics or mixed wood & plastics could replace up to 70% and 50% of the natural sand fraction, respectively.

Table 2: Requirement set for lightweight concretes for panel layers

Requirements	**Target applications**	**Performance of RE[4] lightweight PC concretes**	
	Panel layers	Rigid plastics	Mixed wood & plastics
Consistency class	S4	S4/S5	S5
Density (kg/m^3) @ 28 days	800-1400	1260	1250
Compressive strength (MPa) @ 28 days	4.5-24.0	7.5	4.5
Thermal conductivity (W/mK) @ 28 days	0.16-1.00	0.31	0.29

For panels containing rigid plastics, the plastic aggregates were embedded in polyurethane foam, already a popular cavity insulation material. The ratio of aggregate to binder was varied to create panels of different density values, from 5% plastic up to 50% plastic by volume. The panels performed best at 5% plastic content, keeping the density and thermal coefficient low.

Wood scraps (≤ 4 mm in size) and plastics were also used to prepare insulating panels, moulded into shape. The production process of the panels differed depending on the material used. For wood scrap panels, the wood was first soaked in water for 72 hours. Thereafter, the wood was compacted into moulds and kept under pressure, at 15 bar and 120 °C or 160 °C from 3.5 to 30 hours. Finally, the panels were dried. To improve their fire resistance, prior to making the panels, the wood was mineralised by forcing a MgO solution into the wood under pressure (8 bar). Wood panels were found to be least dense when the curing period was the longest. Optimised wood scrap panels achieved a density of 215 kg/m^3 and thermal conductivity of 0.07 W/mK.

Some of the above types of developed insulating materials (e.g. wood-based panels) have been selected to be used in the construction of demonstration buildings in Northern Ireland and Spain or in the refurbishment of an existing building in Italy as described in Section 6.

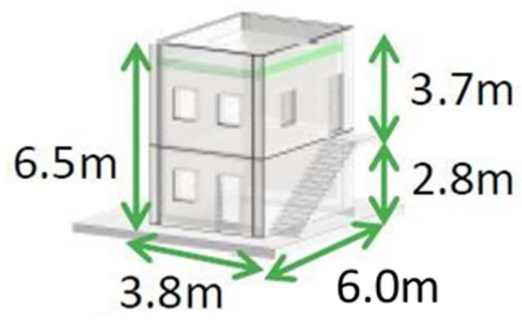
5.2 CDW aggregate in roof tiles

The substitution of virgin aggregates by CDW mineral aggregates was also investigated in extruded tiles. The extrusion process made use of only the fine mineral fraction (0 to 2 mm) and a CEM II/B-LL 32.5 R cement. By replacing 50% of the virgin aggregates with mineral CDW, a mix prepared with 1-part cement and 3-parts sand, with a w/b ratio of 0.3 complied to all relevant standards.

6. PILOT TRIALS

The ultimate test will come during the pilot trials. Several sites have been identified between the partners, including one in Northern Ireland, one in Spain and another in Italy. Table 3 details some of the elements designed to be tested in a 2-storey building with the dimensions shown. With regards to concrete products, the estimated recycling rate varies from 40% to 90%, depending on the elements.

Table 3: Types of elements (structural and non-structural) and components of a 2-storey building to be tested

<table>
<tr><th>Type of Element/Component</th><td rowspan="12"></td></tr>
<tr><td>Beams</td></tr>
<tr><td>Columns</td></tr>
<tr><td>Slabs</td></tr>
<tr><td>Stairs</td></tr>
<tr><td>Sandwich panels (structural & non-structural)</td></tr>
<tr><td>Building blocks</td></tr>
<tr><td>Timber façades</td></tr>
<tr><td>Timber based inner partitions</td></tr>
<tr><td>Wood fibre insulation panels</td></tr>
<tr><td>Rigid plastic insulation panels</td></tr>
<tr><td>Extruded tiles</td></tr>
</table>

At this point in the project, the design of the elements (structural and non-structural) and components is in its final stages. Once industrial production of the elements/components commences, they will be used for making the demonstration buildings in Northern Ireland and Spain and performing the refurbishment of an existing building in Italy. The demonstration buildings as well as the refurbished building will be monitored in terms of energy efficiency and compared with conventional ones. Based on the above, no specific data on the performance of buildings made using the above elements and components is available at this stage of the project.

7. CONCLUSIONS

This project has tackled the concept of reusing and recycling CDW back into the built environment. Building practices were adapted to promote a modular design to facilitate the reuse of whole elements, rather than having them demolished. However, this will likely only be successful if the assembly and disassembly is facilitated, in a first attempt through design (i.e. through the use of reversible connections) and, secondly, aided with Decision Support Systems (e.g. BIM-based DSS). The disassembly adds another challenge, notably how to reuse the elements, and where (e.g. transport). Cost and environmental impact together with associated savings can also be evaluated using Life Cycle Cost (LCC) and Life Cycle Analysis (LCA) assessments. Following on, the quality of the recycled CDW was maximised, and a novel sorting method was developed to improve the quality of recycled aggregates. It is estimated that the improved aggregate will result in CDW containing concrete products with greater performance, thus increasing the amount of embedded recycled aggregates. The reuse and recycling of timber was also heavily investigated given its high potential for reuse, from structural and non-structural elements, with an effective recycling rate of approximately 80% leading up to 95% of CDW timber included in the final element. Ultimately, CDW containing elements were designed as to maximise the recycling rate in order to meet the target set in the Waste Framework Directive, e.g. a 70% recycling and reuse rate of CDW. This will ultimately be tested when building full scale elements, containing as much CDW as possible, to be used on demo buildings in Northern Ireland (CREAGH), Spain (ACCIONA) and Italy (STRESS). If successful, then existing standards and methods of practice can be challenged to facilitate the uptake of CDW in construction.

ACKNOWLEDGEMENTS

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SUSTAINABLE CHOICES FOR THE RESIDENTIAL CONSTRUCTION. THE IMPACT OF SUSTAINABLE CEMENT

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Abstract

Most of new modern building in residential areas are made with concrete, either prefabricated or in situ. This increases the use of cement in concrete, thus increasing the energy inputs and carbon emissions of the entire building. This paper presents the results of the evaluation of the impact of using a ternary cement composed of Portland clinker (50%), calcined clay (30%), gypsum (5%) and limestone (15%), for ordinary concrete, and it compares with the same material produced with a pure Portland cement with clinker content above 90%. The analysis is made considering Life Cycle Assessment, Value Added method and eco-efficiency perspective for specific conditions of Cuba. The subject of the study is only the concrete part of the buildings, which are mainly residential buildings. The study confirms that the use of the new low clinker cement brings about a drastic reduction of carbon emissions during construction, along with higher value added. The contrast between the financial and environmental aspects is defined by the "eco-efficiency index", which has been developed and validated as part of the program and applied to case study buildings in Cuba. Masonry walls made with concrete blocks and precast concrete walls were compared, and conclusions drawn from this study.

Keywords: low carbon cement, concrete, life cycle assessment, eco-efficiency, sustainability.

1. INTRODUCTION

Housing affordability has long been a pressing and challenging issue in Cuba. Alternative solutions need to be rooted under the sustainability umbrella, for at least three reasons: (i) building materials have to be cheaper than usually, (ii) global warming potential should be ameliorated and (iii) social indicators claim for appropriate balance with the economy and the environment [1]. The potential for increasing the building stock is at certain extent linked to the efficiency of concrete manufacture, which is in turn related to cement use. Overall, the production of cement and concrete is estimated to account for around 5-8% of man-made CO_2

emissions [2],[3]. Recently, the use of blended cements has become largely accepted, particularly in developing countries where the need for reducing material consumption determines the future housing affordability. A new blended cement has been proposed by an international team: Limestone Calcined Clay Cement (LC^3). LC^3 is a combination of clinker (50%), calcined clay (30%), gypsum (5%) and limestone (15%). After calcination of kaolinite clay, metakaolin is the resulting calcined clay to be grinded with the remaining ingredients. Previous publications on LC^3 production and its use in building materials can be found in [4],[5],[6],[7].

The partial replacement of clinker by metakaolin directly reduces the clinker to cement ratio, therefore, reducing energy consumption, carbon emissions and production costs. The cost-advantage of LC^3 along with its environmental dominance over Ordinary Portland Cement, makes the new product a sustainable way to face the increasing demand for house in Cuba. This paper aims at assessing the impact of using LC^3 in the construction sector in the island. Two case studies have been analysed, (1) two-storey concrete block building, and (2) two-storey Grand Panel building. The former is a traditional masonry-intensive construction system where manpower is a fundamental production factor. The latest is a prefabricated concrete-based system which is less labour-intensive than block-based technique, however, more equipment is needed in order to assemble the precast elements. Authors have found that Grand Panel building is by far more eco-efficient than concrete block building, by comparing the eco-efficiency index of both case-studies. Energy saving seems to be related to the manufacturing efficiency of the capital-intensive system compared to the technology using low level of industrialization.

2. THE CHOICE OF FUNCTIONAL UNIT

Both case studies were analysed on the basis of same functional unit: square meter of built area. Concrete block building was constructed over a built area of 168 m2 as well as Grand Panel building covered 160 m2. The system boundaries shown in Figure 1 was taken into consideration for calculation purposes (LCA, value added and eco-efficiency index).

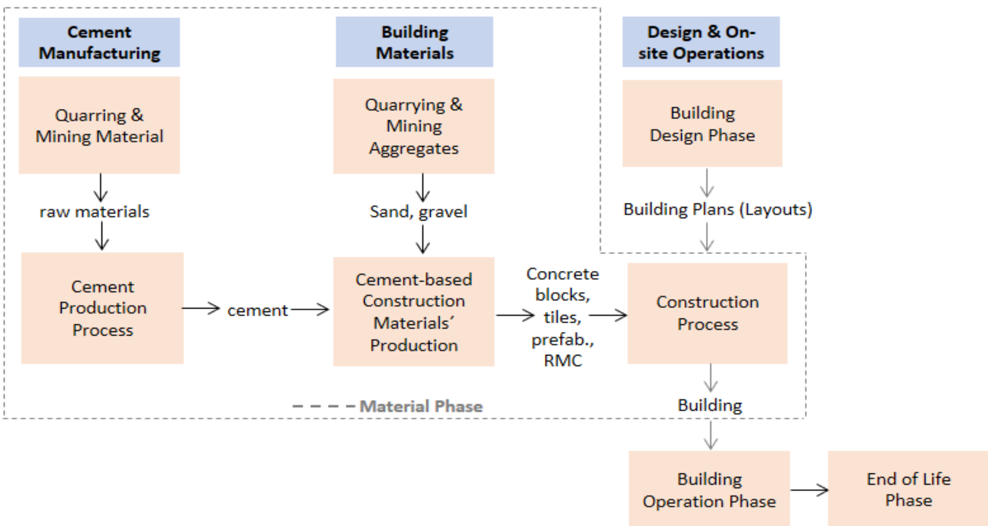

Figure 1. System boundaries for LCA, value added calculations and eco-efficiency index [1]

3. METHOD AND DATA

The Life Cycle Assessment (LCA) method was employed to determine the environmental impact of LC^3 in the material phase of both buildings. LCA is extensively documented in the international standard 14040/2006 [8] and 14044/2006 [9]. The value added was the economic measure ultimately used for eco-efficiency index calculations. Simplified LCA is presented mainly covering the contribution to global warming potential by means of carbon dioxide emissions over 100 years. Energy inputs are also reported. LCA calculations are based on impact factors previously published by the authors of this paper, which belong to former researches in the same context (Table 1). The impact category reported below strictly entails carbon dioxide emissions.

Table 1. Impact factor of main building materials, using regional-based background data and Cuban case-studies-based foreground data [10]

Material	Unit	OPC/PPC	LC^3
Ready-mix concrete	kg CO_2/m^3	400.78	253.98
Prefabricated concrete	kg CO_2/m^3	320.63	203.18
Concrete blocks	kg CO_2/u	1.53	0.97
Aggregates	kg CO_2/m^3	29.6	29.6

Table 2 shows the data inventory for LCA and economic assessment. The amount of cement reported in row 4 is the cement used for mortar in masonry applications. The cement consumption per unit of product is as follows: 450 kg per cubic meter of ready mix concrete, 360 kg per cubic meter of precast concrete and 1.62 kg per block.

Table 2. Data inventory. Foreground data

Material	Unit	Block building	Grand panel building
Ready mix concrete	m^3	30.6	10.9
Prefabricated concrete	m^3	9.5	52
Concrete blocks	u	7560	770
Cement	t	29.3	8.6
Aggregates	m^3	42.9	30.5
Calcium hydrate	t	4.9	2.3
Steel	t	2.9	0.9

CO_2 emissions of OPC, PPC and LC^3 as well as its production costs are reported in Table 3. Those figures have been employed for further calculations at both the building material level and the construction site level.

Table 3. Figures for cement industry in Cuba. Dry clinker scenario [11], [12]

Cement type	Energy consumption (MJ/t)	Emissions (kgCO_2-eq./t)	Production cost ($/t)
OPC	5292.38	890.63	187.70
PPC	4626.33	764.92	174.55
LC^3	4367.53	564.39	160.86

Three scenarios were anticipated in order to derive the eco-efficiency index.

1. Business As Usual (BAU), where conventional OPC and PPC are used.
2. A short-run scenario, where conventional PPC is replaced by LC^3.
3. A long-run scenario, where conventional OPC and PPC are replaced by LC^3.

The actual cases, i.e. both two-storey buildings reported in this study, were built under the assumptions of scenario 2. Both case studies belong to researches carried out in Santa Clara province, Cuba.

4. RESULTS

Figure 2 shows the breaking down of embodied energy according to cement type scenario for each case-study construction method. Concrete block building appears to be less energy efficient than prefabricated building. This trend is maintained regardless the cement type scenario. The overall energy consumption at building level is governed by the amount of cement and concrete used in the construction site. The increase of LC^3 use brings about embodied energy reduction, thus, contributing to higher levels of eco-efficiency.

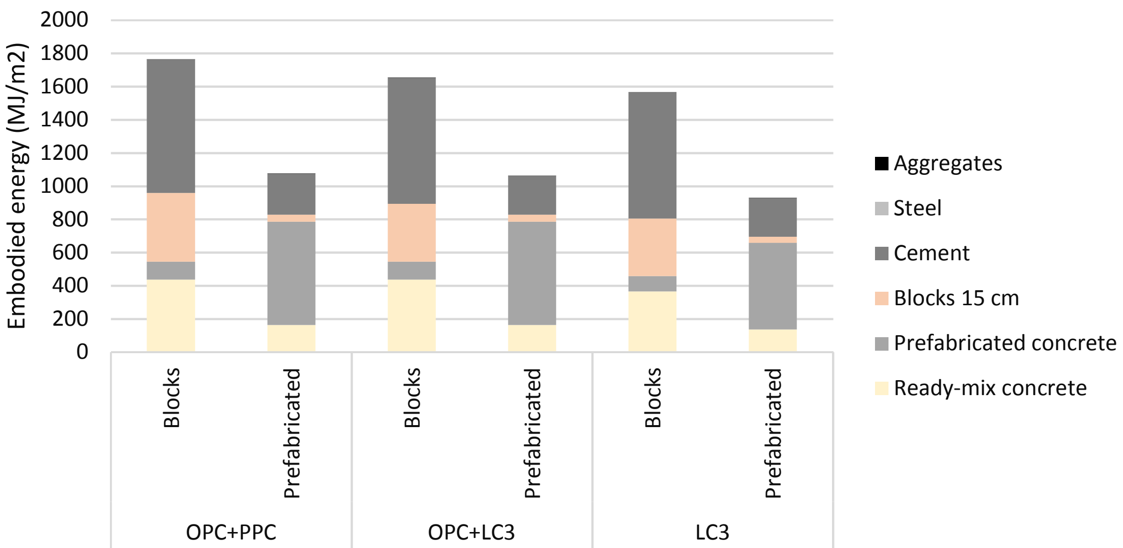

Figure 2. Embodied energy per building technology and cement type scenario

The eco-efficiency index proposed by the World Business Council for Sustainable Development (WBCSD) [13] was derived for each case study according to LCA/Value Added results. Eco-efficiency index = Value added/CO2 emissions. Main results are shown in Figure 3. It appears to be that prefabricated concrete-based building is 29% more eco-efficient than concrete block building. CO2 emissions and value added are inversely correlated and ultimately governed by energy consumption, mainly during cement manufacturing. Carbon mitigation and cost savings potentials are correlated with the level of LC3 introduction. A comprehensive perspective on eco-efficiency indicators can be found in [14].

Authors are aware of the great influence of insulation patterns according to different building system designs on its environmental performance. However, in Cuban conditions heating is not appropriate, thus, the energy consumption of building stock is not influenced by heating. Cooling systems associated with the tropical weather is still low in the country. Moreover, those already existing do not require special adaptations to satisfy insulation requirements. According to this fact, the need for insulation in not included in Cuban standards.

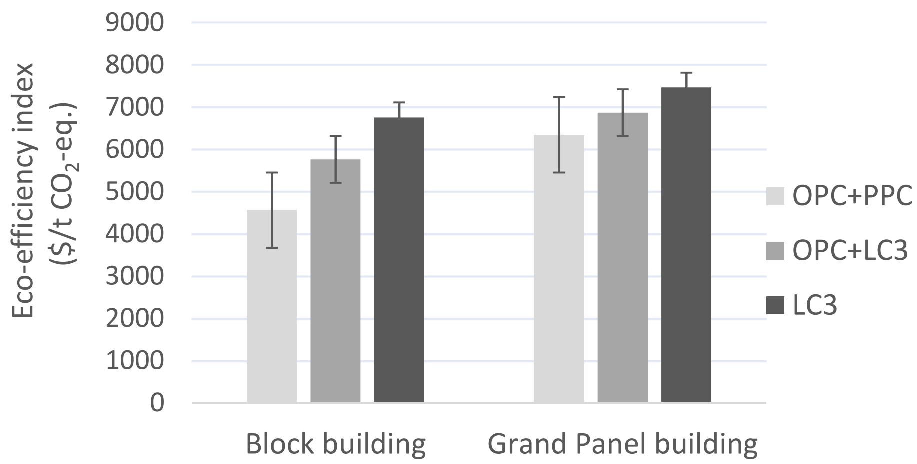

Figure 3. Eco-efficiency index by construction technology and cement type scenarios

5. CONCLUSIONS

The use of LC^3 for building materials production and ultimately employed in construction increases the eco-efficiency of the building stock in Cuba.

The most eco-efficient construction technique is prefabricated building. However, the dominance of concrete block construction in Cuba suggests that LC^3 gradual introduction is the preferable choice for achieving higher levels of value added along with lower levels of CO_2 emissions.

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ASSESSMENT OF THE RECYCLING POTENTIAL AND ENVIRONMENTAL IMPACT OF BUILDING MATERIALS USING MATERIAL PASSPORTS – A CASE STUDY

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Abstract

Concerns about increasing global consumption of non-renewable resources as well as shortages of primary raw materials and reduction of space available for final disposal of wastes are raising important issues for the society. Additionally, the minimisation of resources consumption belongs to the main concerns of EU, resulting in development of strategies for maximizing recycling rates in order to minimize environmental impacts and energy consumption caused by extraction of primary materials. For enabling high recycling rates and low environmental impacts of buildings, detailed knowledge about the embedded materials as well as their characteristics in the building stocks is crucial.

In this paper, we will present the concept of the Material Passport (MP), used for evaluation of the recycling potential and environmental impact of materials embedded in buildings. A Material Passport assesses all materials including their quantitative and qualitative properties, thus significantly supporting recycling and optimisation of environmental impacts. Further, the Material Passport serves as design optimisation tool and it enables the generation and comparison of variants thus supporting the decision making process.

The assessment method and data structure for generating a Material Passport will be demonstrated on a case study. The focus is twofold - on assessing the recycling potential and environmental impact of single materials, as well as of the entire building. The assessment methodology is based on coupling of digital tools and digital building catalogues and eco-databases. The assessment of the concrete construction as case study demonstrates that the recycling potential of the building is about 50%; whereas the LCA analysis shows that the main environmental impact is caused by concrete as material. Thereby the Proof of Concept for the BIM supported MP as decision support tool was generated.

Keywords: Material assessment, data structuring, recycling potential, Material Passport

1. INTRODUCTION

The construction industry is the world's largest consumer of resources and responsible for 25-40% of global carbon emissions [1]. Only 20-30% of Construction and Demolition Waste is recovered, whereby many of the discarded materials have the potential to be recovered for different purposes. These purposes can be fertilizer additive, gravel and road-building materials. Increasing the reuse and recycling of materials, would improve the resource efficiency significantly [2]. The strategies for increasing recycling rates and reusability of building elements and materials in construction is a part of a larger concept: Circular Economy (CE). CE aims to maintain the value of products, materials and resources in the economy as long as possible in order to reach a low carbon and resource efficient economy [3].

In order to enable the increasing of recycling rates, detailed knowledge on the material composition of buildings is needed. Recycling is amongst others depending on features of construction such as accessibility and separability of building elements and materials. As constructive features are defined in early design stages, design-centric tools for architects and planners to enable the evaluation and optimisation of the recycling potentials and environmental impacts in the early design stage are currently lacking. In order to fill this gap, we propose a digital design-centric tool: Material Passport (MP). The MP provides knowledge on the material composition of buildings. It also gives qualitative and quantitative information about the embedded materials, their recycling potentials and environmental impacts.

This paper is structured as follows: in Section 2 the methodology, including relevant parameters, used digital data repositories, the data structure will be introduced, followed by the description of the case study in Section 3. In Section 4 the obtained results of the assessment conducted using MP will be presented, which will finally be analysed and discussed in Section 5.

2. METHODOLOGY AND DATA

2.1 Methodology for the MP compilation

The proposed methodology for compiling the MP consists of a digital workflow (Fig. 1), where eco-data repositories and digital building component catalogues are coupled with the BIM based tools. The workflow starts with modelling in BIM software, for which we provide a building component catalogue based on the Austrian Institute for Building and Ecology (IBO) [4]. The catalogue, integrated in a BIM template, consists of exterior and interior walls, ceilings, roofs as well as floorings. After the building has been modelled with components out of the catalogue, the relevant data, as shown in Fig. 1, is linked to BuildingOne [5] Tool. The eco- and recycling-data, which is obtained from IBO/eco2soft [6] is linked to the materials in BuildingOne, which serves as data management and assessment tool, where the final MP-results are generated.

BuildingOne enables the creation of various parameters, which can be assigned to materials of building components. The main reason, why BuildingOne is used, is that a parametrization of individual materials/layers is not possible in a consistent way in BIM, or would lead to big data sizes. Apart from that, it is capable of conducting the MP-related assessment, which is not the case in BIM. Moreover, it serves as the main tool where all the information is gathered, the assessments carried out and the MP created. Through linking recycling-data (e.g. grade 2: 50% recycling, 50% waste) to the parameters obtained from BIM (material, thickness etc.) in BuildingOne, the total share of recycling and waste is assessed. For obtaining the environmental impacts of the building, eco-data (GWP=Global Warming Potential, AP=Acidification Potential, PEI=Primary Energy Intensity) is linked to the parameters gathered from BIM.

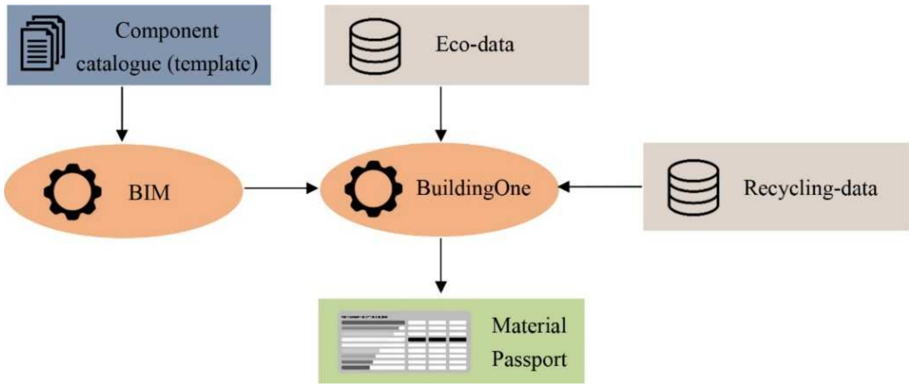

Figure 1: MP-workflow

2.2 Relevant parameters and databases

The relevant parameters for the MP were defined through knowledge gathered in former projects, as well as through interviews with experts from the AEC (Architecture, Engineering and Construction) industry.

The MP displays the total mass, share of waste and recycling, the recycling potential as well as the GWP, AP and PEI of the building. Therefore, various input parameters are necessary, which are provided by different databases. Due to data inconsistencies, such as varying nomenclature and units between various databases, one single database for all the indicators was taken into consideration.

As IBO offers on the one hand digital building catalogues and on the other recycling relevant data, as well as data for assessing the ecological impacts, it was chosen as the main database for the MP workflow. IBO considers three main environmental impacts (GWP, AP, PEI), which are included in the MP-assessment. Relevant parameters among others are the name of the materials, their density, environmental impacts, lifespan, area, thickness, recycling potential and connectivity. All relevant parameters and their sources are displayed in Fig. 2.

2.3 Data structuring

The MP-relevant input parameters are gathered from various sources, as shown in Fig.2. We differentiate between material-specific data, layer-specific data and evaluated data.

IBO is the main source for material-specific data, whereby the eco2soft tool, provided by IBO, was used. Eco2soft offers the possibility to generate as well as import building components from IBO. Parameters obtained from eco2soft are the material, density, GWP, AP, PEI, lifespan and disposal potential. In this paper, only non-renewable PEI was considered; the renewable PEI is not included in the assessment.

As certain building component characteristics, such as the connectivity of two enclosed materials, influence e.g. the lifespan and the recycling potential, the components require an additional evaluation process; which we conduct in MS Excel. Here the data for building components from eco2soft is gathered, analysed regarding above mentioned characteristics and evaluated. If e.g. the outer layer of a wall has a longer lifespan than the inner layer backing it, then the initial lifespan of the outer layer becomes shorter, because the two layers have to be exchanged together. The recycling potential is originally the disposal potential, but depending on the connectivity. Since two materials, which are glued to each other are difficult to separate, the initial disposal potential needs to be downgraded, as proposed by IBO. The recycling potential is a grade from 1-5, proposed by IBO. Grade 1 stands for a recycling potential of 75% and 25% of waste, whereby grade 5 means that 0% of the material is recyclable and 125% are waste (additional 25% in waste for auxiliary materials required for disposal).

In order to assess the area, thickness and volume of the materials, the Building Information Model (BIM) is used. Thereby the model accuracy plays a crucial role; in terms of geometry as well as for proper classification - a wall has to be modelled as a wall element; and materials have to be chosen from the developed template (see 2.1).

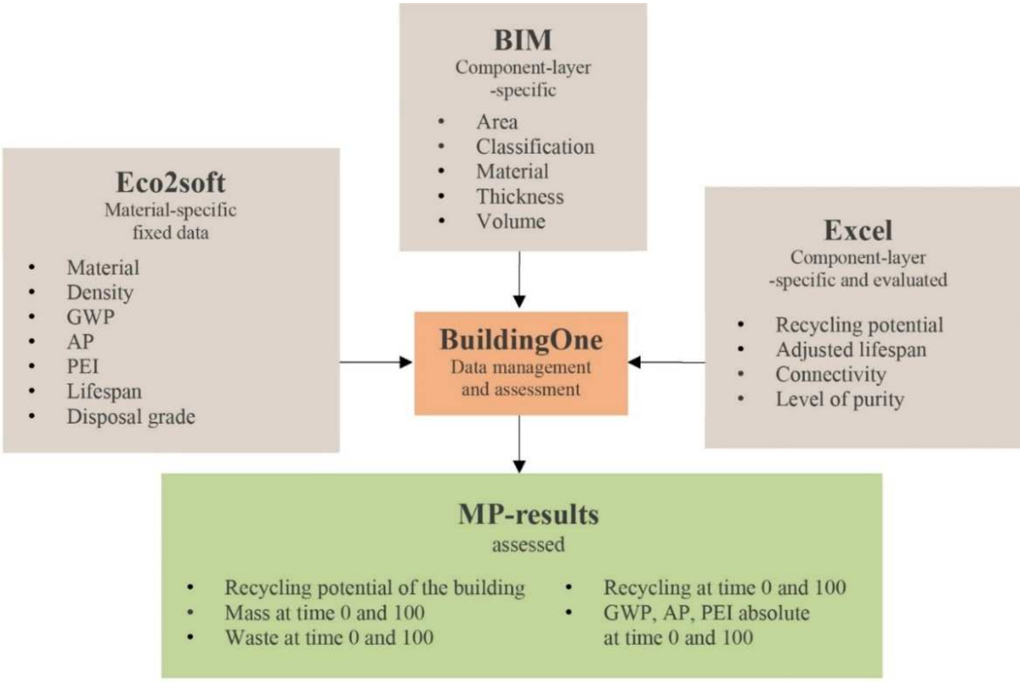

Figure 2: Data structuring

3. CASE STUDY

The MP concept was tested on a case study, which is an office building as concrete construction (Fig. 3). The conceptualised building was modelled with components from the component catalogue template in BIM. It consists of three storeys: one entrance floor with an open space area as well as sanitary facilities and the first and second floor, where office rooms as well as shared spaces are located. The load-bearing elements of the whole building are out of concrete with a thickness varying from 20 to 29 centimeters for exterior walls, ceilings, the basement and roof. The insulation of the outside walls are out of EPS (expanded polystyrene), whereas the roof has a mineral wool insulation and the basement a foam-glass insulation.

Figure 3.: Use case

Following building components were considered in the assessment:

- Exterior walls: I-O (Inside to outside); gypsum filler, concrete, EPS (expanded polystyrene) and silicate plaster
- Interior walls: cement finish plaster, perforated brick, cement finish plaster
- Roof: O-I (Outside to inside); PE (Polyethylene) sealing sheeting, PP (Polypropylene) fleece, timber, air layer with timber beams, PE roof underlay, timber, mineral wool between timber beams, concrete, gypsum filler
- Floorings: 2 variants; 1: solid parquet, internal chipboard, mineral wool; 2: solid parquet, cement, PE sealing sheeting, mineral wool, chippings, PE sealing sheeting
- Ceilings: flooring variant 1+ concrete with gypsum filler underneath
- Basement: flooring variant 2+ concrete, PE sealing sheeting, foam-glass, polymer bitumen sealing sheeting, lean concrete, building paper, sand and gravel, PP fleece
- Glass façade: post and beam out of aluminium, triple glazed glass panels
- Columns: concrete

Not included in the assessment are the windows, doors and staircases. The materials are assigned to groups:

- concrete: concrete, cement, lean concrete
- sand, gravel: sand, gravel, chippings
- timber: timber, timber beams, solid parquet, internal chipboard, building paper
- brick: perforated brick
- mortar and plaster: silicate plaster, cement finish plaster, gypsum filler
- glass: glazed glass panels, foam glass
- various plastics: PE sealing sheeting, PP fleece, PE roof underlay, PP fleece, polymer bitumen sealing sheeting
- mineral wool: mineral wool
- XPS/EPS: EPS
- aluminium: aluminium

4. RESULTS

The application of the MP-method enables the assessment of the total material composition, the recycling potential and the environmental impacts, as it was demonstrated on a case study. The displayed results are for time 0, and therefore for the time when the building is erected. Time 100 stands for the end of the life-cycle, where all materials, which have to be exchanged depending on their lifespan, in course of the years, are considered, however are not shown in this paper.

Fig. 4 displays the material composition of the office building, whereby it is noticeable, that concrete has a share of 82.5% of the total mass of the building. Since concrete is the load-bearing element, having a high density which leads to a high mass, this is an expected result. The second biggest share is represented by sand and gravel (8.4%). Other materials do not have a significant impact to the total mass distribution.

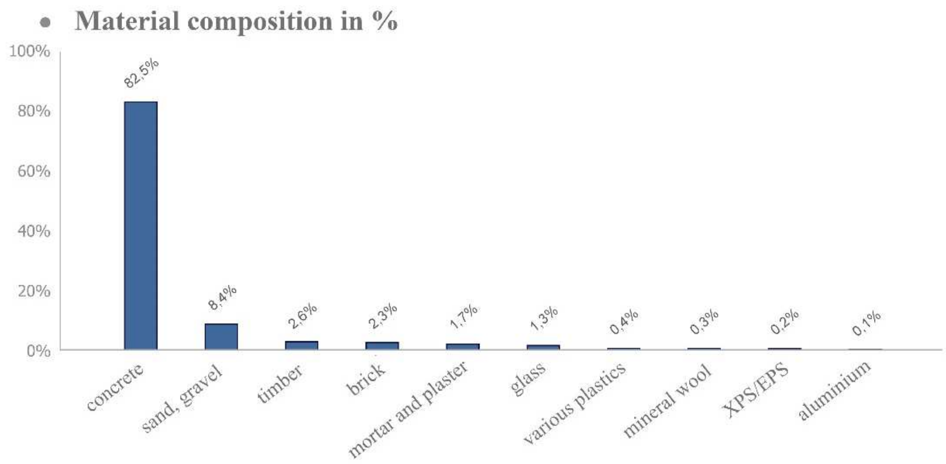

Figure 4: Material composition of the building

Results on building level, where all materials embedded in the building are added up, show, that a total mass of the building adds up to 1338 tonnes whereas 48% of the building materials can be recycled and 52% are waste (Fig. 5). The LCA results are displayed in Fig.6, whereby the level of PEI is significant, as it accounts for about 3000 GJ. The levels of GWP and AP do not have a considerable impact in comparison with PEI.

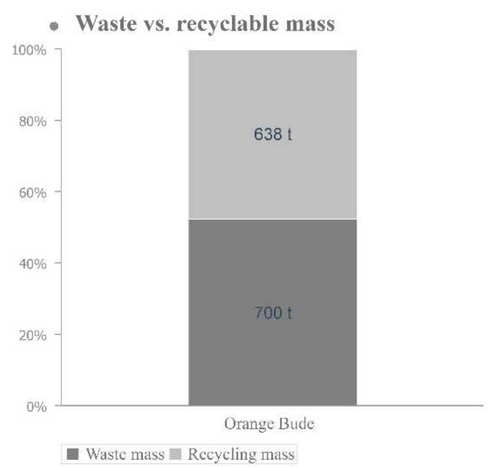

Figure 5: Waste vs. recyclable mass

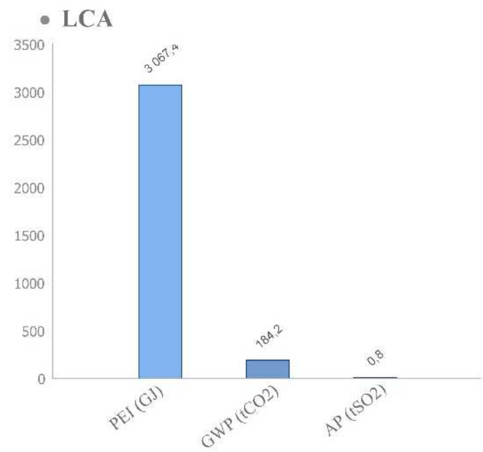

Figure 6: LCA- results

Fig. 7 displays the results on material-level are displayed, whereby the share of recycling is opposed to the share of waste potential for each material. It is evident that concrete has a share of about 50% to 50% for recycling and waste, as well as that concrete leads to the largest amount of waste, causing about 600 tonnes of waste, whereby the waste generated by the entire building adds up to 700 tonnes. Sand and gravel have a high recycling potential, since it is easy to reuse these materials. The other materials except concrete do not have a significant influence to the total recycling potential of the building.

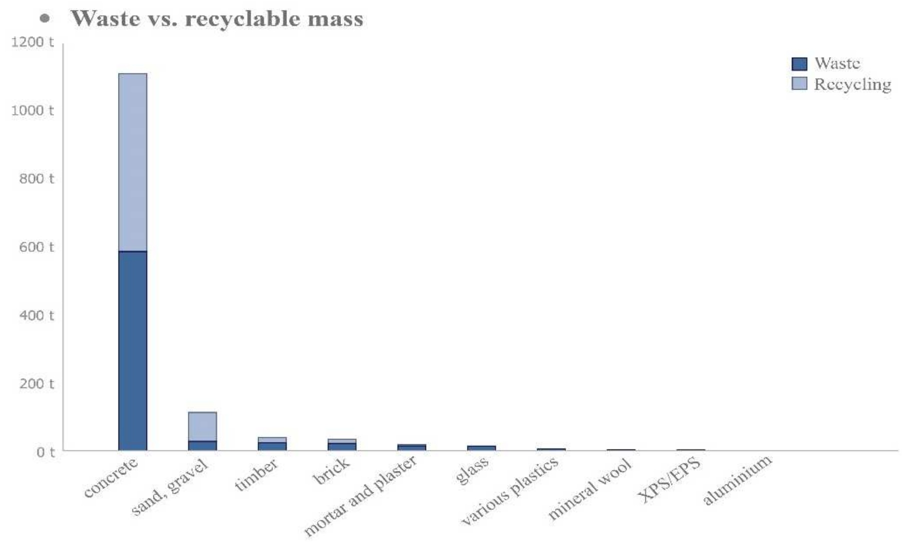

Figure 7: Waste vs. recyclable mass of materials

The vast mass of concrete is also reflected in the LCA-results (Fig. 8), since concrete accounts for about 1200 GJ of PEI. Hence, more than half of the total PEI is caused by concrete. Timber and brick lead to 300 GJ of PEI each, followed by XPS/EPS which accounts for 250 GJ of PEI. If the PEI per kilogram of concrete and e.g. timber is compared, it can be seen that concrete has a lower PEI per kilogram than timber (concrete: 1.14 MJ per kilogram; timber-spruce: 2.5 MJ per kilogram). Therefore, the vast amount of PEI in case of concrete is mostly due to its large mass. The large PEI per kilogram of timber is mainly caused by the energy required for drying wood. The CO_2 emissions of concrete accounts for 175 tonnes of CO_2, which is almost the same amount that is caused by the total building. It is also mentionable, that timber has a negative value for GWP, since timber is absorbing CO_2 from the air and sets free O_2. As the AP has no mentionable impact, it has not been further analysed.

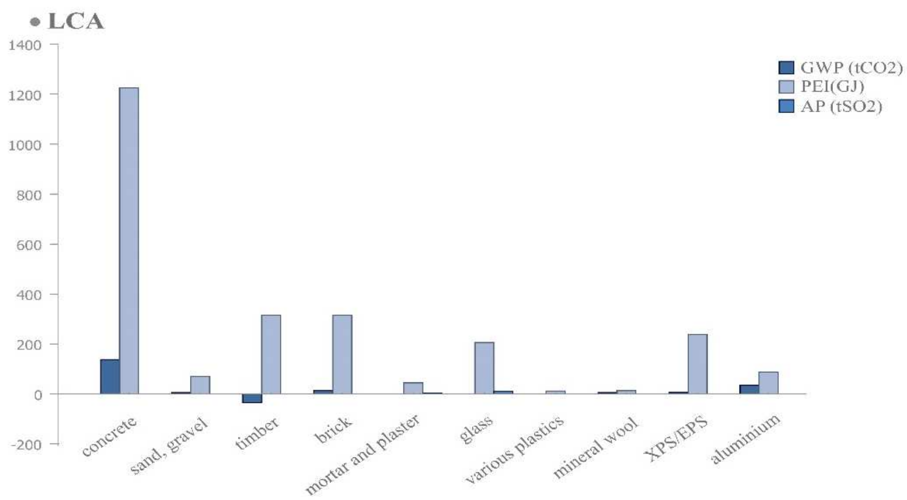

Figure 8: LCA -results of materials

5. DISCUSSION AND CONCLUSIONS

In this paper the methodology for generating a Material Passport using BIM based digital tools and data repositories was presented, focussing on the assessment of the recycling potential as well as the environmental impacts using LCA methodology. Therefore, a case study, which was conceptualised and modelled in BIM, was conducted for the Proof of Concept of the developed workflow, thus applying MP-method and evaluating the results.

The first results of the MP assessment show the percentual distribution of the materials embedded in the building. Thereby it was identified that concrete accounts for about 80% by mass of the entire building. The building displays a total recycling potential of 48%, meaning that 638 tonnes are recyclable and 700 tonnes count as waste. The large mass of concrete is reflected in the waste amount as well as in the LCA-results, since concrete causes 600 tonnes of waste and accounts for 1200 GJ of PEI. The results demonstrate that the main burdens are caused by the huge mass of concrete. Thus the application of the MP methodology implies on possible optimisation, by reducing the thickness of the concrete layer, through an accurate structural analysis. A further possibility is changing the load-bearing elements and using timber instead of concrete, which would lead to less waste, since timber has a lower mass than concrete. What should not be neglected is that timber has a very high PEI. Therefore, it is important to strike the right balance between the various impact factors.

Through the case study we demostrated the advantatges of the Material Passport for the assessment of all materials including their masses and other significant characteristics such as CO_2 emissions and its role as an important decision-tool regarding choice of materials and construction-types already in the early design stages, where the optimization potential is the highest. However, new construction rate across Europe is around 2%. New methods for capturing the existing stocks are necessary in order to make use of the secondary materials. Laser- and Ground Penetrating Radarscan Technologies, which capture the geometry and materials of existing buildings, and further embedment of data into GIS, could support the development of a secondary raw materials cadaster, which plays a crucial step towards enhancement of Circular Economy strategies.

ACKNOWLEDGEMENTS

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VARIABILITY IN CONCRETE WATER FOOTPRINT FROM CRADLE TO GATE

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Abstract

Concrete is the most used material in the world after water. However, impacts related to water use in its production have been neglected or at best inconsistently reported. In general, results on environmental indicators are presented as single value which hides variability and uncertainties from different sources. In this research, a cradle to gate water footprint study was performed to estimate variability in concrete production water footprint including variability due to water use, location and choice of impact assessment method for different concrete formulations. The assessment is done based on a sample of 25 MPa concrete formulations. The main sources of variability for concrete water inventory and water footprint are identified. Direct water use is usually a fixed value 196-249 l/m^3 which is less than 5% of the variability. Variability from indirect water use and energy production water use are in the range of 5 -10 % for specific regions. The choice of impact assessment method accounts for the biggest share, 80-99% of the variability. For the water use inventory, the energy production and aggregates production seem to be the most important contributors. The water footprint varies mainly depending on the location and method used for the assessment. Therefore, special attention should be paid to the choice of method.

Keywords: Cementitious materials. Variability. Water consumption. Life cycle assessment. Sustainable construction.

1. INTRODUCTION

Water is the most demanded substance in the world only followed by concrete [1]. The annual concrete production is approximately 30 billion tonnes, with total mixing water of ~1 trillion liters [2]. These two substances have a tight relationship since water is vital for cement hydration and corresponding concrete strength and workability [3]. On top of this water, there is water use in concrete production activities such as washing the trucks and washing the yard [4]. Climate change and population growth will worsen water availability [5]. Due to water crisis in different regions of the world and on the other hand increasing demand of concrete for housing and infrastructure, it is vital to assess water use in different activities [6].

The life cycle assessment (LCA) approach is commonly used in order to assess potential environmental impacts from products, services, etc [7, 8]. This methodology calculates the potential environmental impacts at different stages e.g. raw material extraction, production, use, end of life phase. In the same line, the water footprint is a tool for calculating potential environmental impacts related to water use in the life cycle of a product [9, 10]. Even though, concrete demand represents a high share, few studies on water footprint have been performed. From 27 studies found between 2015 and 2017, only 3 include water consumption [11–13].

In general, results on water footprint or other environmental indicators are presented in databases, scientific publications and EPDs as single value which hides variability and uncertainties from the processes. A study of CO_2 emissions in concrete formulations from 29 countries has unveiled wide variability even for concretes with the same compressive strengths [14]. Another study on concrete blocks production, demonstrated important variability in CO_2 emissions and energy demand within manufactures of the same product [15]. Significant variation is expected due to energy matrix, technological route, resources availability, cement type, location and characterization factors which vary according to the chosen impact assessment method. Therefore, it is relevant to assess this variability.

In this study we identify sources of variability and estimate ranges of water footprint results in concrete water footprint. The assessment is done based on a sample of 25 MPa concrete formulations with slump of 120 mm. The understanding of variability in the water use and water footprint of concrete production is relevant for decision making of the companies that are trying to reduce environmental loads and improve efficiency of their processes. In addition, the results of the contribution of different sources of variability allows to prioritize where to act.

2. METHODOLOGY

This paper consists of a cradle to gate water footprint assessment of concrete. Therefore, it includes activities happening in the concrete plant -direct water use- mixing the concrete, washing the trucks and washing the yard. Indirect water use is considered for cement production, slag treatment and aggregates production since these activities could be influenced by the concrete producer. The water footprint of the energy is also included.

Water use figures for direct and indirect water use where taken from [4, 16] which include life cycle water inventory figures for concrete production. For the study of variability due to technological route, only ready-mix concrete is considered however different concrete formulations are used for the analysis. Concrete formulations produced in Brazil were used to estimate water consumption including the amount of each concrete constituent, compressive strength and slump. The functional unit is 1 m^3 of concrete of 25 MPa compressive strength with workability of 120 mm slump which is a commonly used concrete.

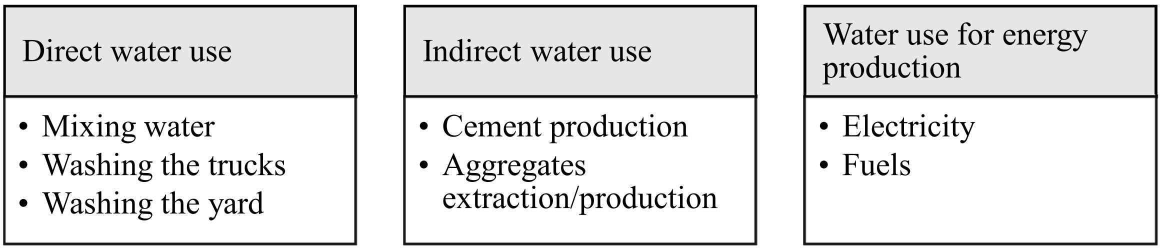

Figure 1 Water use scopes for inventory following the Greenhouse Gas Protocol for reporting emissions [17]

This study is focused on water consumption which is defined as water that is not available anymore at the original source where it was extracted [9]. Water quality is not included in this study. However, it is more common in concrete LCA studies to find water quality impacts such as freshwater eutrophication, ecotoxicity, etc. [18].

For the study of variability due to environmental impact (water footprint), three methods are used: AWARE [19], Hoekstra [20] and ReCiPe 2016 H [21]. These methods have the same unit and therefore we can compare the results. In addition, three regions were chosen to estimate variability due to location -Brazil (BR), Switzerland (CH) and Rest of the World (RoW). Table 1 presents the characterization factors for the impact assessment in each region according to the three methods. In the case of the ReCiPe 2016 H method [21], the values of 1 and -1 are not precisely characterization factors but only used to calculate the water consumption.

Table 1 Characterization factors for water footprint (AWARE [19], Hoekstra [20] ReCiPe 2016 H [21])

	Unit	Water use (AWARE [19])			Water scarcity index (Hoekstra [20])			Water consumption (ReCiPe 2016 H [21])		
		BR	CH	RoW	BR	CH	RoW	BR	CH	RoW
Water withdrawal	m^3/m^3	2.17	1.34	44	0.05	0.12	1.39	1	1	1
Water returned to the same source	m^3/m^3	-2.17	-1.34	-44	-0.05	-0.12	-1.39	-1	-1	-1

A final analysis was performed to compare the sources of variability and their importance.

Variability in the water footprint in construction aggregates and cement is studied in detail in another publication [22].

3. RESULTS AND DISCUSSION

3.1 Variability in the water inventory of concrete production

Water use for concrete production is divided according to the 3 Greenhouse gas Protocol scopes [17]. Direct water, used in the concrete production plant includes mixing water, water for washing of the truck and water for washing of the yard. Indirect water includes water to produce cement and aggregates. Finally, there is water for energy production -electricity and fuels.

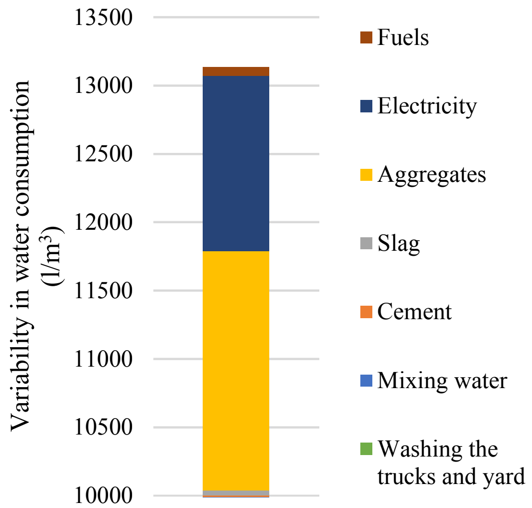

Figure 2 Variability in the water consumption of concrete production (1 m^3, 25 MPa, 120 mm) for direct and indirect activities

Direct water use ranges from 196-249 l/m^3 including mixing water, water for washing the yard and washing the truck. The mixing water varies according to the workability and compressive strength requirements [14] but compared to other water uses, this activity represents a small fraction. The water for washing the yard and washing the trucks is considered constant independently from the concrete design. However, there could be a difference in the amount of water used to wash the trucks since depending on the rheology of the mix, more or less concrete would stay in the bottom of the truck to be washed. For water efficient companies -focused on reducing water use, water losses and implementing recycling/reuse practices- the water use for washing the trucks and yard could be considerably lower. Indirect water use varies from 302-2100 l/m^3 including water for cement production, water for slag treatment and water for aggregates production. From the chart we can observe that the activity that presents highest variability is the aggregates production. This is probably because this activity is usually performed near superficial or underground water sources and the water withdrawal and consumption is not controlled as usually the company gets a permit to use this water sources and does not need to pay depending on the water use but only a fixed price that is very cheap. Also, the use of water in aggregates production depends on weather conditions (e.g. if it rains, it is not necessary to control dust or to wash the aggregates) but also on industry practices such as washing the aggregates for a better performance of the material. Finally, water for energy varies from 9400-10785 l/m^3 including water for fuel production and for electricity production. The water use for energy production is high, this is after CO_2 emissions another reason to improve energy efficiency in concrete production.

To reduce the water consumption per activity, the direct water use could be target, the indirect water use even if is not controlled by the concrete producer could be somehow influenced in order to be more efficient since for these activities and products -cement and aggregates production- the concrete producer is their main client. Finally, for energy production, this would be a background activity since it is difficult to be influenced by the concrete producer. However, as mentioned before, the concrete producer would reduce its energy water consumption by being more efficient in terms of energy consumption.

3.2 Variability in the water footprint of concrete production due to location and the choice of impact assessment method

Water related impacts are local [19] and for this reason the impact assessment characterization factors vary according to the region where the water is extracted and used. The characterization factors also vary according to the water footprint method (see Table 1). Figure 3 presents variability for concretes of 25 MPa (120 mm) for Brazil, Switzerland and Rest of the World. The results vary up to 60 times depending on the method. The highest results correspond to the AWARE method that is based on a characterization factor 1/AMD, which is the inverse of the difference between availability per area and demand per area [19].

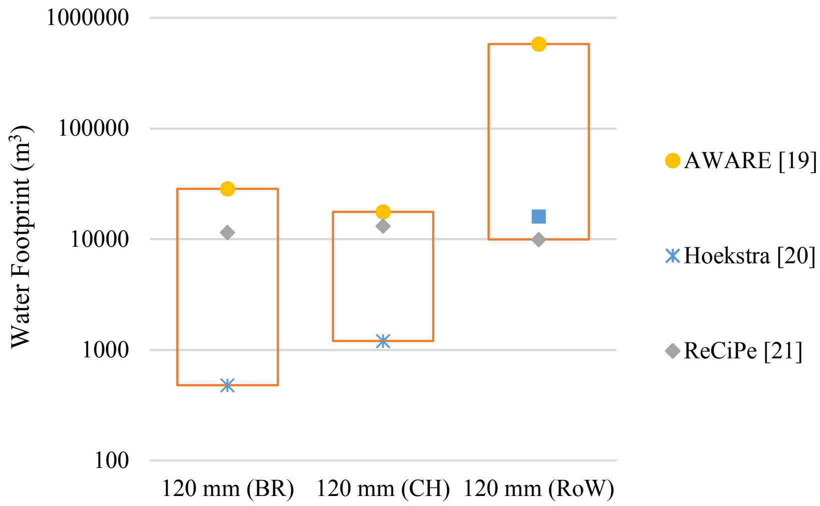

Figure 3 Variability in concrete water footprint due to the choice of method for different regions for 1 m^3 of concrete, 25 Mpa, 120 mm (the vertical scale was adjusted since RoW values are >100,00 m^3)

The characterization factors for each method were downloaded from the SimaPro software v 8.5. For the AWARE method [19] and Hoekstra method [20], the characterization factors are presented per country and type of water. For ReCiPe 2016 H water consumption [21], the factor is 1 since they do not have characterization option in their last update of the method. Characterization factors should vary according to region, and in the case of Brazil for instance, the availability of water varies from places like Amazonia to São Paulo were water drought have affected (see Figure 4). On top of this variability there is the water demand in function of the population of the region. One number representing the potential impact of water consumption of a whole country is unacceptable, ever worse to represent the rest of the world.

These results demonstrate that the choice of method is crucial. Moreover, the understanding of the method before it is used and for interpretation of results. Finally, the location is critical when performing a water footprint study. It is important to understand that the "RoW" location includes all countries that do not have a local inventory in the Ecoinvent database. This option is commonly used but should be avoided since the results usually present the worse cases and not the reality of the region.

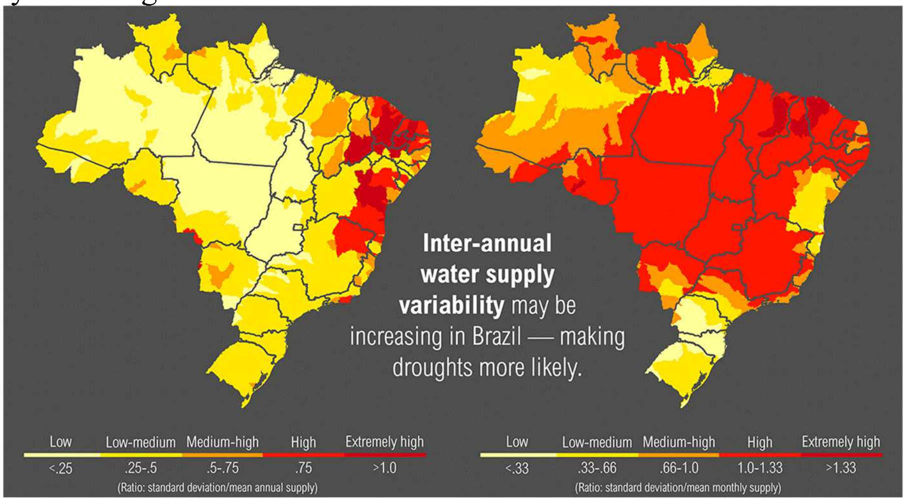

Figure 4 Annual variability (on the left) and seasonal variability (on the right) for water availability in Brazil. Source: www.wri.org [23]

3.3 Influence of each source of variability

The sources of variability were classified as direct, indirect and method. At the same time, we can observe variability depending on the region (BR, CH and RoW).

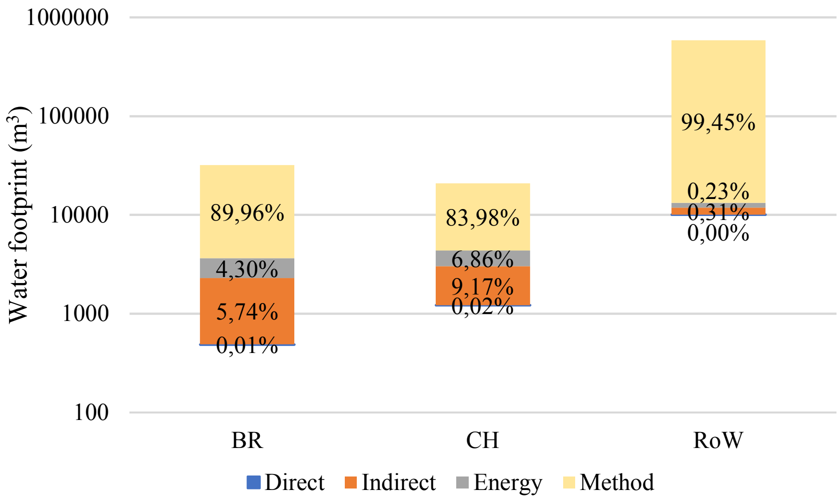

Figure 5 Contribution of variability due to direct water use, indirect water use and impact assessment method for 1 m^3 of concrete, 25 Mpa, 120 mm (the vertical scale was adjusted since RoW values are >100,00 m^3)

Comparing the three regions in Figure 5, Switzerland (CH) has the lower variability. This happens because the ecoinvent database is developed there, i.e. the Swiss inventory is the most complete and accurate available. For the Brazilian case (BR) we can observe larger variability, but the results are still better than for the Rest of the World case (Row). This is because Brazil has developed some inventories with local data but not all. However, this variability is underestimated since Brazil should have characterization factors per region or even better per watersheds. For RoW, the variability comes from the characterization factor that generalizes the worst-case scenario for all the regions without local information including regions where the water availability super exceeds the water demand.

Comparing the sources of variability, direct water use is low -this does not mean that the water use in the concrete plant should not be carefully assessed but is more or less a fixed value. After this, we can observe that variability from indirect water use and energy production water use are in the range of 5-10 % for Brazil and for Switzerland. The difference is that the indirect activities could be influenced by the concrete producer in addition to be more efficient in terms of materials use while for energy production the only possible strategy in terms of reducing water consumption would be to increase efficiency in energy use. The highest variability comes from the choice of method. In the case of Row, this source of variability represents almost 100%. This means that before performing a water footprint assessment, the impact assessment method should be carefully chosen, studied and understood in order to avoid misleading results.

4. CONCLUSIONS

- A case study of variability in concrete production was performed including variability due to water use, location and choice of impact assessment method.
- The highest water consumption is due to energy production. Therefore, it is important to continue with efforts to reduce energy demand not only because of CO_2 emissions but also because of its high water footprint.
- The most important contributor in terms of water use after energy production is aggregates production. This activity is rarely controlled. Measurements to improve water efficiency in this activity should be considered.
- Most of the variability comes from the choice of method which could influence the results by a factor of 60. The use of water footprint methods and interpretation of water footprint results should be carefully done since the methods have an important influence and represent different situations. Moreover, water footprint methods should converge to one universal method.
- For ecoinvent-type databases to be useful, local information per basin is needed.

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EXPERIENCE OF IMPLEMENTATION OF ENERGY PERFORMANCE REQUIREMENTS FOR BUILDINGS IN LITHUANIA

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Abstract

The main objectives of improving energy performance of buildings, which each EU country has to achieve, is presented in EPBD, but the ways to achieve these goals must be found by each country paying attention to the climatic conditions, internal climate of the premises, the country's energy and economic situation and construction traditions. Lithuania is in a cold climate zone, has limited resources for solar, wind and hydro power generation, and creating energy performance requirement the first challenge was always to reduce the energy demand of a building. According to the COST Optimal methodology, minimum optimal requirements were set for the energy efficiency of buildings and their engineering systems, additional ways of reducing energy in the building were found, and additional verification indicators were introduced to ensure efficient design and use of buildings.

Motivation of introducing these measures and the impact on the energy performance of buildings are discussed in detail in the presented article.

Keywords: building energy performance, COST optimal

1. INTRODUCTION

Reduction of energy consumption and the use of renewable energy in the building sector are important measures that are necessary for reducing the Union's energy dependency and greenhouse gas emissions. The Directive 2010/31/ES [1] of energy performance of buildings promotes an increase of the energy performance of buildings in the Union, considering external climatic conditions and localities, as well as indoor climate and cost-effectiveness (Article 1f of the Directive 2010/31/ES). These measures should not affect other requirements of buildings, such as accessibility, safety and use of the building. The energy performance of buildings has to be calculated using a methodology that can be differentiated at national and regional levels. Countries should apply their own methodology for calculating the energy performance of buildings in accordance with the principles of the integrated calculation of energy performance of buildings and parts of buildings referred to the Directive 2010/31/ES (according to the general framework defined in Annex I, Article 3). In the methodology, other important factors, not only thermal properties, for energy efficiency can be provided. Preparing the methodology European standards must be considered; it must comply with the relevant Union legislation [1]. The methodology for calculating the energy performance of buildings in Lithuania started in 2005 and is constantly being improved. While preparing the methodology, in addition to the requirements specified in the Directive, other energy experiences of buildings were analysed, since the reduction of energy costs was always an urgent task in Lithuania. The following energy efficiency measures for buildings, which are applied in the methodology, are presented in the article. All energy costs of the building are calculated according to EU standards [5-9], but their assessment is adapted to Lithuanian conditions in order to achieve the following objectives. The appropriateness of the applied measures was demonstrated by analysing data on the determination of the energy performance of a A class single family building, apartment building and educational building. The information about technical - construction parameters of analysed buildings are presented in Tables 1 - 5.

Table 1. Technical parameters of the investigated buildings

	Technical parameters of the buildings					
The building	Area, m²	Volume, m³	Height, m	Length, m	Width, m	Massiveness, J/m²·K
Single family	103.95	267.66	5.92	10.00	7.00	260000
Apartment	1066.96	2777.12	11.95	28.67	27.34	260000
Educational	11641.40	39604.90	17.50	81.70	52.10	370000

Table 2. Partitions areas of the buildings

	Walls area, m²	Roofs area, m²	Doors area, m²	Windows area, m²	Floor area, m²	Overlay area, m²
Single family	175.42	69.99	2.20	33.21	54.00	0.00
Apartment	674.40	382.93	1.89	268.15	229.67	136.00
Educational	3278.60	3961.58	14.00	3318.13	3753.10	333.00

Table 3. Parameters of the partitions of the investigated buildings

	Thermal properties of building partitions, W/m²×K					Air tightness, n_{50} [3,4]
	Walls	Roof	Floor	Windows	Doors	
Single family and apartment	0.12	0.10	0.13	1.00	1.40	1.00
Educational	0.15	0.11	0.10	1.30	1.40	

Table 4. Windows area (m²) in buildings by orientation

	North	East	South	West	Horizontal	TOTAL
Single family	0.90	19.37	6.58	6.36	0.00	33.21
Apartment	41.36	2.10	133.90	90.80	0.00	268.15
Educational	1018.22	454.31	1193.94	500.78	150.88	3318.13

Table 5. The parameters of the engineering systems of the investigated buildings

Characteristics of building engineering systems					
Heat source for heating	Energy efficiency for heating, SCOP	Heat source for HW	Energy efficiency for HW, SCOP	Ventilation system	Energy efficiency of ventilation system
Heat pump „ground – water "	3.50	Heat pump „ground – water "	3.00	Mech + recuperation	80 %

2. METHODS AND RESULTS

2.1 The meaning of optimization of building forms and glazing area for building energy consumption for heating

The amount of energy for building heating is further restricted in order to optimize the shape of the building and the area of transparent partitions (mainly windows). The monthly energy consumption for heating the building should cover the heat losses of the building through partitions and ventilation losses. Internal heat dissipation (from people, equipment and DHW system inside building depending on the purpose of building) and Solar heat gains reduce the energy demand for heating. This restriction has been introduced to optimize shape of the buildings and areas of transparent partitions.

Table 6. Non-renewable primary energy consumption

	Non-renewable primary energy consumption, kWh/(m²×year)				
The building	Heating	Cooling	Electricity	DHW	TOTAL
Single family	41.16	21.83	133.26	29.32	225.57
Apartment	43,62	9.44	156.65	47.40	257.11
Educational	26.12	11.81	73.21	14.25	125.39

In single family building which area of glazed parts make 10 percent of external partition area, heat losses through them make 42 percent of all of the heat losses of the building. In educational building which area of glazed parts make 23 percent of external partition area, heat losses through them make 73 percent of all of the heat losses of the building. During the summer, the transparent partitions are the only source of overheating of the premises, because other well-insulated partitions prevent the internal partition walls from heating up. The same motives are applied to the shape of the building. Energy performance of buildings is based on the energy consumption of 1 m² per heating area. The larger the area of external partitions for 1 m² of heated area, the higher energy consumption of the building with the same insulation level of the partitions. The restrictions imposed by the Regulation encourage designers to design compact buildings without extensions and superstructures.

Table 7. The proportions (P) of windows to the external partitions area and distributions (D) of the heat loses through the windows of analysed different type buildings

	The proportions (P) of windows to the external partitions area and distributions (D) of the heat loses through the windows, %				
The building	Windows	Walls	Roof	Floor	Thermal bridges

	P	D	P	D	P	D	P	D	P	D
Single family	10 %	42 %	52 %	27 %	21 %	9 %	16 %	9 %	-	9 %
Apartment	16 %	59 %	40 %	18 %	23 %	10 %	13 %	7 %	-	2 %
Educational	23 %	73 %	22 %	8 %	27 %	7 %	26 %	8 %	-	3 %

2.2 Values of the heat transfer coefficient of specific dimensions windows

For the calculation of the energy performance of buildings of "A", "A +" and "A ++" classes, the U values determined for each dimension window (group of specific dimension windows) must be used. The values of the heat transfer coefficient of the window of the appropriate size can be calculated according to LST EN ISO 10077-1 [2] using data from measurement of the windows using "Hot box" method. It is recommended to design the buildings that the same area of transparent partitions is achieved using a smaller number of windows. Then larger windows are used, with an increased percentage of glazing for 1 m2 of all windows. In Lithuania three-pane glass units with heat transfer coefficients smaller than the coefficient of the window frame is used for completed windows, which means that the total U value for larger windows is smaller than that of smaller ones. This more accurately evaluates the heat losses of a building through windows and makes it easier to reach the required energy class. Heat losses of A class building using values of standard windows and U values of different dimension windows are presented in the example (Figure 1 and 2).

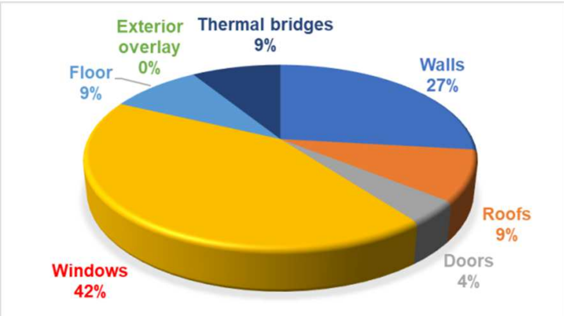

Figure 1. Heat losses through partitions using U values of standard dimensions windows of the single-family building

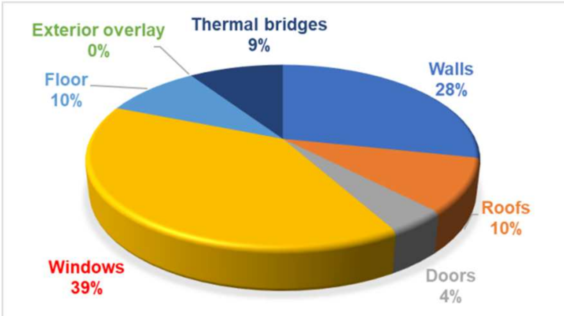

Figure 2. heat losses through partitions using U values for each dimension windows of the single-family building

2.3 Influence of building mass on energy consumption for heating

When designing the energy performance of a building, the internal thermal capacity (thermal inertia) of the building must be assessed. Increasing the thermal mass of the building's partitions and internal structures increases the internal thermal capacity of the building. During the heating season, the more massive structures accumulate more Solar heat getting into the room through the transparent partitions and then give it to the indoor air. This reduces energy consumption for heating of the building, shortens the building's heating time. During the summer, massive building design prolongs the time before the overheating of the building, thus avoiding or reducing the energy consumption of the building for cooling. Increasing the thermal mass of building partitions and internal structures allows achieving a higher class of energy efficiency of a building. In design the energy-efficient buildings, priority should be given to massive partitions and massive internal structures of a building. The examples show how the energy consumption for heating of the same buildings varies depending on the thermal mass of the building. The results of designing the single-family building showed that in the case of similar thermal properties of partitions and engineering systems, the energy consumption of a very massive building for heating will be about 3.6 % lower than that of medium-sized building constructions and about 10.5 % lower than that of lightweight building constructions.

2.4 Estimation of heat loss of buildings through insulated unheated premises

In order to increase the energy efficiency of new and renovated buildings, unheated but well insulated garages, balconies and other premises are often connected to the building main conditions, under which the unheated premises connected to building could be evaluated as insulated, are:

- the class of the air conduction of windows, roof windows, gates and external doors is not lower than the third;
- the heat transfer coefficient of the walls does not exceed 0.5 ($W/m^2 \cdot K$);
- the heat transfer coefficient of windows, roof windows, gates and external entrance doors does not exceed 2.0 ($W/m^2 \cdot K$).

It is obvious that the heat losses through the partitions separating the heated and unheated insulated premises are different than heat losses through the partition walls, separating the inside and outside of the building. The developed and implemented methodology is used for more accurate evaluation of the heat losses of a building and its energy efficiency, when such unheated well insulated premises are connected. As example, well insulated balcony reduces heat losses through wall with windows up to 80 % comparing to the same wall separating the inside and outside of the building.

2.5 Air tightness requirements for determining the heat losses of the building

For determining the heat losses of the building due to infiltration and for the quality control of construction, a compulsory measurement of the air tightness of buildings was introduced, and only by measurements determined air tightness values are used for the calculation of energy efficiency. The building air tightness requirements have always been in Lithuanian building regulations, however only with the introduction of high energy efficiency requirements the obligatory measurements of the building's air tightness were validated and only measurement results it is allowed to use for calculation of the heat losses of a building due to air exchange.

Table 8. Building air tightness requirements according to Lithuanian building regulation document STR 2.01.02:2016 [3]

Purpose of the building	Energy class	$n_{50.N}$, (1/h)
Residential, administrative (office), educational and hospital	C	2.0
	B	1.5
	A	1.0
	A+, A++	0.6
Supply, trade, culture, hotels, services, sports, transportation, special and recreation	C, B	2.0
	A	1.5
	A+, A++	1.0

Only after implementation of this requirement, the construction market was essentially concerned about the air tightness of the building. Three main aspects of ensuring the air tightness of the building are distinguished: use of additional sealing materials, better supervision of construction work and a higher qualification of construction workers. After implementation of these measures, the overall quality of construction work increased, the total value of the building increased, the ventilation systems worked more efficiently. In the near future, it is planned to introduce an additional requirement that the building's air tightness have to be measured before each repeated energy certification of the building in order to ensure the durability of the sealing.

An analysis of the energy consumption for heating the building and the loss due to ventilation of a single family building showed that depending on the air tightness of the building, changing the air circulation in the premises from 2.0 times/h to 0.6 times / h at a pressure of 50 Pa between premises and outside, the energy consumption for heating decreases from 15.43 kWh/m²×annual to 14.41 kWh/m²×annual, and the heat loss due to ventilation is almost double - from 2.24 kWh/m²× annual to 1.28 kWh/m²×annual.

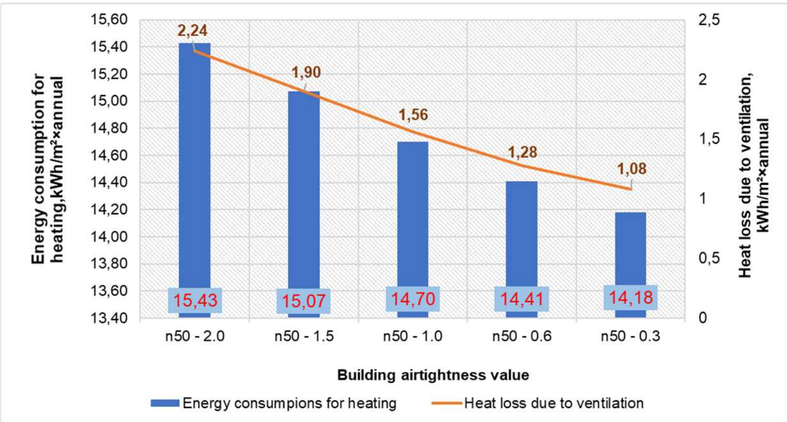

Figure 3. Dependence of the energy consumption for heating and heat loss by ventilation due to airtightness of the building

2.6 The impact of renewable energy in central heating networks on the energy performance of buildings

Over the past 5 years, Lithuanian district heating networks have been using more and more biofuels for the production of thermal energy, which resulted in a significant increase of renewable primary energy in the heat supply network, which has increased the attractiveness of this heat source and easier achievement of energy efficiency. In Lithuania about 50 percent of dwelling houses use thermal energy from centralized district heating networks. The heat networks of small towns make a larger part of thermal energy from biomass, therefore, their primary non-renewable energy consumptions are significantly smaller than that of larger cities heat networks, where gas and fuel oil are still used a lot and heat production equipment and networks themselves are inefficient and therefore, their primary non-renewable energy consumptions are higher. During last 5 years, the use of biofuel in district heating networks was increased, the boilers were modernized, their efficiency increased. In 2018, after recalculation the factor of primary non-renewable energy produced by district heating networks in big cities, it turned out that this value fell from 1.30 to 0.62 compared to 2013. As the energy efficiency of a building is determined by the consumption of primary non-renewable energy, this change will significantly reduce the value of indicator C1, thus making it easier to meet the energy performance requirements.

The example: A single family building consumes 46.41 kWh / m² × annual kWh of heat from a heating network for heating. Calculating according to the primary energy factor values of 2013, this building uses 46.05 of primary non-renewable energy for heating, and according to the values of 2018 it uses 27.85 kWh / m² × annual of primary non-renewable energy.

2.7 The impact by using of renewable Solar electricity to the building's energy consumptions for heating

Significant impact on the production and use of renewable Solar electricity in the building provided the opportunity to supply all the generated energy to the electricity grids and use it in the building when it is needed. Production of photovoltaic (PV) electricity in the building or its surroundings is not efficient in the Lithuanian climate when it used directly for the needs of the building. Electricity in single-family building isn’t mostly used during the day time, when inhabitants are not in buildings, more at night time, when there is no solar radiation. The accumulation of generated electricity is expensive due to additional equipment and inefficient due to the losses incurred. In order to increase the attractiveness and efficiency of photovoltaic solar collectors, the storage of this energy in power grid networks has been implemented. This made a possibility to supply the amount of electricity generated in photovoltaic solar collectors to the electricity grids at any time and then use it in the most efficient way. One of the most efficient ways to use the energy, produced in the building for heating is to use it for the compressor of the heat pump. In this case, the entire energy generated by the heat pump is classified as primary renewable energy and is not included in evaluation of the energy performance of a building. This reduces the energy demand for building’s heating; more transparent partitions can be used; the required energy efficiency class is achieved with smaller investment. There may be cases where the primary non-renewable energy is not used for heating.

The single-family building, where three types of heating system were modelled, was selected for analysis in this article:

- The energy from district heating networks (“bio mass + natural gas”) is used for heating the building;
- The energy of the heat pump "air-water" is used for heating the building;
- The energy of the heat pump "air-water" + 12 m² photovoltaic solar collector system is used for heating the building.

The results showed that using a heat pump and installing 12 m² photovoltaic solar collector system with two-way electricity accounting for heating of the building, the annual primary non-renewable energy consumptions would be equal to 0.00 kWh/m²×annual. This shows that nearly all annual energy requirements for heating the building are compensated by the annual electricity produced by photovoltaic solar collectors. Meanwhile, using a heat pump without a photovoltaic solar collector system, the annual primary non-renewable energy consumptions for heating of the building reaches 41.16 kWh/m²×annual, and using energy from district heating networks reaches even 46,05 kWh/m²×annual.

3. CONCLUSIONS

- Separation of energy use for domestic hot water increases the value of the building's energy efficiency indicator C1influencing the accuracy of the determination of primary non-renewable energy for heating, ventilation, cooling and lighting.
- Windows of energy efficient buildings make up from 10% to 23% of the total partition area, and the heat loss through the windows make up from 42% to73 % of the heat loss of buildings, so their area must be limited by the requirements of the illumination.
- The heat loss through the windows can be reduced by using smaller number of windows with a higher glazing percentage and the size of the windows corresponding to their heat transfer coefficient values.
- In design the energy-efficient buildings, priority should be given to massive partitions and massive internal structures of a building. It increases the utilization of solar heat gains.
- Well insulated unheated premises connected to buildings could reduce heat losses through wall with windows up to 80 % comparing to the same wall separating the inside and outside of the building.
- The air circulation in the premises of a single-family building changing from 2.0 times/h to 0.6 (1/h) at a pressure of 50 Pa between premises and outside, the energy consumption for heating decreases from 15.43 kWh/m²×annual to 14.41 kWh/m²×annual, and the heat loss due to ventilation is almost double - from 2.24 kWh/m²× annual to 1.28 kWh/m²×annual
- The amount of primary non-renewable energy supplied from the heating network to heat the same single-family building decreased 60 % over its 5year period. Thus, it makes easier to meet the energy performance requirements.
- Using a heat pump and installing 12 m² photovoltaic solar collector system with two-way electricity accounting for heating of the building, the annual primary non-renewable energy consumption would be equal to 0.00 kWh/m²×annual. This indicates that the heating of the building does not require external energy supply.

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ACHIEVING NZEB TARGETS THROUGH ENERGY RETROFIT OF EDUCATIONAL BUILDINGS

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Abstract

Nowadays several technological and constructive options are available to improve energy efficiency and indoor environmental quality in buildings. Techniques exist to cut existing buildings' consumption by half or three quarters and to halve the energy consumption of typical appliances. But the renovation rate of buildings is too low, as is the uptake of the most efficient appliances. In order to determine the profitability of investments in building energy retrofit, a number of retrofit scenarios should be developed. The authors of this paper offer an approach for determining the energy retrofit effectiveness based both on expected energy savings and the increase in market value of the retrofitted buildings. In line with the proposed approach, the paper will present a comparison between the energy consumptions of a building in four given scenarios.

Keywords: energy performance, thermal comfort, energy retrofit, sustainable buildings, costs

1. INTRODUCTION

According to the World Business Council for Sustainable Development, buildings account for up to 40% of energy use in most countries. Reducing energy consumption and eliminating wastage are among the main goals of the European Union. The identification of the most appropriate retrofit options is a topic of outstanding importance given the potential costs and environmental impacts involved.

There is no specific target set for the renovation of existing buildings in the Energy Performance of Buildings Directive (Directive 2010/31/EU), but member States of the European Union are encouraged to follow the leading example of the public sector by developing policies and take measures such as targets in order to stimulate the transformation of buildings that are refurbished into very low energy buildings. The Romanian methodology for calculating the energy performance of buildings Mc001/2006-2009 gives the methodology used in the energy auditing activity for existing buildings. The new released orders 2641 from 2017 and 386 from 2016 specify the nZEB values that must be achieved by several types of buildings from Romania, the educational buildings being one of those types of buildings.

The educational building stock, i.e. schools, from Romania is about 19.000 buildings, most of them being built before 1990. Thus, these types of buildings need to be energy retrofitted in order to improve their indoor environment and lower their negative impact on the environment. Improvement of the energy efficiency of buildings has a direct impact on the energy consumptions of buildings, thermal comfort and indoor air quality of a building. Therefore the paper will assess the way in which the nearly Zero Energy Buildings targets are achieved through energy retrofit process of an educational buildings.

2. METHODS

2.1 Calculation methodology

The calculation methodology Mc001/2006 gives the required steps in evaluating the energy performance of a building and also in establishing the retrofitting solutions both from the energy consumptions and cost efficiency point of view. The energy consumptions will be established for four cases scenarios of the building: the real building, the notional building and for two retrofitting strategies. The cost efficiency for the two retrofitting variants was analysed. The results for the studied cases are compared to standardized indicators that indicate the energy behaviour of a building:

- the energy class: is established based on the values obtained through calculations of several energy consumptions and the overall energy consumption of the building;
- the total energy consumption of the building: is established based on the energy consumptions of the building utilities in [kWh/m^2·year];
- the CO_2 equivalent emission index: knowing the specific energy demand of the building and the type of fuel used, using the energy conversion factors, the primary energy demand by fuel type can be calculated. With the energy demand value and annual CO_2 emissions the equivalent CO_2 emission index can be established.

The energy consumptions calculated for the studied case were:

o energy consumption for heating:

$$Q_{fh} = Q_{fh} + Q_{th} - Q_{rh,h} - Q_{rw,h} \quad \text{[kWh/yr]} \tag{1}$$

where Q_h is the energy demand for heating in [kWh/yr], Q_{th} are the total heat losses of the heating system including recovered heat losses in [kWh/yr], $Q_{rh,h}$ is the recovered heat from the heating subsystem in the interior of the building in [kWh/yr], $Q_{rw,h}$ is the heat recovered from the domestic hot water preparation subsystem in the heating period of a year in [kWh/yr].

o energy consumption for domestic hot water preparation:

$$Q_{acm} = Q_{ac} + Q_{ac,c} + Q_{ac,d} \quad \text{[kWh/yr]} \tag{2}$$

where Q_{ac} is the heat demand for the preparation of the delivered domestic hot water in [kWh/yr], $Q_{ac,c}$ are the heat losses due to losses and domestic hot water dissipation in [kWh/yr],$Q_{ac,d}$ is the thermal energy lost on the distribution network in [kWh/yr].

o energy consumption for lighting:

$$W_{il} = 6 \cdot A + \frac{t_u \cdot \sum P_i}{1000} \quad \text{[kWh/yr]} \tag{3}$$

o the primary energy:

$$E_p = Q_{fh} \cdot f_h + Q_{fw} \cdot f_w + W_{il} \cdot f_{il} \quad \text{[kWh/yr]} \tag{4}$$

where f_h primary energy conversion factor for natural gas, f_w primary energy conversion factor for natural gas, fil primary energy conversion factor for electrical energy.

o the CO_2 emissions:

$$I_{CO2} = \frac{E_{CO2}}{A_{useful}} \qquad \text{[kg/m}^2\text{·yr]} \tag{5}$$

where A_{useful} is the useful area of the building in [m^2]

For the energy certification of the building the following formula were applied:

o the specific annual energy consumption for heating, with values varying between a minimum of 70 [kWh/m^2·yr] and a maximum of 500 [kWh/m^2·yr]:

$$q_{heat} = \frac{Q_{fh}}{A_{useful}} \qquad \text{[kWh/m}^2\text{·yr]} \tag{6}$$

o the specific annual energy consumption for domestic hot water, with values varying between a minimum of 15 [kWh/m^2·yr] and a maximum of 200 [kWh/m^2·yr]:

$$q_{dhw} = \frac{Q_{acm}}{A_{useful}} \qquad \text{[kWh/m}^2\text{·yr]} \tag{7}$$

o the specific annual energy consumption for lighting, with values varying between a minimum of 40 [kWh/m^2·yr] and a maximum of 120 [kWh/m^2·yr]:

$$w_{light} = \frac{W_{il}}{A_{useful}} \qquad \text{[kWh/m}^2\text{·yr]} \tag{8}$$

o the total specific annual energy consumption, with values varying between a minimum of 125 [kWh/m^2·yr] and a maximum of 820 [kWh/m^2·yr]:

$$q_{tot} = q_{heat} + q_{dhw} + q_{light} \quad \text{[kWh/m}^2\text{·yr]} \tag{9}$$

In order to establish the energy note of the building the penalty factors (i.e. going from p_1 up to p_{12}) that apply for the studied building are chosen based on predefined values given by Mc001 calculation methodology. The penalty factor p_0 is calculated based on the chosen values:

$$p_0 = p_1 \cdot p_2 \cdot p_3 \cdot p_4 \cdot p_5 \cdot p_6 \cdot p_7 \cdot p_8 \cdot p_9 \cdot p_{10} \cdot p_{11} \cdot p_{12} \cdot \tag{10}$$

The energy grade is calculated with the following formula:

$$N = \exp\left(-\mathrm{B}_1 \cdot q_{tot} \cdot p_0 + \mathrm{B}_2\right) \tag{11}$$

where: B_1 and B_2 are numeric coefficients for buildings chosen based on the building utilities

The analysis of the economic efficiency for the proposed energy retrofitting solutions implied calculating the next indicators:

ΔCE=c ΔE which gives the annual operating cost reduction due to the application of energy efficiency measures in [€/yr], where c is the specific cost for energy and ΔE energy saving achieved by applying the energy retrofitting measure.

VNA which is the net present value related to additional investment in [€]:

$$VNA = C_m + \Delta CE \cdot \sum_{t=1}^{n} \left(\frac{1+f}{1+i} \right)^t \tag{12}$$

where f is the annual growth rate of energy price, and i is the annual rate of depreciation for the reference currency, Nr or t is the duration of return investment in [yrs], Ns is the estimated life for the proposed energy retrofitting solution in [yrs], e is the energy cost saving over the solution lifetime in [€/kWh]: e= Cm/(Ns. ΔE).

2.2 The case study

The assessed building is an educational building located in Săliştea de Sus town, region of Maramureş, N region of Romania. Săliştea de Sus town is in the IV^{th} climatic zone of Romania characterised by an exterior temperature of θe=-21°C, based on C107 design norm (C107). The height regime of the building is GF+2F. The building has an L shape and the main façade of the building has a South orientation. The height of the ground floor is 3.65 m, of the first floor 3.50 m and of the second floor 3.55m. The structure of the building is a reinforced concrete frame construction defined by:

- interior walls: aerated cellular concrete masonry with a thickness of 10 cm;
- exterior walls: aerated cellular concrete masonry with a thickness of 40 cm with reinforced concrete lintels and tie beams;
- reinforced concrete floors and reinforced concrete slab on the ground;
- unheated attic;
- exterior glazing- double glazed windows in wooden frame and single glazed doors in wooden frame

The geometric characteristics for the elements of the building envelope were calculated:

- building heated perimeter: PGF=148.75 (GF) and P1+2=235.2m (1F+2F);
- attic roof: Aar=398.515 m^2
- slab on the ground (interior contour of the building): Asg=405.18 m^2;
- exterior windows: Aw=323.25 m2 and exterior doors: Ad=15.24 m^2;
- opaque surface exterior walls: Aop=908.523 m^2;
- building envelope: Abe=2057.373 m^2;
- direct and indirect heated area of the building: Aheated=1202.21 m^2;
- direct and indirect heated volume: Vheated=4234.3 m^3;
- the ratio Aheated/Vheated=0.284

Values considered in calculation for the primary energy conversion factors were: f_h=1.1, f_w=1.1 and f_{il}=2.8.

Values considered in calculation for emission factors were: $f_{h.CO2}$=$f_{w.CO2}$=0.205 kg/kWh and $f_{il.CO2}$=0.09 kg/kWh

The penalty factors chosen for the real building case scenario were: p1= p4= p6= p7= p8= p9= p10=p11=1, p2=1.01, p3=1.02, p5=1.05, p12=1.1. Therefore the calculated penalty factor p0 was: p0=1.19. For the notional building and for the retrofitted case scenario p0=1 . The numerical factors considered were: B1=0.001053 and B2=4.73677. The values were chosen for the case without mechanical climatisation and ventilation systems.

For the energy retrofit two variants were proposed. The first variant: 10 cm of expanded fireproof polystyrene for the exterior walls R'=2.219 $m^2 \cdot K/W$, 10 cm of extruded polystyrene for the slab on the ground R'=5.420 $m^2 \cdot K/W$, 25 cm of water repellent (hydrophobic) thermal insulation of mineral wool for the attic floor R'_m=5.04 $m^2 \cdot K/W$, triple glazing filled with Krypton with a R'_w=0.83 $m^2 \cdot K/W$. For the building services the following were modified: replacement of heat distribution pipes from the ground and domestic hot water pipes with thermally insulated pipes, disassembly and cleaning of heating components, thermostatic radiator valves installation on each component, flow meters installation and insertion of single command fittings at washing basins, and replacement of existing incandescent bulbs of 100 W with fluorescent lamps of 23 W having an equivalent luminous flux.

Figure 1: Building Plans. a) Ground floor, b) Cross-section

The second variant: 15 cm of expanded fireproof polystyrene for the exterior walls R'=2.914 $m^2 \cdot K/W$, 15 cm of extruded polystyrene for the slab on the ground R'=7.37 $m^2 \cdot K/W$, 30 cm of extruded polystyrene for the attic floor R'=6.03 $m^2 \cdot K/W$, triple glazing filled with Argon with

a R'_w =0.77 $m^2 \cdot K/W$. For the building services the following were modified: restoration and supplementation of thermal insulation using mineral wool for the heat distribution pipes from the ground and domestic hot water pipes, thermostatic radiator valves installation on each component, disassembly and cleaning of heating components, flow meters installation and insertion of single command fittings at wash basins, and replacement of existing incandescent bulbs of 100 W with LED lamps of 18 W having an equivalent luminous flux. For the economic efficiency the specific energy cost was considered c=0.0567 €/kWh, 1 € =4.5 Romanian Lei, f=0.10 and i=0.05.
The necessary values to be ensured based on the nZEB Romanian targets for educational buildings are for primary energy 172 [$kWh/m^2 \cdot yr$] and a CO_2 emission index of 48 [$kg/m^2 \cdot yr$].

3. RESULTS

Several comparisons were made between the simulated cases. The results shown in table 1 and table 2 were obtained for the four studied scenarios. It can be noticed that both energy retrofit interventions for the building have positive results on the thermal behaviour of the building envelope and for the entire energy efficiency of the building. Also the I_{CO2} emission index decreases with increasing energy performance of the studied building. Nevertheless, the nZEB requirements are not met by the building, at least from the energy consumption perspective.

Table 1. Energy consumptions, I_{CO2} and energy note: real building and notional building

Studied Building Case	The Real Building					The reference Building				
	q_{heat}	q_{dhw}	w_{il}	q_{tot}	Ep	q_{heat}	q_{dhw}	w_{il}	q_{tot}	Ep
Specific annual energy consumption [$kWh/m^2 \cdot yr$]	399.06	47.85	34.65	481.56	588.62	278.41	42.52	27.2	370.06	399.80
Energy efficiency class	F	C	A	E		E	C	A	C	
I_{CO2} equivalent emission index [$kgCO_2/m^2 \cdot yr$]	94.74					68.24				
The energy note	62.40					77.25				

Table 2. Energy consumptions, I_{CO2} and energy note: retrofitted cases

Studied Building Case	1st Retrofitting variant					2nd Retrofitting variant				
	q_{heat}	q_{dhw}	w_{il}	q_{tot}	Ep	q_{heat}	q_{dhw}	w_{il}	q_{tot}	Ep
Specific annual energy consumption [$kWh/m^2 \cdot yr$]	192.09	39.79	13.05	244.86	289.26	186.98	39.79	11.65	238.42	279.97
Energy efficiency class	D	C	A	C		D	C	A	C	

I_{CO2} equivalent emission index [kg/m^2·yr]	48.71	47.54
The energy note	88.14	88.74

Table 3 and 4 includes the economic efficiency indicators expected to be achieved from the application of the two proposed retrofitting solutions. Because VNAm<0, Nr<Ns and E<c it results that the investment is opportune for both proposed solutions not only in terms of energy efficiency but also from the economic point of view.

Table 3. Economic efficiency indicators - 1st energy retrofitting solutions

Retrofitting Solutions	C_m [€]	ΔE [kWh/yr]	Ns [yrs]	ΔCE [€/yr]	VNA_m [€]	Nr [yrs]	e [€/kWh]
Building Envelope	87710	180684.6	20	10244.8	-267982.2	8	0.0243
Building Services	11965	81015.61	30	4593.6	-308487.12	3	0.0049
B.E.+B.S	99675	261700.2	20	14838.4	-415503.15	6	0.0190

Table 4. Economic efficiency indicators - 2nd energy retrofitting solutions

Retrofitting Solutions	C_m [€]	ΔE [kWh/yr]	Ns [yrs]	ΔCE [€/yr]	VNA_m [€]	Nr [yrs]	e [€/kWh]
Building Envelope	103900	186633.8	20	10582.1	-263503.5	8	0.0278
Building Services	14515	82260.7	30	4664.18	-310862.0	3	0.0059
B.E.+B.S	118414	268894.5	20	15246.3	-410926.2	7	0.0220

4. DISCUSSION

As observed from the obtained results the energy efficiency and the cost effectiveness are the only criteria in choosing the energy retrofit solution. The concern regarding the Romanian assessment methodology is that the chosen energy saving solutions may have an adverse effect on the indoor environment, considering that the environmental impact is evaluated only from the CO_2 index point of view but not from the air quality aspects. Therefore, if the outdoor air quality is better than the indoor one, a reduction in the outdoor air supply will inevitably increase the concentration of pollutants in air of the interior spaces and thus decrease the indoor air quality. The increased pollutants effect will be on occupants' comfort, health and productivity. Moisture could also be another negative effect that might have a negative impact on the health of building occupiers. A positive effect on the indoor air quality could be the occupants' behaviour with respect to the opening of windows. Due to the fact that usually the educational retrofitted buildings have no mechanical ventilation, the air exchange rate is ensured by opening the windows. Although that in Romania the habit of leaving the windows opened for a longer period of time than needed is not sustainable from the energy consumption point of view, it usually has a positive effect on the indoor air quality. In this manner, the occupant has the opportunity for individual control of his environment. In order to achieve a good indoor air quality and thus good energy efficiency, the air flow rates are also very important. When choosing energy efficient solutions the ventilation requirements should be addressed properly. Based on the total pollutant load in a building, the needed ventilation requirements should be established in order to provide good indoor air quality, but also to protect the building structure, the installations and the furnishings. As mentioned by Spengler, natural ventilation compared to mechanical ventilation is friendly with the environment, consumes little energy and requires little maintenance. The energy retrofit design strategy should also consider when possible the implementation of such solutions.

The national methodology applied for the energy retrofit strategies should take into consideration both energy and indoor air quality aspects, and not only energy an economic aspects. Nevertheless, the nZEB values still represent a real challenge in optimising the existing building stock, due to a very poor initial thermal design, very difficult to be optimised. Even for the given case, the nZEB required value was not full field (see table 1 and 2).

5. CONCLUSIONS

- In the Romanian energy retrofit activity, only the energy consumptions and the financial aspect are evaluated by specialists in the field of building energetics.
- Stakeholders are interested in the financial aspects (costs) of the given solutions, and less on the energy performance and sustainability impact issues. Usually, the less expensive and less energy efficient solutions are chosen for implementation.
- The Paris Agreement on Climate Change is imposing the need of creating a sustainable building stock. Thus, the Romanian construction market must adapt to the needs of the planet in order to be able to create a healthy and implicitly sustainable building stock.
- The approach must be changed and the focus should be placed on the real needs of the occupants of a building.

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BREATHE, BREATHE IN THE HEALTHY AIR: INFLUENCE OF BUILDING DESIGN AND RECENT BIOMEDICAL RESEARCH DIRECTIONS ON INDOOR AIR QUALITY

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Abstract

Indoor air quality (IAQ) management and the influence it has on health are complex issues requiring a multidisciplinary approach. People in industrialized nations spend about 90% of their time indoors, which makes the quality of indoor air an important contributor to health. IAQ can be up to 5 to 100 times worse than outdoor air. Building pathology is a multidisciplinary field that studies abnormalities in the structure and functioning of the building and its parts, many of which affect IAQ. Some important factors that affect IAQ are soil gas (radon), human activities (cooking, housekeeping), building components, furnishings, moisture levels and mould growth along with heating, ventilation and air conditioning. Ventilation systems need to be properly designed and maintained to prevent dust accumulation and microbial growth. The choice of building materials, coatings, equipment, and furniture is of crucial importance in the context of IAQ. Important contributors to poor IAQ are growth of toxic moulds and volatile organic compound emissions, which constitute an important problem in modern, energy efficient building design. The aim of this review is to provide a comprehensive review of influence of modern trends in building design and biomedical research on IAQ and outline future challenges in improving IAQ.

Keywords: indoor air quality, building pathology, passive house, construction materials, environmental health

1. INTRODUCTION

Air pollution from various sources represents the single largest environmental risk to health globally. Governments and institutions recognized burden of disease due to air pollution as a public health concern [1]. Populations spend about 90% of their time indoors and concentrations of various air pollutants are often higher in indoor air than outdoor air [2, 3, 4]. Quality of indoor air can be 5 to 100 times poorer than quality of outdoor air [5]. In the past several decades, the World Health Organization has raised focus on IAQ, declaring the healthy indoor air is a right as a part of safe and healthy physical and social environment at home, school workplace and in the local community by releasing specific guidelines addressing exposure to indoor air pollutants [1, 6]. Most common health conditions related to IAQ include allergies, hypersensitivity reactions, respiratory infections and malignancies [5]. Sick building syndrome (SBS), common in general population, is a phenomenon where people experience symptoms of unclear ethiology while staying in certain buildings and is related to factors such as ventilation, building construction and maintenance, humidity and mould [7].

Proper building design, construction and maintenance is of vital importance for appropriate indoor air quality. By law, construction of buildings needs to meet certain requirements, and among them is the demand concerning hygiene, health and environmental protection [8]. The shift towards sustainable, energy efficient building construction can sometimes interfere with demands for health and hygiene [9]. In this review we will outline building requirements for appropriate indoor air quality and describe the health effects of poor indoor air quality. Finally, we will review the burden of disease related to IAQ, as well as contemporary challenges in improving IAQ, and comment on relationship between IAQ and energy efficiency.

2. BUILDING DESIGN AND IAQ

There are 7 essential requirements for construction works defined according to Croatian Building Act (Official Gazette 153/13, 20/17) [8]. Among them is demand concerning hygiene, health and environmental protection. It stands out that construction has to be designed and executed in the way that does not endanger human health or hygiene. It is strictly forbidden to use materials that emit toxic gases, or dangerous radiation. Also, construction stakeholders have to take care of the presence of dangerous particles or gases in the air, and pay attention to ground and water pollution. Furthermore, it is necessary to remove wastewater, smoke, solid and liquid waste in a proper way. A specific problem is the presence of moisture in the building or on the surfaces of construction. It encourages mould growth that can cause the appearance of numerous allergies and increase respiratory problems. The way to verify fulfilment of the hygiene, health and environmental protection requirement is provided by a series of interconnected measures, such as construction calculation and analysis. Properties and behaviour of construction materials has to be monitored and controlled in every phase of the construction project. The use of construction products in proper way along with high performance and needed maintenance is also determined. Hygiene, health and environmental request needs to be fulfilled during economic life cycle of the building.

Control of moisture and constant monitoring is mandatory, specifically if there are old, masonry buildings. Old buildings were often exposed to long lasting wetting, and wet can cause different physical devastation, i.e. efflorescence, mortar corrosion, corrosion of armature or other metal elements in masonry [10]. Moisture in the air of building can be controlled by [11]:

- increasing or reducing of air temperature (heating, cooling, isolating)
- ventilation of rooms (artificial or natural)
- drying or wetting the air in indoor spaces
- removing or reducing the source of humidity

- separating activity that produces moisture
- avoiding or preventing infiltration and penetration of pitting water and rainfall.

Most of the buildings in Croatia have been built before 1987 and they have poor (or even none!) thermal protection and improper waterproof installation that cause leaking. Approximately 83.0 % of today's buildings don't satisfy standards from 1987 (consumption: 150.0 – 200.0 kWh / (m^2*a), energy class E) [12]. Consequently, there is a large number of thermal bridges (sometimes called "cold bridges"). Surveys about building pathology also detected a side effect – higher emissions of CO_2 [12]. EU is also aware of this problem(s) and, therefore, EU directive 2012/27/EU on energy efficiency established a set of measures for each member country [13, 14]. In case of buildings owned by government, that means that at least 3.0 % of the total floor area of heated and/or cooled buildings have to be renovated until is standard from 2014 (or higher) satisfied [13]. Implementation of energy efficiency measures has a major impact on IAQ (according to system dynamics[1] model provided by Asere and Blumberga) [14].

Also, the way of building design may contribute to IAQ. There are research papers that show increase of IAQ in passive houses (in comparison to new objects, built in traditional way). Passive house had significantly lower levels of humidity, but total volatile organic compounds (TVOC) concentrations had higher levels. Passive house use mechanical system for ventilation that works automatically, so it's an easy way to achieve adequate IAQ. It is noticed the absence of microflora, too [15]. Condensation cause dampness and mould growth – it's very important to have adequate ventilation in closed spaces (e.g. toilettes in residential buildings). Some investigations show that mechanical ventilation is better than natural ventilation concerning IAQ. These researches measured climate, chemical and biological pollutants to found out range of IAQ in passive and nearly-zero houses (energy-efficient buildings) compared to conventional ones. As a result, it is shown that ventilation from open door/windows doesn't perform as good as artificial one [16]. Automated sensors and developing of new technologies will make easier to control an entire spectre of indicators [17]. Characteristics of suitable materials for indoor surfaces are temperature, humidity and corrosion resistance, durability, stability; material has to be easy to maintain. Reduction of water vapour diffusion is highly recommended. Some of the materials that can be used are extruded polystyrene, natural wood, glass foam, glass wool, even metal foams. Inappropriate can be resin or MDF (Medium Density Fibreboard) because they can cause allergies.

Choose of material for building envelope is very important because moisture cause 75.0 – 80.0 % of building defects [1, 18]. Each material has specific critical humidity level that causes mould growth [19]. Correct identifying types of material used in construction is a good starting point for reducing building defects and costs for maintaining [10]. Finnish scholars found out that moisture and mould damages are more frequent in ground floor structures and structures in contact with soil. External walls and roofs are, in general, well protected by different types of isolating materials, so they don't need many reparations [20]. "Smart" materials are defined as materials that can adjust to given conditions. Wood is well-known such material, but first artificial "smart" material was Hadfield steel [21]. Investigation in this field, in combination with research on energy transformation materials, can bring many benefits in the future.

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[1] System dynamics (SD) is an approach to understanding the nonlinear behaviour of complex systems over time using stocks, flows, internal feedback loops, table functions and time delays (e.g. application of SD in steel industry).

3. HEALTH EFFECTS OF IAQ

Indoor environments represent a mix of outdoor pollutants which are mostly associated with industrial activity and vehicular traffic, which can enter by infiltrations and/or through natural and mechanical ventilation systems, as well as indoor contaminants, which originate inside the building such as emissions from building materials and furnishings, central heating and cooling systems, humidification devices, moisture processes, electronic equipment, products for household cleaning, pets, and the behaviour of building occupants [22]. IAQ can be affected by various chemicals, including gases, volatile organic compounds (VOCs), particulate matter (PM) and fibres, organic and inorganic contaminants, and biological particles such as bacteria, fungi, and pollen [22]. Poor IAQ increases the risk of Chronic Obstructive Pulmonary Disease, causes or contributes to the development of acute respiratory infections, lung cancer, and chronic lung diseases such as asthma and it has also been associated with many cardiovascular diseases, other symptoms include dry eyes, nasal congestion, throat irritation, dizziness, headaches, fatigue, nausea/vomiting [23]. A Portuguese study has shown that IAQ is connected to inadequate classroom renewal in schools and accumulation of CO_2. They showed that probability of having poor concentration was 2.143 times higher in the children who were exposed to CO_2 levels above the reference range than in those who were not which connected to other study where high CO_2 levels in schools were associated with rales and cough in children [24, 25]. One of the most widely spread problems remains indoor smoking. Exposure to tobacco smoke in indoor environments increases the risk for bronchitis and asthma. Most of the parents/legal guardians in Portuguese study who smoked at home had children with asthma (76.9 %), chronic bronchitis, rales/wheezing (69.0 %), sneezing attacks (56.0 %), allergic rhinitis (65.0 %), stress (66.7 %), dizziness (85.7 %), irritability (71.4 %), headache (75.0 %), irritation of the mucous membranes of the eyes (66.7 %), dry cough (53.0 %), insomnia (72.7 %), breathing difficulties (70.5 %), and lack of concentration (62.2 %) [24]. In a review by Mendell et al. there was sufficient evidence of association for four outcomes (upper respiratory tract symptoms, cough, wheeze, and asthma symptoms in sensitized persons) for the two kinds of risk factor considered: exposure to damp indoor environments and presence of moulds or other agents in damp indoor environments and also between hypersensitivity pneumonitis in susceptible persons and mould or other agents in damp environments [26]. Since IAQ depends on outside air quality as well as indoor behaviour of residents it is important from an epidemiological and medical perspective to put an emphasis on every-day habits of the residents that are rather easily manageable and have a great impact on IAQ such as smoking and air ventilation.

4. WHERE IS IAQ NOW?

Many factors affecting indoor air quality, different parties responsible for generating and controlling air pollution and complex relationships of pollutants with various aspects of health outcomes make mitigating risks of indoor air pollution exposure and reducing disease burden due to poor IAQ a significant challenge [27].

4.1 IAQ and burden of disease

In 2008, European EnVie project estimated that the annual burden of disease related to inadequate IAQ is 2 million disability adjusted life years (DALY) in European Union [28]. In 2011, WHO has released a guide on estimation of disease burden due to inadequate housing, where various indoor air quality problems were addressed, including dampness and mould, indoor radon, second-hand smoke, carbon monoxide, formaldehyde and indoor smoke from solid fuel use, with focus on children as the vulnerable population [29].

In the 2011 WHO guide, estimated burden of disease attributable to radon varies from country to country, Switzerland having 8.3 % lung cancer deaths attributable to radon, Germany and France 5.0 %, while in Netherlands this percentage is very low. An ecological study conducted in north of Portugal (average indoor radon concentration 16-210 Bq m^{-3}) indicated that up 18.0 % to 28.0 % of lung cancer deaths there could be attributable to radon [30]. This is in line with other studies indicating that radon concentrations even below 100 Bq m^{-3} are a cause of concern, and even though the WHO sets the maximum acceptable concentration 100 Bq m^{-3}, in many countries the accepted maximum is still 200 Bqm^{-3} or higher [31, 32]. Another long-term risk, asbestos, isn't addressed in the 2011 WHO guide. Use of asbestos is banned and greatly reduced in many developed countries, which is accompanied by falling incidence of mesothelioma, but exposure still remains from asbestos in existing buildings, and there are still countries where use and exposure to asbestos is not monitored, such as India and China [33]. Although in developed countries relatively low proportion of population uses solid fuels, the household pollution from use of solid fuels from cooking was estimated to be responsible for 3.5–4 million premature deaths worldwide in 2010, and continues to be a significant indoor air pollution problem in developing countries [34]. However, airborne particulate matter (specifically $PM_{2.5}$) still accounts for a large proportion of environmental burden of disease in Europe (68%), as well as in the United States [35, 36]. Given that the 20-100% concentrations of outdoor air pollutants are transferred indoors and that 90 % of EU citizens live in areas where the WHO guideline for air quality for $PM_{2.5}$ is not met, this is an important factor to consider in improving IAQ [27, 37]. Second-hand smoke also continues to be a significant factor contributing to burden of disease, accounting for 510 – 1200 DALYs per million in Western Europe and in United States [35, 36].

In its guide to burden of disease due to inadequate housing, WHO estimated percentage of asthma onset in children attributable to indoor mould in Europe was approximately 12.0 % and that attributable to dampness approximately 15.0 %. It was estimated that formaldehyde accounts for 0.30 % - 0.62 % wheezing in children and that up to 2.0 % of asthmatics are exposed to formaldehyde concentrations which could aggravate their response to allergens. In a subsequent ENVIE (Co-ordination action on Indoor Air Quality and Health Effects) report it was estimated that about half of all asthma and respiratory allergies are caused by indoor air exposures [27].

The most frequently encountered VOCs indoors are benzene, formaldehyde, naphthalene, toluene, and limonene [38]. Although disease burden attributable to VOCs is not very high, some of them, like benzene and formaldehyde, are known carcinogens, and their concentration should be kept as low as possible [35, 39]. The WHO sets the maximum acceptable concentration of formaldehyde at 100 μg m^{-3} (80 ppb) and several surveys in Central Europe and United States have concluded that the estimated concentrations in normal living conditions are below 40 ppb [40].

4.2 Contemporary challenges of IAQ improvement

The growing understanding of effects of human activities on environment, evidence of our limited energy supply, and the health effects of pollution have caused a shift towards energy efficient, sustainable, "green" practices in building design and construction [41]. Although studies examining the effects of energy saving measures and green building practices on indoor air quality have shown mixed results, there are several issues that call for attention [41, 42]. For example, cooling equipment efficiency may increase humidity, and building more air-tight dwellings and reducing ventilation rates may lead to increased concentrations of indoor contaminants [9]. In recent years, particular focus has been on compliance to standards of air tightness and ventilation rates. Some studies have come to the conclusion that adhering to the prescribed standards for air tightness, without proper ventilation strategies, could be detrimental to indoor air quality [43]. However, maintaining proper ventilation often inevitably leads to increased energy consumption, creating a dilemma [14].

The simulations made in Promoting actions for healthy indoor air (IAIAQ) project show that adequate ventilation can significantly reduce burden of disease, and available epidemiological data shows that there are minimum ventilation rates above which acute health outcomes can be avoided, but there is no sufficient evidence for universally applicable health-ventilation relationship [44]. Furthermore, simulations from HEALTHVENT project show that although setting a minimum air exchange rate of 0.5 h^{-1} is expected to reduce the indoor generated burden of disease by 21.0 %, this is not possible without adjusting the infiltration of ambient pollution indoors [28].

From 2010 – 2013 a framework for developing European health-based ventilation guidelines was created as a part of HEALTHVENT project, in order to determine the ventilation requirements and the best policies that will reduce the IAQ related burden of disease [37]. The project conducted several exposure control simulations: dilution with health-based optimum level ventilation scenario, filtration of intake scenario and source control and minimum ventilation scenario. While the results showed that largest health effects can be achieved in source control scenario, where the lower need for air dilution allows for lower rate of ventilation and consequently leads to lower ambient pollution infiltration, all three approaches simulated reductions in the health risks (20.0 % - 50.0 %).

Inconsistent relationship between ventilation rates and health outcomes, as well as recent findings from the HEALTHVENT project, show that IAQ/energy efficiency dilemma isn’t a simple matter of tradeoffs between air quality and energy savings. Furthermore, the results of the HEALTHVENT source control scenario indicate that more efforts should be directed towards implementing energy neutral and energy saving measures for IAQ improvement (improving building envelope design, contaminant source control, improved cleaning practices, heat recovery ventilation, more efficient particle filtration) [9].

5. CONCLUSIONS

Since modern people spend more than 90.0 % of their life indoors, it is important to consider IAQ during the planning and construction of the public buildings, and also private homes. Consideration of causes at the very beginning of construction works can notably increase IAQ and by that prevent a lot of IAQ related illness. Regarding the IAQ there is also a need to develop a validated and widely used measuring and diagnostic tools for IAQ and its medical management. As an interdisciplinary problem, it acquires a cooperation between many fields so it can be adequately resolved. Energy saving and sustainable building have become essential in modern building design, and it is important to elucidate its relationship with IAQ, to prevent problems such as dampness and insufficient ventilation. Modern green houses have shown mixed results regarding the IAQ, with some studies showing improvement, while others warning about poorer IAQ when certain energy saving requirements are met. Simulations carried out as a part of HEALTHVENT project may help in elucidation of this dilemma, suggesting that source control and minimal ventilation have the most potential for reducing the burden of disease related to indoor air quality.

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LIVING IN MULTI-FAMILY NZEB BUILDINGS – END-USERS' PERSPECTIVE ON CHALLENGES AND DOUBTS

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Abstract

The paper presents the findings on end-users' experiences and expectations about living in NZEB multi-family buildings. The analysis was done in four European countries (Slovenia, Italy, Denmark and Germany) as part of H2020 CoNZEBs project on cost reduction of NZEBs (2017-2019). A survey that covered end-users living or thinking about living in multi-family buildings was supported by housing organizations in the respective countries. Significant differences among apartment building sectors in countries were identified. Targeted end-users were living (as tenants or as owners) in either ordinary buildings or advanced, high-energy performance buildings such as NZEBs, that will become mandatory after 2020, according to EU legislation (Directive 2010/31/EU). In the investigation, the following topics were addressed: the level of end-user's understanding of the NZEB concept, the source of information on NZEB and the quality of the information from the end-users' perspective, the importance of various apartment features for the end-users, opinion on technologies that most significantly characterize NZEBs, and decision triggers for living in NZEB. Finally, also concerns, doubts and eventual fears about living in NZEBs and other high-energy efficient buildings were studied in order to provide a tailored information for future end-users and to increase the demand for NZEB and beyond NZEB buildings and improve their acceptability.

Keywords: NZEB, multi-family buildings, end-users, questionnaire, opinion

1. INTRODUCTION

According to EU legislation Directive 2010/31/EU [1] (EPBD recast) all new buildings will have to comply with national requirements for nearly zero energy buildings (NZEB); the rule shall be implemented after 31 December 2018 for new public buildings and after 31 December 2020 for all other new buildings. As per EPBD recast NZEB is a building with very high energy performance where the nearly zero or very low amount of energy required should be predominantly covered by renewable energy sources (RES) produced on-site or nearby. Setting the national NZEB definition and its integration into the national building codes is the obligation and responsibility of each EU member state (MS).

At the same time, EPBD recast required MSs to report on the comparison of the minimum energy performance (EP) requirements and those calculated on the basis of the cost optimal levels [2,3]. As current national NZEB definitions represent at the same time the targeted minimum EP requirements in 2020/2018 national building codes, NZEB definitions have also been considered in relation to cost-optimal levels of EP of today's buildings. In its Recommendations [4] EC stated that by the year 2020 technology costs are likely to be lower due to more mature markets and larger volumes of new NZEBs. Thus is the costs gap between NZEB and cost optimal level caused due to more complex technologies shall be reduced and it is expected that the NZEB levels will correspond to the cost-optimum for 2020.

Although European Commission (EC) did not provide any specific numeric guidelines on the expected reduction of primary energy (PE) in NZEBs in comparison to cost optimal levels, various documents [4] and studies [5,6,7] discuss recommendations for slightly lower PE in NZEBs than cost-optimal PE.

MSs prepared action plans for construction of early NZEBs before the full implementation of EC requirement on NZEBs after 2020/2018. In the transitional period, several technical concepts for construction of highly energy efficient buildings targeting the anticipated NZEBs performance levels were tested in practice [8]. According to the CoNZEBs project [9] NZEB like multi-family buildings built in various countries (Germany, Italy, Denmark and Slovenia) significantly differ in building's energy efficiency, in implemented technologies, in the share of RES used and above all in construction costs. Although the life cycle costs (LCC) of a NZEB building indicated the gap in costs between NZEB and regular buildings would become negligible after 2020/2018, the higher investment costs of NZEB remain a significant barrier for wider penetration of (early) NZEBs. In addition to that, early NZEBs are often associated with the lack of trust among end-users, due to complexity of systems and end-users' believes about various constraints regarding living in NZEBs. CoNZEBs project (2017-2019) aims at reduction of the above barriers by studying in detail the costs reduction opportunities and by addressing most common end-users' myths and fears about living in NZEBs.

The apartment buildings sectors in four countries involved in CoNZEBs project strongly differ as per the building tradition, and state of the art in buildings' energy performance, NZEB technical definition, the share of rental and users' owned flats, penetration of early NZEB, end-users experiences, confidence, attitude and readiness to live in NZEB. The research presented in this paper focused on the identification of end users' attitude to living in NZEBs and the comparison of the findings from different countries. Understanding the doubts and fears as well as benefits of the end-users living and planning to live in NZEBS will enable the development of focused information activities for better acceptance of NZEBs among (current and future) tenants and owners.

2. METHODOLOGY

To perform a survey of end-users' attitude to living in NZEBs, a questionnaire was developed aiming at current and potential future users of NZEBs. The goal of the questionnaire was to learn about the opinion of end-users in existing and future multi-family NZEBs regarding their expectation and experience with living in NZEBs, their potential doubts and fears, the used technologies, the quality of life in such buildings, the relative impact of NZEBs on the real-estate value.

The questionnaire had the list of common questions used in all participating countries and an additional set of specific questions adapted for each country (Germany, Italy, Denmark, Slovenia) so that they reflect the national situation of early NZEBs.

The common part addressed the following main questions:

- Do you know what an NZEB (Nearly Zero Energy Building) is?
- Where did you get the information about the NZEB (Nearly Zero Energy Buildings) and how good (useful, understandable) this information was for you?
- What is important for you as an apartment user?
- What do you think which technologies characterize most NZEBs?
- What would be/were your decision triggers for living in an NZEB?
- Age group of the interviewed end-user
- In which type of building do you currently live?
- Was your building recently energy renovated?
- Are you considering moving in a new apartment within the period of the next 5 years?
- Which type of renewable energy sources do you use?
- Do you have any other concerns/doubts regarding living in high energy efficient buildings?

English questionnaire was available via the project web site [10], while the partners used adapted version translated into the national languages. Participating countries also adapted the methodology of information collection, so that Denmark used the online survey tool, Germany, Slovenia and Italy combined direct mailing (regular mail, e-mails) with printed questionnaire distributed to interested end-users during meetings, Italy also applied the online survey by using Google Forms and some face-to-face interviews. The survey was implemented by housing organisations in CoNZEBs and elaborated along the common template by research partners.

The participation in the interviews for end-users was voluntary and the interview results were anonymised. Altogether, the interviews covered 293 end-users of which 112 are currently living in an NZEB and 181 are potential future users of NZEBs.

3. RESULTS

3.1 Germany

In Germany altogether 46 respondents completed the questionnaire. 36 of the respondents already live in an NZEB and the other 10 are potential future users of NZEBs. The questionnaire was distributed by ABG Frankfurt using different ways. First, they inserted the questionnaire as letters in the mailboxes of end-users of some of the ABG owned houses. Second, they displayed the questionnaire in an energy consulting center that is open to everybody. Third, they distributed it after some of their events for architects, (local) politicians and other interested people, who are of course also end-users of residential buildings. The survey results were elaborated by Fraunhofer IBP. People seem to be well informed about NZEBs. The location of the flat and the financial constraints of the end-user are still predominant factors in taking a decision for a flat or against it. However, in the survey also other triggers were identified (Fig. 1), such as financial aspects of housing including the energy costs, and triggers related to comfort (daylight, thermal comfort and indoor air quality). The indoor air quality, especially the dry air during winter is an ongoing point of concern, and it should be properly addressed as fast as possible in order to prevent negative associations with NZEBs. Concerning the maintenance costs, the potential future and the current NZEB users clearly differ in their opinion on the topic. While 53% of the current NZEB users think that the maintenance cost are lower in NZEBs, only 11% of the potential NZEB users support that opinion. Since low costs (rent, energy and maintenance costs) are still the most important decision parameters for the end-user, the costs reduction in NZEBs is an important way to increase their attractiveness and their share in the building stock, as it is required in the context of the German energy transition.

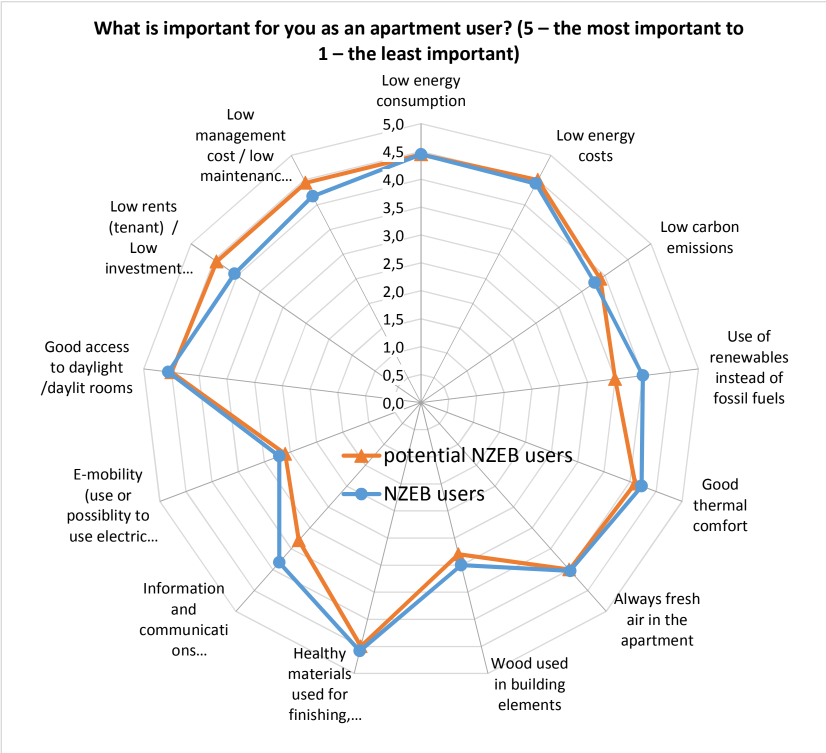

Figure 1: Importance of topics related to living in NZEBs for current and potential future NZEB users in Germany [10]

3.2 Denmark

The Danish questionnaire was partly modified, as it targeted primarily the residents in apartments of social housing companies and at the same time solely residents in NZEB multi-family houses (all together 19 respondents). The Danish survey was conducted in the Copenhagen area using the online survey tool 'Relationvice', supported by the communication department of Danish Social Housing (BL) and elaborated by Aalborg University and Kuben. Questionnaires were circulated to the social housing company Lejerbo Coenhagen/Bo-Vita.

In general, residents in Danish NZEBs are happy about living in a NZEB and would choose a NZEB again if they had to move to another apartment. The residents in Danish social housing care a lot about the environment and expressed concern about their energy consumption, although they neither have exact knowledge about technical requirements of NZEBs and nor they are familiar with declared energy features in this kind of buildings (Fig. 2). Mainly they connect NZEBs with the presence of solar PV panels that are visible from the street and with mechanical ventilation. The latter is an issue of concern, since it is visible in the flats and it is sometimes the source of noise and/or draughts in the flats.

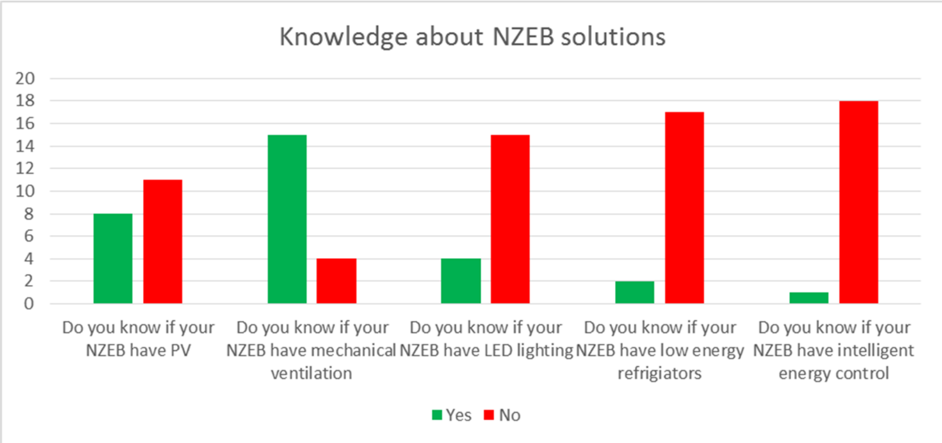

Figure 2: Knowledge about NZEB solutions among NZEB users in Denmark (N=19) [10]

2.3 Italy

In Italy 131 respondents completed the questionnaire, 50 of them currently live in an NZEB and the other 81 are non-NZEB users, i.e. potential future users of NZEBs. Questionnaires for non-NZEBs users were distributed either by email, by hand or by Google Forms.

They were mainly completed by people living in the Centre or South of Italy. Questionnaires for NZEB users were distributed and collected by ACER, moreover the interviews were conducted by ACER Reggio Emilia during condominium meetings and elaborated by ENEA.

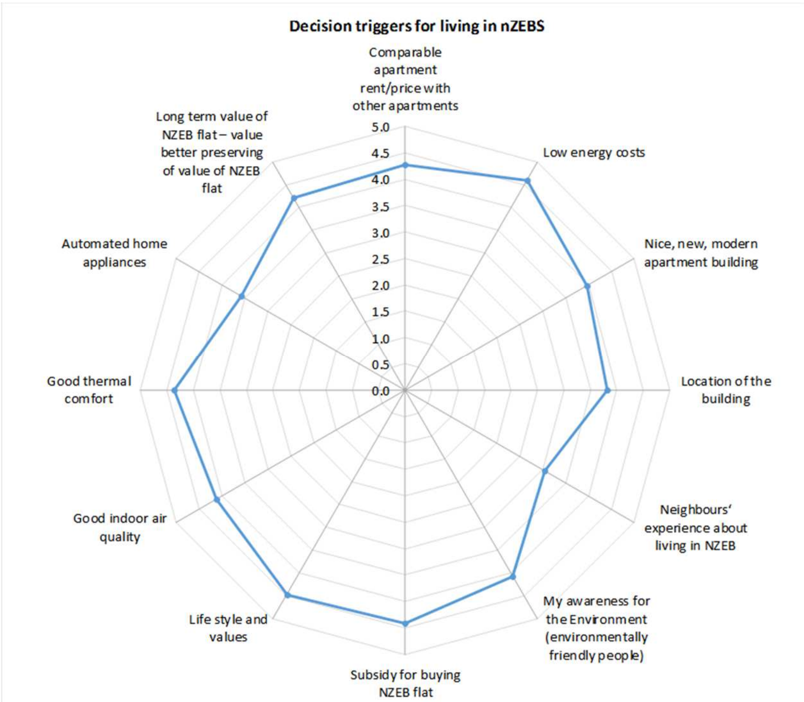

Figure 3: Importance of decission triggers for living in NZEBs (N=81, non NZEB users, Italy)

Respondents are aware of the meaning of an NZEB, although they do not have an easy-to-access source of info about NZEBs. The decision triggers for future NZEB users are compared in Fig. 3. All respondents highly value good thermal comfort, fresh air in the apartment and the use of healthy materials in buildings. However, potential NZEB users give more importance to low energy consumption, low energy costs, low carbon emissions and the use of renewable energy sources comparing to current NZEB users, which surprisingly consider more valuable the possibility of having good access to daylight, low rents and investment costs, respectively.

Regarding the maintenance costs, future NZEB users have more optimistic expectations, since 58 % of them believe that the maintenance costs might be lower in NZEBs, while only 28 % of current NZEBs users experience lower costs.

2.4 Slovenia

In Slovenia 90 potential and 7 current NZEBs users participated in the survey. Questionnaires for non NZEB users were disseminated at events joining the stakeholders in multi-family buildings and at DOM fair advisory stand. Housing fund of the Republic of Slovenia (SSRS) delivered questions by e-mails to current NZEB users in Ljubljana Brdo; GI ZRMK sent out e-mails to NZEB end-users of ECO Silver House [11] and analysed the survey. Respondents in Slovenia seem well informed about NZEBs. They highly appreciate low energy costs and low energy consumption (Fig. 4). They value good thermal comfort, fresh air in the apartments and good access to daylight. However, they exposed some concerns, especially regarding technical buildings systems in NZEBs and the reliability of their performance.

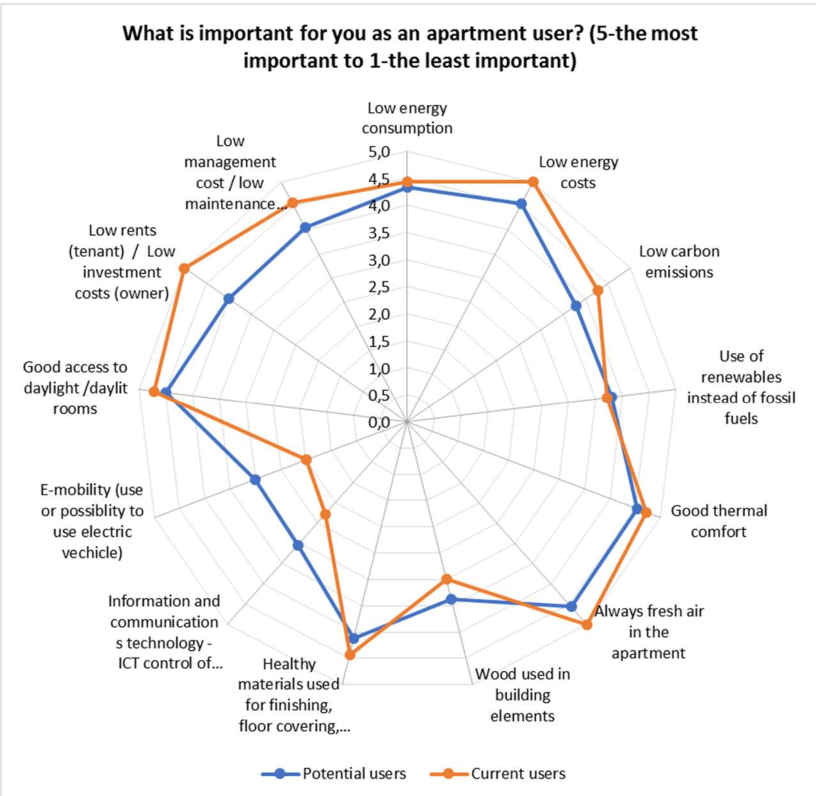

Figure 4: Importance of topics related to living in NZEBs for current and potential future NZEB users in Slovenia [10]

They do not appreciate too many electronic devices (automatization and control) within the apartment, as in their opinion this may worsen living conditions in NZEBs and at the end actually increase investment and maintenance costs. Also, mechanical ventilation and its performance during the summer season was one of the common constraints. Regarding the maintenance costs current and potential users have notable differences in their opinion, 32 % of potential users believe that they would have higher maintenance costs in NZEBs, while none of the current NZEB users experienced higher maintenance costs.

3. DISCUSSION AND CONCLUSION

The common findings based on the survey of end-users opinion on NZEBs in CoNZEBs project countries (Germany, Denmark, Italy, Slovenia) indicate that the costs reduction and comfort related benefits of living in NZEBs (i.e. low energy costs, low energy consumption, good thermal comfort) are the most important for both groups of respondents, i.e. for current and potential future users of NZEBs. Significant is the perception of technologies that characterize NZEBs as explained by potential NZEB users in various countries (Fig. 5). In Italy solar collectors, PV panels, use of RES, smart technologies, A++ appliances with LED lighting are of utmost significance if building is to meet NZEB level, while in Germany NZEB is associated mostly with triple glazing, good thermal insulation, envelope airtightness and mechanical ventilation. Understanding end-users shall enable further deployment of NZEBs.

An important part of the survey addressed respondents' concerns and doubts about living in NZEBs. Common finding on end-users opinion for participating countries are:

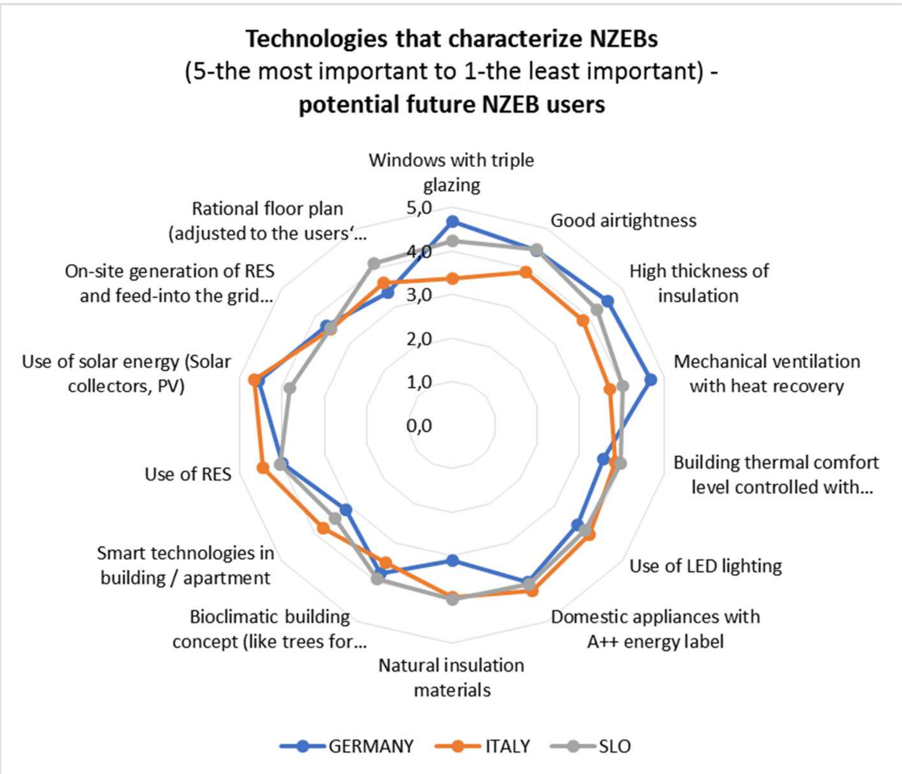

Figure 5: Opinion on which technologies characterize most NZEBs – potential future NZEB users (Germany, Italy, Slovenia) [10]

Positive experiences about living in NZEBs: good sound insulation, silence in rooms when the windows are closed, less grid electricity needed due to the self-supply with PV panels, good quality of energy efficient components, good indoor climate, high quality of life in NZEB, very good thermal comfort and low energy consumption, raised awareness about energy efficient living, transparent and controllable personal energy consumption through user's display.

Negative experiences: humidity is too low in winter and in summer, it is too warm, very dry indoor air and the increase of respiratory infections, very common failures of technical equipment, frequent change of air filters is needed, ventilation system in use when the outside temperature is very low, increase of investment and maintenance costs due to ICT equipment not important for regular use, problems with mechanical ventilation at lower outside temperatures.

Concerns: use of NZEB in case of power outage or if supply of electricity from PV failed, possible feeling of distress and discomfort, high construction/renting costs, concerns about the quality of living indoors in NZEBs, smart systems cannot operate in case of a power outage, restrains about the building envelope performance and mechanical ventilation, EM radiation due to many smart devices, too many devices may be burdensome for an average user

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POSSIBILITIES OF USING BIM FOR DEEP ENERGY RENOVATION ANALYSES

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Abstract

With unsustainable greenhouse gas emission and irrational energy consumption, building sector have big impact on environment pollution and climate change. In order to reduce the building sector impact, the majority of current buildings need to be renovated and new buildings built as Nearly Zero-Energy Buildings (NZEB). Since for building renovation and new NZEB, together with integrated design, management of relevant information is crucial, the use of Building Information Modelling (BIM) becomes evident. BIM is a concept which promotes integrated design process in a way that connects all key stakeholders by collaborating on the same information model. In order to assess energy demands of renovated building and therefore perform an optimization process, BIM must be transformed in Building Energy Model (BEM). Today, BIM-to-BEM Information Process (BBIP) is still not fully developed which results with some information being lost during BBIP. Those lost information must be re-entered to create correct BEM. This paper proposes a procedure for tackling this BBIP information loss. This procedure is summarized in the workflow steps needed to acquire correct information about the building as an input for optimization of envelope design in deep energy renovations and exploitation of the building during its lifecycle by using BIM tools and processes. Moreover, to increase the use of BIM for energy efficiency purposes, competences of all building stakeholders must be enhanced.

Keywords: BIM, Deep Energy Renovation, Building Performance Simulation, Envelope Design, Net-UBIEP, BIMzeED

1. INTRODUCTION

Contribution of building sector in the energy consumption and greenhouse gases emission is unsustainably large. Energy consumption in the building sector mostly manifests through energy demands for heating and cooling, so the influence of the building envelope cannot be underestimated [1]. Therefore, European Union made political decision (with Directive 2010/31/EU) to increase the number of Nearly Zero-Energy Buildings (NZEB), but society in general should also recognize the impact of each and every individua as well. As large portion of current building stock do not have the NZEB performance (especially residential buildings), extensive retrofit of those energy poor-performing buildings should be carried out in order to meet the performance goals set by EU 2020, 2030 and 2050 targets. Additionally, new NZEBs must be built from 2021. Those NZEB buildings, due to their complexity need to be designed following the integrated design principles, i.e. all engineering professionals should be involved from the start, all in order to achieve cost optimality. Building Information Modelling (BIM) is a solution to gather all the engineering professionals and architects to develop a project altogether by working on the same building model which contains the relevant information (integrated design approach). BIM is changing design process according to the MacLeamy Curve introduced in [2] and shown in Figure 1 (curve marked with *4 – preferred design process* is integrated process design), so it is considered to be a good tool for designing the NZEB because more time and effort is invested upfront in the early design phases and therefore a better solution could be provided, i.e. cost optimal solution of the NZEB. Not only more variant solutions could be examined but also they could all be checked by preliminary energy simulation as BIM model can be, reasonably quickly, transformed into the Building Energy Model (BEM).

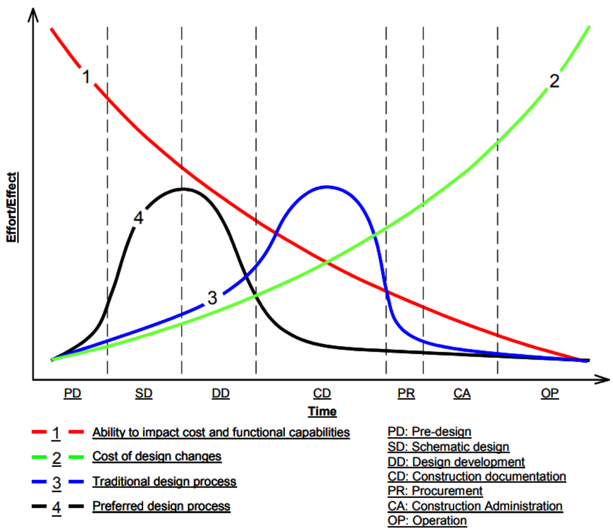

Figure 1: MacLeamy Curve [2]. Curve 4 (preferred design process) describes BIM design process.

Many BIM software have add-ins for creating BEM, and energy simulation can be carried out in the same BIM interface, but since they are often not in line with national standards or calculation algorithms and lack the possibility of defining all the necessary inputs, those simulations could be performed just for variant checking. This variant analysis in early design (schematic) phase can significantly contribute to cost savings and functional capabilities. It is very important to create as-built model to ensure that all the correct information are collated in BIM model, which can then be prepared not only for possible future retrofit designing process but also for storing all the information about the building for future processes as well (refurbishment, maintenance, facility management, demolition…). BIM as-built model is prerequisite for creating more reliable BEM from trustworthy input data. More reliable simulations are needed to ensure compliance of the NZEB with regulatory requirements as well as to develop building mock-up model which reflects the real building. Reliable simulations could then be used for a whole range of applications intended to manage the energy consumption in buildings. Accurate geometry of the BIM as-built model could be achieved through the inspection strategies as described in [3] or with laser scanning through the importing point-cloud into BIM [4] and by comparing model created by 2D drawing inputs with one of proposed methods. In order to create more reliable BEM, it is important to accurately determine the hygrothermal properties of building elements and building in general. Destructive and/or nondestructive methods could be used to determine the thermal properties of building elements, i.e. thermal transmittance. It might be trivial to say that accurate input data will result with more reliable energy simulation, but regarding the energy consumption simulation to collate and manage this different data which is influencing the simulation results. When reliable as-built BIM and BEM are created and tested, design phase could proceed. To ensure the optimal energy balance, optimization of the building envelope and technical systems (HVAC, MVHR, RES) should be carried out in the design phase and it could be performed in BIM software because of quick transition between BIM and BEM so every variant could be checked in a reasonably short time. After the optimal global solution check it is important to perform detail solution check, i.e. including Thermal Bridges (TB) in energy simulation, and other detail design solutions by all professions involved. Impact of TB can be included by comparing numerical models of TB details (multidimensional heat flow equation) with 1D heat flow which can be included in energy simulation by adding exact thermal properties on TB area to copy heat flow of multidimensional model. A helpful method for determine TB when construction is finished is through the Infrared Thermography (IRT) [6-8] and numerical simulations which could then combined help to determine real linear (or point) thermal transmittance.

There is one more important property of the building envelope to be included in the energy simulations – it is airtightness, which could be predicted or measured [8]. For optimization process, predicted value should be used as construction phase has not started yet, while for final energy simulation (and BIM as-built model), measured value should be used in order to get BEM as close as possible to the real building consumption.

This paper is divided into three parts, except section 1 (Introduction). Section 2 shows recent research review papers concerning BIM – BEM connection and BIM usage for renovation and retrofit design. Section 3 describes model for BIM usage in deep energy renovation and BIM as input for required energy simulations. Last section represents some guidelines for the model testing and provides general conclusion of this research.

2. REVIEW OF CURRENT RESEARCH

Analyzed papers are literature and case study reviews from which a general conclusions are presented in order to explore possibility of proposed model's (section 3) feasibility. For BIM based energy simulation, information transfer between BIM software and energy simulation software is crucial. Gao, Koch and Wo [9] made studious research in the connection between BIM and BEM models as they named it BIM-based-BEM. That connection is in view of the information transfer between BIM modeling software and energy simulation software. They described information transfer through Industry Foundation Classes (IFC) and green building XML (gbXML). In this paper information transfer is examined and divided in 6 steps: geometry (step 1), material (step 2), space type (step 3), thermal zone (step 4), space load (step 5) and HVAC (step 6). With exploring transfer between large cup of software (BIM to energy simulation BEM) they concluded that the IFC schema transfer is at step 1 as only geometry characteristics can be transferred correctly and the gbXML schema is at step 3 as, apart from geometry information, material properties and space type can be transferred too. The same group of authors [9] conclude that correct information transfer is not user friendly as there are many steps between BIM and BEM. On the other hand it can be concluded that even if there is no BIM to BEM connection at all, BIM should be used for the building renovation design as Sanhudo et al. [10] found BIM's finest benefit is in storing and organizing data. They see BIM as a connection between data acquisition and data management as shown in Figure 2. Sanhudo et al. [10] have analyzed BIM-to-BEM connection and, like in [9], they found information loss to be the main problem in BIM-to-BEM workflow, which means a lot of stored information must be re-entered to BEM.

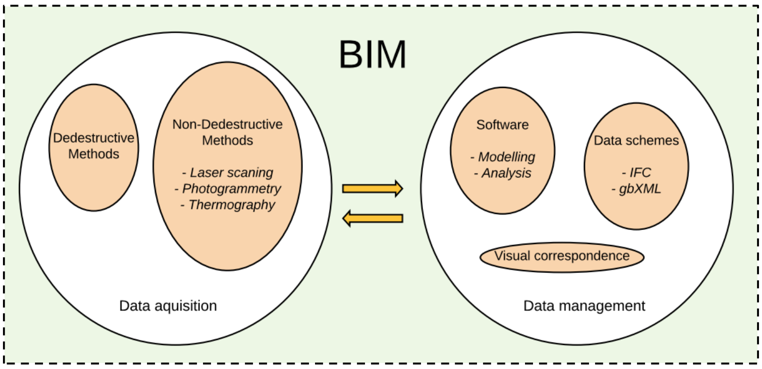

Figure 2: As-built BIM methodologies for retrofitting. [10]

Kamal and Memari [11] also analyzed the connection between BIM and BEM and the process of information exchange between them which they called BIM-to-BEM interoperability process (BBIP). Similar as in [10], they found the main contribution of BIM in energy modeling as the "*ease of handling data, which can lead to automation in energy modeling, better presentation of output, capability of storing and organizing new building data especially the real-time information to have an up-to-date energy model, and enhancing existing libraries by adding new attributes to the normal energy simulation process*." [11]. As main problems, they see the lack of standards and the lack of easy solutions which is, probably, the main reason why energy simulations are not performed more often in BIM tools. On the other hand, Habibi [12] sees lack of reliable data sources as one of the biggest barrier to retrofit and renovation design so he concludes that it is important to consider integrated steps which could be also managed using BIM. BIM can be a key factor to optimize energy consumption in the existing buildings by providing a good input for a deep energy renovation in view of stored and organized building information database, i.e. as-built BIM. Energy simulation is playing a significant role in decision making where in design phase, especially in the early design phases where, with optimization methods, large energy savings could be achieved [12]. Habibi [12] also reports that in order to ensure reliable BEM for energy simulation, lost information in BIM-to-BEM information transfer must be re-entered manually from BIM.

Several conclusions could be drawn from the analyzed research papers. Firstly, the BIM and BEM information transfer is not yet fully developed, but as concerning geometry, material properties and space type information transfer (gbXML) the connection could be realized. Some data should be re-entered, and other needed data should be added (e.g. climate data). Even if there is no connection between BIM and BEM, BIM is useful for managing the building information data and for controlling quantities needed in energy simulations.

3. PROPOSED MODEL

Taking into account existing BIM to BEM issues identified from the literature review and experience in BIM and BEM modelling, a procedure for deep energy renovation using BIM is proposed in this paper. The Model consists of three phases: input phase, design phase and output phase; and they are focused only on building envelope. Figure 3 shows flow chart of all required steps in each defined phase.

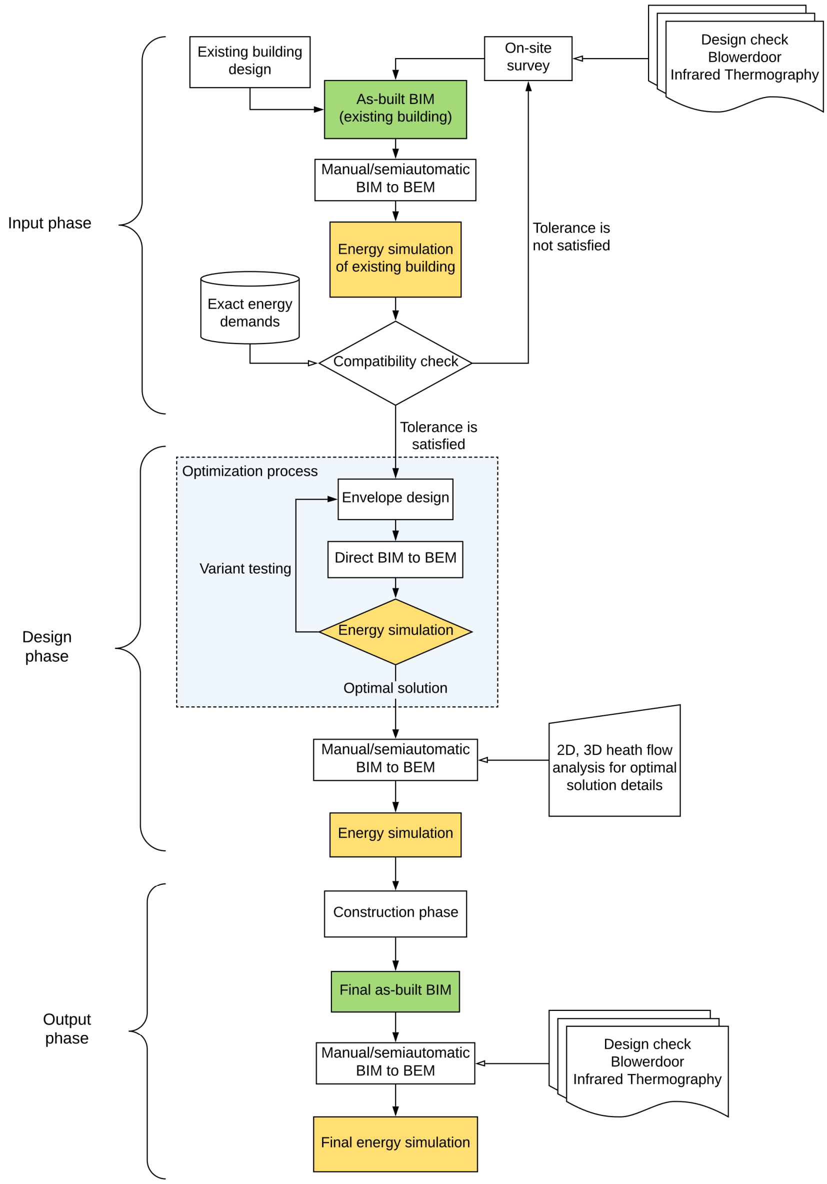

Figure 3: Proposed procedure for deep energy renovation using BIM.

Each phase is equally important and should not be left out. In the start of the project, as-built BIM model needs to be created regarding existing building design and on-site survey. As the goal is to perform a reliable energy simulation, thermal properties of building elements should be explored during the on-site survey using nondestructive or destructive methods, e.g. heat flux measurements (U-value), IRT for TB exploration and BlowerDoor (BD) for airtightness of existing envelope, etc. It is very important to create correct as-built BIM as possible, because energy model (which is input to renovation design) needs to have as close energy consumption as real building in order to be used in future energy related analyses. After as-built BIM is created it has to be transformed into BEM. BEM is created combining information which could be transferred through gbXML or IFC schema with re-entering lost information in BBIP, this step is called Manual/semiautomatic BIM to BEM. After energy simulation is performed, the results should be compared to real energy consumption of the building. If satisfied with the results, input phase is completed, if not, differences of the BEM and real building must be explored.

Finishing input phase, correct as-built BIM and BEM are created which means reliable input for the design phase is provided. BIM design software (e.g. Revit, ArchiCAD, Allplan) often have solutions for preliminary energy modelling in the same BIM environment. Lacking some harmonization with specific country legislation, standards and input data for energy simulation and building performance analyses, these solutions should be viewed only as a general assessment and could be used during the optimization process of envelope and building systems design. Loses through building envelope is one of three main factors which influence energy demands. Other two are building systems and schedule of building usage which would not be explored for optimization in this model, but analogous principles can be applied. With described solutions for direct BIM to BEM in BIM environments, variant checking is quickly done, and optimal solution should be chosen for further steps of the design phase. Numerically modeled TBs are another manual/semiautomatic BIM to BEM which needs to be performed. Thus, after general optimization process is finished, detail numerical analyses is to be carried out (i.e. 2D/3D heat flow (TB) analysis for details of chosen optimal solution). This would result with more reliable design phase energy simulation while on the other hand would save resources of numerous and tedious analyses of all possible variations. Output of this step is BIM of planed deep energy renovation design with BEM including TB analysis.

The final phase is called an output phase because the final as-built BIM is created after construction process has finished and handed over to be exploited during the building's life cycle and end of life stage. Since BIM model of a building should be used through all the building's lifecycles – from early planning and designing stages [13, 14] through facility management and (possible) renovations to deconstruction [15, 16], in the output phase, final energy simulation must be carried out after as-built BIM is finished, so that investor and users have a reliable information on building's energy performance. Therefore, as an input in the final energy simulation there should be as-built BIM containing information from the tests performed and on-site survey of the newly constructed building. Those information (TB and airtightness) must be determined with IRT and BD test and included in energy simulation through Manual/semiautomatic BIM to BEM.

The proposed procedure was checked on the case study on deep energy renovation design of an abandoned exhibition hall building into a NZEB museum. Input and design phases with all their parts were completely tested while the output phase is to be tested after the building renovation is completed. Input phase with as-built BIM shown in Figure 4 is created from design drawings and on-site checking while BD and IRT testing was not performed since the whole building envelope was in a condition which requires complete replacement (Figure 4: a - c) and both tests would thus be futile. While in design phase, variations of roof, curtain wall and shading were examined, and optimal solution was chosen with demand to fulfill Croatian NZEB standards. In this case study, structural stability and load bearing capacity check were also explored using SAP2000 and as-built BIM as an input (Figure 4: d). The result was that current building does not satisfy the Eurocode 1998 requirements, i.e. building is weak under the action of horizontal forces. This resulted with strengthening the building's structure together with the energy renovation.

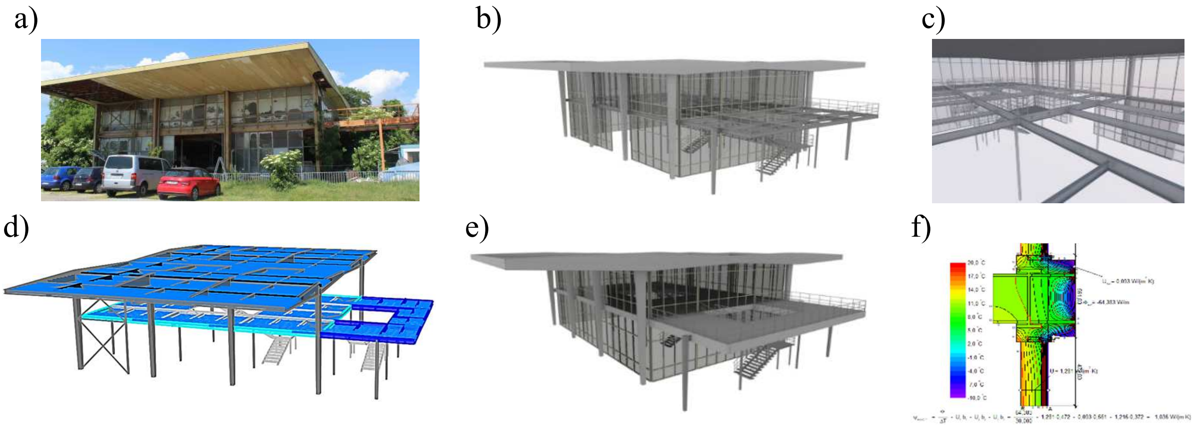

Figure 4: Deep renovation project for model testing [17]. a) Analyzed building, b) as-built BIM input - exterior, c) as-built BIM input - interior, d) numerical model for structural bearing analysis, e) BIM of renovation design and f) numerical thermal bridge analysis.

4. CONCLUSION AND FURTHER RESEARCH

This paper describes the procedure of BIM usage for deep energy renovation projects (concerning optimal envelope design). It describes phases and steps for providing more accurate as-built BIM and BEM through three predefined phases. The model should be used to enhance the BIM use for fulfilment of ever-increasing building performance demands. Proposed steps of described phases are logically deduced from the authors' experience with energy renovation and BIM. Further research is needed on direct BIM to BEM connection which should be explored by comparing it with widely accepted building performance simulations to approve its usability. Described possibility of including impact of numerically determined TB in energy simulations is plausible, but to better exploit advantages of BIM should be fully automated. Airtightness can be included in BEM as the number of air changes per hour for pressure difference of 50 Pa between interior and exterior environment (n_{50}). The n_{50} is the output of BD test and should be included in energy simulations because of its impact on the energy balance. The proposed process can be analogously used not only for building envelope aspects of the energy performance simulation but also for technical systems design and performance, including HVAC, MVHR, RES, automation. In other words, analogous process using BIM can ensure integrated design approach in building's deep energy renovation resulting with the solution which will be cost optimal during the building's lifecycle. In order to increase the use of BIM for energy efficiency purposes, BIM competences of all professionals must be enhanced. EU projects Net-UBIEP and BIMzeED are working on developing training programs and training materials to tackle this issue.

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BIM-BASED WORKFLOWS FOR BUILDING ENERGY MODELLING – A VARIANT STUDY

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Abstract

The AEC (Architecture, Engineering & Construction) industry counts to the most wasteful ones, thereby urgently needing improvement for achievement of sustainable built environment. Early design stages, where project is conceptualized, are of great importance for the future energy performance of buildings. Tools such as the Energy Performance Certificate (EPC) - a rating scheme to express the energy efficiency of a building during operation - are used for the rating of building performance. Building Information Modelling (BIM - as emerging digital design tool) coupled to EPC has the potential to serve as an early decision-making tool for building performance optimization. However, the interoperability of the software tools is still a challenging task, causing problems with data exchange, thus resulting in information losses.

This paper presents a comparative study of different BIM to EPC workflow-variants, generated by applying three different BIM tools (ArchiCad, Revit and Allplan) for the same case study; thereby comparing the variation of the obtained EPC (ArchiPhysik) results. The process design, interoperability and the validation of the EPC results of the three variants were evaluated. Varying requirements regarding the Level of Detail between the BIM and the Building Energy Modelling (BEM) and the discrepancies in the EPC results were identified as main problems. Finally, through comparison of the various exchange combinations and identification of the potentials and deficits, suggestions for improving BIM-based workflows for energy modelling are proposed.

Keywords: Building information modelling (BIM), Building Energy modelling (BEM), Energy performance certificate (EPC), Interoperability, Design process

1. INTRODUCTION

The building sector is one of the biggest contributors to global environmental influences and consumes up to 40% of all raw materials extracted from the lithosphere. Furthermore, it is responsible for about 50% of global greenhouse gas emissions [1]. The early planning phase is crucial for defining important sustainable variables, relevant throughout a building´s lifecycle;

these variables can minimize the environmental impact of construction projects [2]. BIM can contribute to a more consistent decision-making process and can therefore serve as a support for sustainable assessment of building projects in early phases [3]. The BIM model itself serves as a joint knowledge database and offers the possibility of data transfer between multiple models [4]. BIM has been recognized as a useful tool for collaboration of professionals to manage complex communication and information processes, thus in practice, there are still difficulties with the implementation and actual performance. [5] Energy simulation programs used in the early design stage can assist the decision-making tools, progression of optimization methods, calculating and indicate the building energy performance [6]. The EPC certificate provides reliable information about the building's energy performance. It gives information about the heating and end energy demand, CO_2 emissions or the energy performance factor [7]. "…architectural design tools have poor connections to thermal and environmental analysis software, which is exacerbated by a lack of knowledge of the data requirements of other disciplines both upstream, and downstream [8]." In order to import, export, adapt or modify information with BIM, a continuous cooperation between all project participants over the entire lifecycle is necessary. In practice, the planning process participants working with BIM and BEM still need to manual re-enter numerous data, make additions and set new parameters in the energy performance tools in addition to the input data obtained from BIM.

The main aim of this study is examining three BIM-based workflows for energy modelling within one case study. It investigates the quality of data exchange between the discipline models (the 3D-Models with the EPC tool) within a Variant Study. It identifies the problems of the BIM to BEM design process and validates the EPC results. The focus is on the modelling process and the interoperability between the BIM models and the EPC tool and provides an assessment for the integration of energy efficiency aspects into the overall BIM workflow.

2. LITERATURE REVIEW

Interoperability has been identified as a challenging task due to the multiple heterogeneous applications and systems applied by diverse planning process participants. In practice, the vision of a seamless global interoperability has not turned into reality yet [9]. Gourlis and Kovacic [4] state that the most common information exchange format from BIM to BEM is the open non-proprietary interface IFC (Industry Foundation Class), developed and supported by buildingSMART [10] and the gbXML (green building extensible markup language) [11] data format. Arayici et al. [12] developed an interoperability specification for an effective and efficient data and process integration in BIM-practice for collaboration and information exchange for performance based design.

Currently the most common way of sustainable planning in practice is modelling the building with traditional CAD (computer-aided design) tools first and entering the design data into an energy simulation tool to analyze the performance afterwards. Salguerio and Ferries [13] pointed out that there are still limitations in the interoperability capabilities, which make iterative interventions of the designer inevitable. The problem is that although BIM has the capability to allow designers to compare project variants and generate important quantitative data volumes, there is still no interface or software to organize and classify this data for enabling an easy multiple criteria assessment. Beazley et al. [8] claim that the main problem is the integration of different tools, the multiple data entry and the data flow between BIM models and energy analysis tools. Pinheiro et al. [14] claim that preparing BEPS (Building Energy

Performance Simulation) models require multiple manual operations and this fact is connected with data fragmentation and poor quality of data.

Literature review has identified numerous problems with BIM to BEM workflows such as data exchange and iterative manual design process loops. This paper is addressing these issues and identifies within a Variant Study remaining bottlenecks in BIM-based workflows for EPC.

3. VARIANT STUDY

In order to evaluate the potentials of BIM for EPC, a comparative study was carried out. Based upon a design brief of a real industrial facility (dwg. and pdf. files), BIM Models of the same production hall were created. The building is located in Völs in Tyrol, Austria. The building envelope characteristics are displayed in Table 1 and the facility's basic data such as gross floor area, volume and the energy supply in Table 2.

Table 1: Construction and u-values of the building envelope

Roof	Facade and walls	Bottom Plate
30 mm OSB plate (650 kg/m³) 260mm timber (475kg/m³) with 260mm mineral wool insulation 15 mm OSB plate 30 mm plasterboard **U-value: 0,170 W/m²K**	*Post and beam facade* **U-value: 1,30 W/m²K** *Outer wall massive* 60 mm aluminum sheet 200 mm thermal insulation 200mm reinforced concrete wall **U-value: 0,187 W/m²K** *Outer wall lightweight* 60 mm aluminum sheet 20 mm OSB plate 260 mm timber(475kg/m³) 260 mm thermal insulation 20 mm OSB plate **U-value: 0,171 W/m²K**	200 mm XPS 300mm reinforced concrete 60 mm cement composite screed **U-value: 0,186 W/m²K**

Table 2: Basic data and energy characteristics of the production hall

Climate	-1,4°C – 18,6°C (outside); 17°C – 20°C (inside)
Gross floor area	10.023 m²
Volume	120.648 m³
Energy supply	District heating
Electricity supply	Electricity mix Austria 85%, 15% photovoltaics
Window ventilation	1,5 1/h (with night ventilation)
HVAC (heating, ventilation, and air conditioning)	No mechanical ventilation; no cooling

The EPC calculations were generated using ArchiPhysik, a statistical analysis software for building physics and energy performance assessment, authorized by the Austrian regulative.

The tool is linked to baubook [15], a building material eco-data repository, including data on thermal conductivity, density and specific heat capacity of construction layers, which is directly available as default data. It does not offer IFC import/export. The software provides two proprietary interfaces; for ArchiCad, an architectural BIM CAD software by Graphisoft and for SketchUp, a 3D modelling software by Trimble.

For the comparative Variant Study four Variants of the same case study were generated: A Referential Variant – EPC only; Variant A – ArchiCad to EPC; Variant B – Revit to EPC, Variant C – Allplan to EPC.

For the referential variant, a reference EPC was created manually with ArchiPhysik; based on the dwg. and pdf. files provided by the design brief of the industrial facility.

The BIM Model for Variant A was created with ArchiCad based on the provided documentation. For data exchange the ArchiCad - ArchiPhysik Add-On was applied.

To obtain the model for Variant B, the architectural ArchiCad Model was imported via IFC into Autodesk Revit. Some further re-modelling steps regarding geometry adaption were necessary to obtain the architectural model in Revit. As Revit lacks interface to ArchiPhysik, the model was transferred via IFC into SketchUp and for the EPC the SketchUp-ArchiPhysik Add-On was used.

Variant C was created based on the provided documentation with Allplan, a Nemetschek software. The geometry data was exported via Excel and transferred manually into ArchiPhysik, as there is neither available interlink to Allplan nor an IFC. Interface.

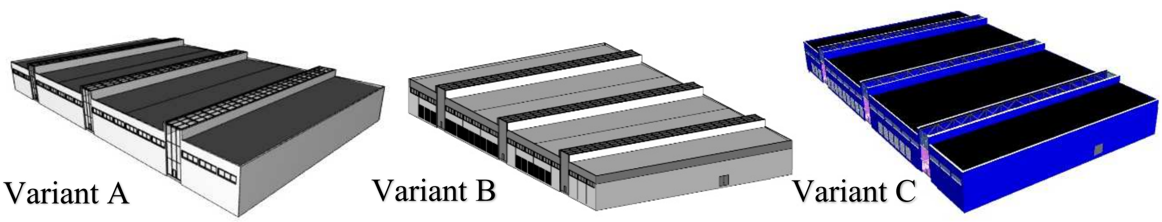

Figure 1: BIM models: Variant A in ArchiCAD; Variant B in Revit; Variant C in Allplan

4 RESULTS

4.1 Workflows

The comparative analysis of the Referential Variant and Variant A workflows are displayed in Figure 2. Based on the original planning documentation the data entry for the EPC was carried out manually in the Referential Variant. In the Variant A, the software used in the modelling process included on the BIM side ArchiCad for architecture and ArchiPhysik via the ArchiCad Add-On for BEM. However, to transfer the BIM model to the energy calculation software without receiving error messages, it was necessary to re-model the architectural model to a more simplified model (BEM Model) regarding geometry and setting specific layer combinations. With the Add-On and the simplified BIM Model, it was possible to transfer geometry, construction and the building envelope to ArchiPhysik. In ArchiPhysik, it was necessary to apply the project data, the construction and component list and the facility properties for HVAC manually to create the EPC. The Add-On recognized constructions consisting of several drawing elements as a common structure from ArchiCad and grouped them accordingly in the ArchiPhysik component list to assign the material properties such as thermal conductivity, density and specific heat capacity. An error occurred by importing the post and beam façade. It was imported from ArchiCad as a wall and had to be changed to a window in ArchiPhysik. Further manual corrections were the change or delete of room stamps (gross floor area and volume adaption).

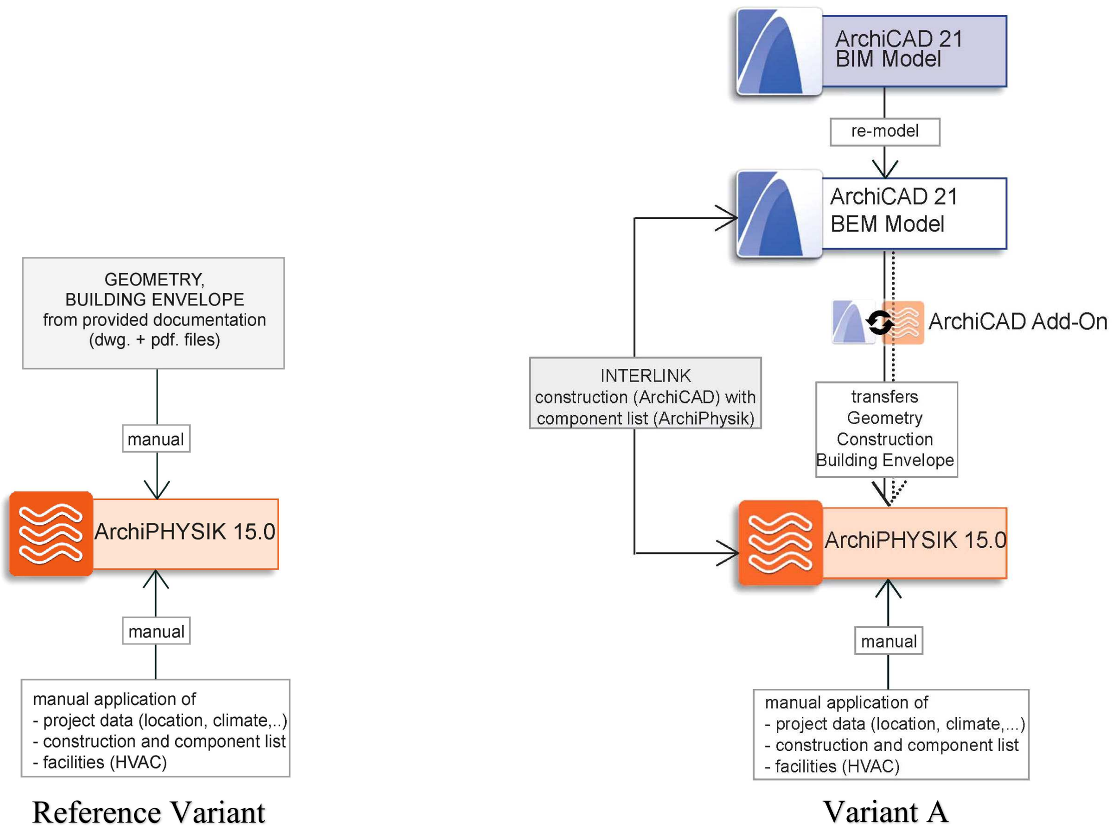

Figure 2: Workflows with software constellations – Reference Variant and Variant A

The workflows with software constellations in the modelling process for Variant B and C are displayed in Figure 3. In the Variant B the ArchiCad BIM Model was transferred via IFC to Revit, with additional geometry re-modelling necessary. The Revit BIM Model was converted via IFC in SketchUp. By making use of the SketchUp Add-On the geometry of the building could be imported to ArchiPhysik. As SketchUp is not a BIM software, only the geometry could be transferred. As in Variant A, the project data, component lists and HVAC properties had to be applied manually in ArchiPhysik. The geometry from SketchUp was interlinked with the component list in ArchiPhysik and the building envelope was defined. Manual Corrections in ArchiPhysik were required as the change or delete of room stamps (gross floor area and volume adaption) and the change or reproduction of the building envelope. For Variant C the BIM Model was created with Allplan and the geometry and building envelope data was exported into Excel. As ArchiPhysik offers no IFC. interface, the EPC in Variant C was carried out by applying the data manually in ArchiPhysik.

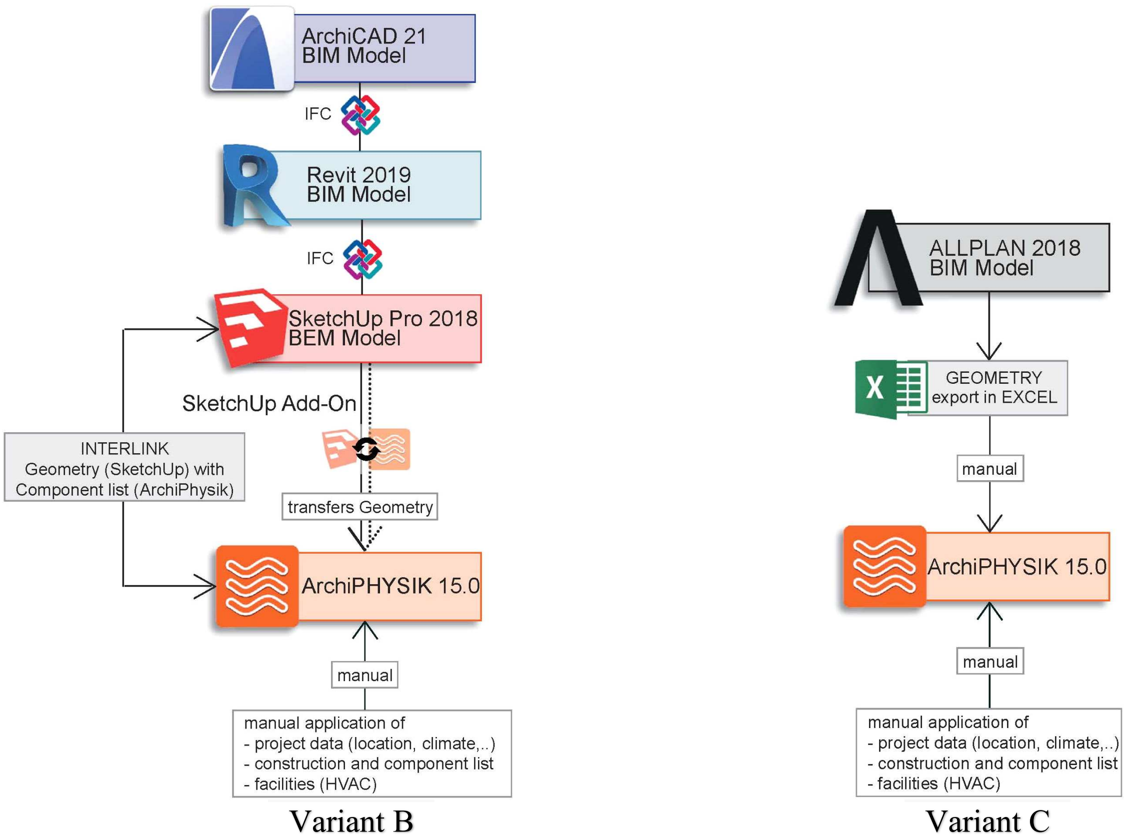

Figure 3: Workflows with software constellations – Variant B and Variant C

4.2 Validation

The results of the quantities such as gross floor area and volume obtained from the three different Variants based on three different BIM Models are presented in Table 3 and validated by comparison to the Reference Variant.

Variant A shows a negligible deviation of the gross floor area and volume and Variant B and C both differ by 0,29% from the Reference Variant. The heating and final energy demand results of the EPC differ by 12%. Variant A has a 6% higher and Variant B a 6% lower heating demand than the Reference Variant. The ArchiCad and Revit Model display a difference of 12,38% for the heating demand. Variant C's heating demand is around 3% lower than the Reference. The final energy demand ranges from +1,95% in Variant A to -1,59% for Variant B (total difference 3,5%). The final energy demand of Variant C is 0,9% lower than the referential values.

Table 3: Geometry outcomes and EPC results

	REFERENCE	VARIANT A	VARIANT B	VARIANT C
Gross floor area (m^2)	**10.023** 100%	10.019 -0,045%	10.052 +0,29%	10.052 +0,29%
Volume (m^3)	**120.648** 100%	117.547 -2,57%	121.879 +1,02%	119.213 -1,19%
Heating energy demand (HED) (kWh/m²a)	**44,01** 100%	46,66 +6,02%	41,21 -6,36%	42,64 -3,11%
End energy demand (EED) (kWh/m²a)	**194,67** 100%	198,46 +1,95%	191,57 -1,59%	192,92 -0,90%

5. DISCUSSION AND CONCLUSION

A comparative study of three different BIM-based workflows for energy modelling investigated the modelling process, the interoperability and the EPC results.

Thereby, following observations of the **modelling process and interoperability** were captured: The BIM Models were created for architectural purposes. Thereby, the modelling did not consider specific modelling requirements of energy analyzing software; resulting in displaying too many room stamps, geometrical errors and requiring re-modelling efforts on the building physics side. In Variant A, despite the fact that the BIM model required re-modelling to a simplified BEM Model, the inconsistencies were kept to a minimum level as ArchiCad has a direct Add-On to ArchiPhysik. Variant B in Revit made use of the SketchUp Add-On; which imports only geometry to ArchiPhysik, therefore requiring revisions of gross floor area and volume. As Variant C does not have an interface with ArchiPhysik, problems with data transfer did not occur, but the workflow resulted in more manual, time affording work, making the process error-prone. Although all BIM models would have contained very detailed construction and HVAC information, these had to be applied manually in ArchiPhysik.

Regarding the **validation of the EPC results**, following discrepancies were identified: Variant A displays a HED of 46,66 kWh/m²a and Variant B 41,21 kWh/m²a; the difference of 12% results from the varying gross floor area and Volume data from the BIM model.

This test implies that BIM for EPC calculation is possible with a semi-automated workflow but still requires re-modelling and adaption, which can be time consuming, disruptive and error-prone. In AEC practice, many different stakeholders with different mindsets are involved in a building project, using a heterogeneous software landscape. This leads to problems in data exchange and information losses. Even though in this study the BIM and BEM modelling was carried out by “one hand”, problems in the design process and discrepancies in the results occurred. The architectural model is very detailed and has a large number of room stamps and product information, whereas the energy model needs simplified information. Due to the oversimplification of the BIM models to BEM, they are not for architectural purposes anymore.

The comparative study identified the advantages of semi-automated BIM-based workflows for EPC calculations as time saving in order to obtain precise geometry for the purposes of building performance analysis. In order to enable full benefits of BIM, the focus on further development of open interfaces between interdisciplinary software tools is needed. Recommendations for an improved BIM-based workflow for energy modelling are:

- Establishing a modelling standard at the very beginning of the design process; determining the required Level of Detail.
- BIM Model shows high Level of Detail - setting own layer definitions for BEM in BIM
- Setting own BEM room stamps and hiding BIM room stamps when transferring
- Seamless modelling of components is important for exchange

In our future research, we aim to develop an optimized semi-automated BIM to EPC workflow based on the results of this study; As well as to extend the study to BIM to LCA (life-cycle assessment) workflows, an additional early-decision making tool for sustainability.

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POTENTIALS AND LIMITATIONS OF LOCAL FISCAL POLICIES AS INSTRUMENTS FOR SUSTAINABLE DEVELOPMENT IN SLOVENIA

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Abstract

Local communities are one of the main cornerstones of sustainable development. They play a vital role in utilisation of national policy instruments and exhibit the largest influence on the energy use in the building and transport sectors. Sensible energy management can also positively enhance evolution of local sustainability features by incorporating concepts of local energy self-supply, decentralised energy production and circular economy. Positive economic and social impacts can be generated by adapting strategies and policies to the local environment while considering its endogenous potentials.

By analysing the current status, identifying and quantifying potentials, and setting clear delimitation of responsibilities and legal constraints, local authorities can be helped to shape innovative local fiscal policies focused on intensification of use of local renewable energy sources and fostering of more efficient use of energy both in public and private sectors. Those revenues whose height and content can be determined by local authorities have a very different role in the budget already in 8 analysed Slovenian municipalities. They were quantified and used as an analytical basis for solution-oriented steps in the design of measures to adapt local fiscal policies to the increased use of renewable resources energy.

Keywords: fiscal policy, municipality, energy use, renewables, sustainability

1. INTRODUCTION

Energy origins, means of transformation of primary sources and efficiency of energy use directly influence sustainability levels on particular and general scales. Two common key barriers identified on the local level are: (1) limited autonomy of local authorities in shaping of their own fiscal policies with regard to the central legislative framework, and (2) technological, organisational or political progressive visions and innovative steps forward usually take more than a duration of a single mandate of municipal officers and main decision makers to fully evolve and unfold.

Municipalities have formal executive responsibility to deliver some public services that are most commonly provided at the local level by the subsidiary principle. There are many reasons why public-service delivery should be provided by the lowest level of government that can still provide these services efficiently. Three core arguments are frequently advanced [1]:

- Efficiency; local decision-making can encourage fiscal responsibility and efficiency, as local politicians are directly answerable for the performance of local services. This is especially the case if the financing of services is also decentralised.
- Proximity; local government is closer to local residents, can better understand their concerns and could be considered more transparent from the perspective of democratic accountability;
- Flexibility: local decision-making can be responsive to the people for whom the services are intended and can tailor local services to local needs.

Aim of this article is to present in depth analyses of fiscal measures that can be taken by Slovene municipalities in order to effectively implement renewable energy resources policies. The municipal capacity to introduce renewable energy resources policies (these policies are within local jurisdiction) is inevitably dependant on how to finance these projects and enable sustainable development in energy resources.

2. FISCAL AUTONOMY: THE SLOVENIAN CASE STUDY

With few exceptions, Slovenian municipalities (212 in total; 11 of them declared as urban) have a negligible influence on their own determination of the degree of local income. Also, when observing individual municipalities no common denominator can be found for the utilisation of the self-manageable part of their budget. However, by analysing the current status, identifying and quantifying potentials, and setting clear delimitation of responsibilities and legal constraints (as done within the Interreg-MED LOCAL4GREEN project [2]), local authorities can be helped to shape innovative local fiscal policies focused on intensification of use of local renewable energy sources (RES) and fostering of more efficient use of energy both in public and private sectors.

The basic mission of a Slovenian municipality is to take care of local affairs, within the framework of the law. That includes primary education (school buildings and facilities), social welfare (child care, elderly care and social assistance), health (primary health care and pharmacies), social housing, culture and leisure (museums, libraries, theatres, sport facilities, leisure centres) and local public utilities and networks (waste and water management, urban city transport, local road network, urban heating, etc.). The central government can transfer certain responsibilities to the municipalities if it provides necessary financial means (Art. 140, Constitution). Municipalities autonomously regulate and perform duties and functions assigned to them by law.

The competences of municipalities are regulated by the Constitution, the Local Self-Government Act [3] and special laws, and by autonomous local regulations. Financial resources of the municipalities are defined in the Constitution that grants municipalities to the sufficient financial sources of their own as part of the state's economic policy, which municipalities then use at their discretion within their competences.

2.1 Municipal financial sources

The financial resources of Slovenian municipalities are stipulated in a specific article of the Constitution, which states that "A municipality is financed from its own sources. Municipalities that are unable to completely provide for the performance of their duties due to insufficient economic development are assured additional funding by the state in accordance with principles and criteria provided by law."

Additionally, the Constitution states that "local communities raise funds for the performance of their duties by means of taxes and other compulsory charges as well as from revenues from their own assets." However, the central government never waived its fiscal sovereignty in the past two decades.

As laid down in Article 53 of the Local Self-Government Act, municipalities are entitled to the property tax, inheritance tax and gifts, tax on prizes from games of chance, tax on real property transactions and other taxes as specified by the law. Municipal own non-tax (other) sources are imposed contributions, fees (dues), fines, concession fees, payments for local public services, etc.

2.2 Municipal fiscal capacity: in theory

The municipal ability to adopt own fiscal policy to gain revenue (and/or reallocate it to RES) can be understood as municipal fiscal capacity. Thus, the level of fiscal autonomy is important tool for delivering public policies. The constitution defines that the state and local communities raise funds for the performance of their duties by means of taxes and other compulsory charges as well as from revenues from their own assets, and that local communities impose taxes and other charges under conditions provided by the Constitution and law.

Although municipalities can implement a new tax or non-tax measure that has not already been implemented by legislation (not the specific tax, but the area of taxation), this almost never happened. The reason is that overregulation resulted in very few (if any) areas that are not already regulated.

Out of existing tax and non-tax measures, there are few areas that a municipality can modify (but not set fully independently). The most important (regarding the size of the revenue) is Compensation for the use of building land, followed by revenues from communal contributions, Tourist tax, Municipal fees from legal entities and Municipal fees from natural persons.

There are two revenues that are closely linked to the area of environmental protection and sustainable development:

- Tax for environmental pollution due to the discharge of waste water (a 100 % municipal revenue, however the municipality is not allowed to modify taxation)
- Environmental levy on pollution caused by the disposal of waste (84 % of this tax revenue goes to the municipality; the municipality is not allowed to modify taxation)

However, both financial instruments are earmarked by the Financing of Municipalities Act [4]. Additionally, according to a study on financing systems [5] there are two fiscal mechanisms that are enabling local governments to gain revenue for RES promotion as they are more flexible regarding municipal modification of the taxation and regarding how revenue from them is spent. These are:

- Compensation for the use of building land,
- Municipal fees (possibly; depends on the content of the taxation area).

Compensation for the use of building land is most commonly cited as the major own municipal tax and it is the second biggest tax revenue for municipalities. There is an elaborate legal blueprint how it is determined and it mostly takes into consideration the type of infrastructure in the area, the purpose of the activities in the buildings, ownership etc.

There is an option for the local government to exempt buildings that use RES from this taxation. However, the efficiency of such activity is linked to the amount of the Compensation that would be paid in the first place. So, the question of exemption is inevitably linked to existing taxation on the area. Alternatively, a local government could increase the Compensation significantly, while exempting users of RES.

Municipal fees are in full (100 %) municipal revenue. Municipality fees may be imposed by an ordinance that specifies the nature and amount of the fee, as well as the persons liable to pay the fee. The amount of a fee should not be assessed by the value of the item, actual turnover or actual revenue. The municipality should not require payment of municipality fees for activities where it is prohibited by an Act or if another mode of payment is specified or agreed upon by contract. So, although municipal fees are a flexible mechanism to gain and to reallocate revenue local authorities should be careful not to impose fees on an area where a similar tax burden is already in place.

Another tax that is contextually linked to RES is Tourist tax, especially if the municipality is promoting green tourism. An advantage of this tax is that the municipality can to some extent modify it (discretion to decide if additional groups of users will be charged – e.g. real estate owners that use facilities for own leisure, overnight stays in vessels – or if some groups are excluded from paying the tax – thus promoting specific types of activities).

A disadvantage is that the Promotion of Tourism Development Act [6] earmarks this tax so that a municipality can finance tourism promoting activities from this revenue, like informing activities, promotion activities, marketing activities, developing joint touristic infrastructure, development and maintaining of public space intended for tourism etc. Therefore, if a municipality gains substantial revenue from this tax with some contextual manoeuvring there is a high probability that this revenue could be used for RES promotion.

2.3 Municipal fiscal capacity: in practice

The next step is to explore how existing financial mechanisms are being utilized. This gives us an insight into (a) which areas of taxation offer most revenue, thus are potentially large enough to finance RES projects from them, and (b) which areas of taxation are underutilized and could be utilized more (also as an earmarked revenue) for RES.

When tax and non-tax revenues are compared, the latter represent only about a quarter of tax revenues. The main source of revenue is gained through taxes. The major tax is Income tax, however it is not set by local government and is reallocated through different equalization mechanisms.

The next major tax is the Property tax category, however a great majority of this amount is gained through Tax on immovable property. Other taxes represent only a fraction of these two combined, however still significantly more than non-tax revenues.

If we focus on the tax revenues that are within municipal authority to modify (again, there is a possibility to introduce a completely new municipal tax, but due to legal restrictions - there should be no other existing taxation on the area - this never happens) we have four taxation possibilities available (see Table 1): Compensation for the use of building land (Slovene acronym: NUSZ), Tourist tax, Municipal fees and Communal contribution.

With the exception of NUSZ tax revenues that are for a municipality to set (at least to some extent) do not represent a major income, thus it should be explored if they are utilized to their full capacity within individual municipality. In the next chapter we present the amount of revenue raised from these four fiscal mechanisms for all LOCAL4GREEN partner municipalities.

Table 1: Municipal taxes and non-taxes that can be modified (or set) by municipalities

Type of revenue	**Level of taxation**	**Can a municipality modify taxation?**	**Revenue in 2016 (all Slovenian municipalities)**		**Share of total income**
			EUR	EUR/capita	
Compensation for the use of building land	Depends on the individual municipality.	Yes (with some minor limitations)	208.553.517	100,95	12,4%
Tourist tax (earmarked)	Varies according to categories and exceptions + municipal decision.	Yes (with some limitations)	11.808.432	5,72	0,7%
Municipal fees	Potential purposes: advertising, organisation of exhibitions and events, parking and other activities which differ from their planned use.	Yes	4.159.084	2,01	0,2%
Revenues from communal contributions (has to be earmarked)	Depends on type of land and other factors.	Yes, to some extent	44.426.970	21,50	2,6%

3. FISCAL CAPACITY ANALYSIS OF SELECTED SLOVENIAN LOCAL COMMUNITIES

A thorough analysis of fiscal policies of the 8 Slovenian municipalities included in the LOCAL4GREEN project was done as the basis for elaboration of possible interventions into the existing mechanisms to enhance the use of RES in their local environments. The main results are presented in Table 2 and Figure 1.

When observing proposed four financial resources that can be set or modified by a municipality, for each partner municipality individually an estimation was made if they represent a high enough potential to make a difference when allocating to RES, as shown in Table 2.

Table 2: Fiscal mechanisms in each Local4Green partner municipality in 2016; adapted from Internal reports of the Ministry of Finances.

Municip.	**Compensation for the use of building land**		**Tourist tax**		**Municipal fees**		**Communal contributions**	
	EUR	EUR/ capita	EUR	EUR/ capita	EUR	EUR/ capita	EUR	EUR/ capita
Kočevje	535.708	33,73	7.459	0,47	3.876	0,24	127.337	8,02
Kamnik	1.769.430	60,15	55.142	1,87	912	0,03	422.017	14,35
Grosuplje	1.027.632	50,66	12.854	0,63	47.491	2,34	753.010	37,12
Trebnje	788.495	62,97	6.702	0,54	0	0,00	472.789	37,76
Ivančna Gorica	795.528	48,62	355	0,02	0	0,00	573.568	35,06
Lenart	349.212	42,32	0	0,00	0	0,00	137.155	16,62
Križevci	94.055	26,03	0	0,00	0	0,00	42.687	11,81
Kranj	4.417.061	78,76	93.265	1,66	94.166	1,68	1.509.538	26,92

3.1 Compensation for the use of building land

As mentioned above, Compensation for the use of building land is one of the major municipal own taxes and there is an option for local governments to exempt buildings that use RES from this taxation. Local governments could increase the Compensation significantly while exempting users of RES. As seen from the values in Table 2, the Municipality of Kranj raises by far the most revenue - even when compared to the country average. The general conclusion is that the Compensation for the use of building is a tax resource that offers most potential revenues for the future.

3.2 Tourist tax

We mentioned above that if a municipality gains substantial revenue from this tax with some contextual manoeuvring there is a high probability that this revenue could be used for RES promotion.

Although none of the partner municipalities are a major touristic destination, Kranj raises well over the national average. Smaller municipalities like Lenart and Križevci have no income yet from this mechanism. However, when the absolute revenue is divided with the number of inhabitants then Kranj does not stand out anymore. Kamnik and Kranj raise the most out of partner municipalities, however per capita still significantly less that the national average

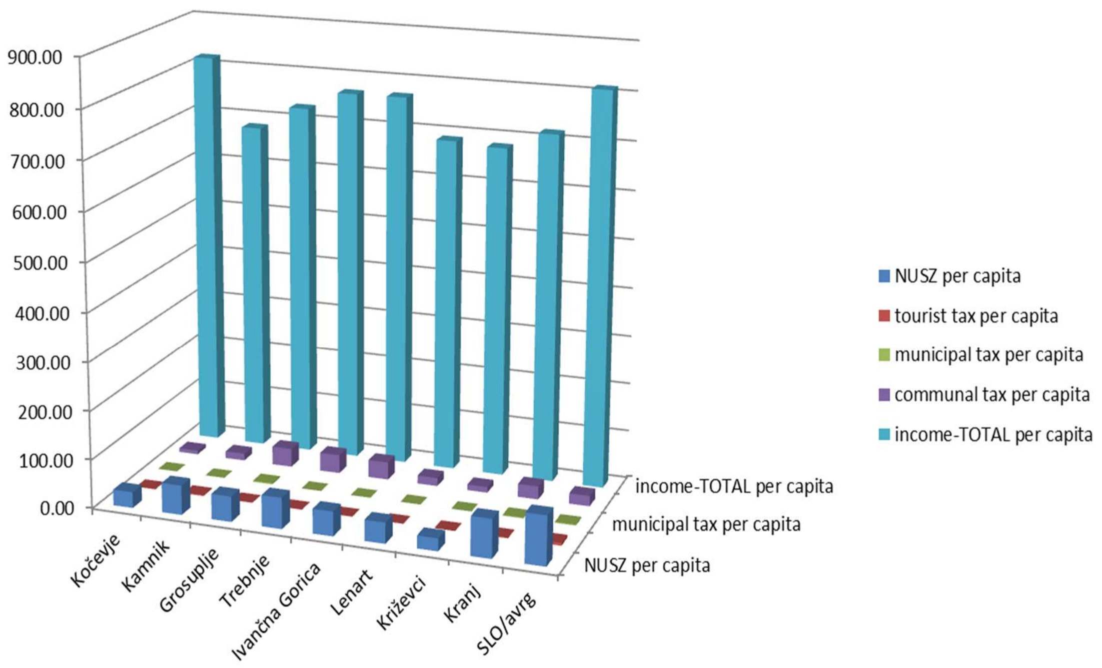

Figure 1: Analysed revenues and the total revenue per capita in 2016 (in EUR) in the Slovenian Local4Green partner municipalities.

3.3 Municipal fees

Municipal fees are another important fiscal mechanism to promote RES. They are generally underused in Slovenia. Among the partner municipalities, Kranj and Grosuplje raise most revenue with this mechanism. This picture is again significantly different when we divide the revenue amount with the number of population. On an average, municipalities in Slovenia raise about two Euros per inhabitant per year through Municipal fees. Only Grosuplje (in comparison to other partner municipalities) raises 2,34 EUR per inhabitant per year, which is above Slovenian average, but in absolute terms still a very small amount. Many municipalities raise no revenue from this mechanism at all.

3.4 Revenues from communal contributions

Revenues from communal contributions are earmarked to be used for development of communal infrastructure. The Spatial Planning Act [7] lists among communal infrastructure also energy distribution infrastructure, thus Communal contribution could potentially be used for promotion of RES. Municipalities are restricted with definitions of types of infrastructure and calculations of floor area, but can adjust the quotient of taxation from 0,7 to 1,3. In this sense there is some leverage for financial policy. There is a significant difference among municipalities if we compare the Communal contribution revenue per capita, however this might be misleading. A more accurate assessment might be reached if the number of buildings (residential and commercial) would be taken into consideration.

4. CONCLUSIONS

- A thorough analysis of 8 Slovenian municipalities and their current fiscal policies was done as the basis for elaboration of possible interventions into the existing mechanisms to enhance the use of RES in their local environments.
- The situation and potentials were analysed, and competences and legislative restrictions on possible fiscal policy measures to promote the use of renewable energy at the municipal level in Slovenia were identified.
- The analysis showed that the municipalities in Slovenia have no influence on determining their level in most of their revenues and that their financing is to a large extent centrally regulated.
- The Compensation for the use of building land and the Municipal fees seem to be potentially the most important own fiscal mechanism to promote RES on local level.
- However, the analysis also shows that an absence of a common denominator is actually the only common feature. Each municipality is an example for itself, with its needs and unused endogenous potentials also in the fiscal area. The set of innovative fiscal policy measures for the promotion of RES is generally appropriate for all local communities, but compliance with the development strategy, the rational suitability and potential benefits of a particular measure (or even some new, specific ones) need to be established in a dialogue with local authorities and stakeholders.

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EU POLICY GOALS AND IMPLEMENTATION IN THE BUILDING SECTOR: THE ROLE OF SOCIAL SCIENCES AND HUMANITIES

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Abstract

Based on the understanding that consumer and investor behaviour change at both individual and social units' level is crucial for enabling the EU energy transition towards zero-carbon economy, the article provides an overview of the EU strategic initiatives and policies supporting energy efficiency in the building sector and an analysis of the major policy instruments in terms of potential areas of intervention of Social Sciences and Humanities (SSH) expertise. Employing a historical perspective, it follows the development of strategic policy frameworks and legislative acts, focusing on the overall surge of positioning of the consumer in the centre of the EU energy system, shifting the paradigm from measures in energy production and distribution to actions influencing proactive end user behaviour, thus necessitating systematic integration of SSH perspectives, research methodologies and expert input in the design of the implementation programmes. Thus, the article lays the foundations of future research on the quality and scope of transposing the EU policies at different governance levels from social sciences' perspective, and outlines areas of further collaborative efforts in the view of the new EU policy tools being currently in final stages of adoption under the Clean Energy for All Europeans legislative package.

Keywords: energy efficiency, nZEB, Social Sciences and Humanities (SSH), consumer behaviour, Clean Energy for All Europeans

1. POLICY FRAMEWORK

1.1 The EU 20-20-20 goals

The EU 20-20-20 goals were probably the major marker of an unparalleled paradigm shift towards carbon-free, climate friendly European economy and society. By 2020, the EU set as its goal to reduce its greenhouse gas emissions by at least 20%, increase the share of renewable energy to at least 20% of consumption, and achieve energy savings of 20% or more. While striking a balance between a PR venture and a technically and economically sound goal, the targets have an undoubted impact on the public awareness on the challenges of climate change and air pollution, the role of energy efficiency for stimulating local economies, and the environmentally and energy responsible behaviour, both in the business sector and in the private households.

As widely known, buildings are responsible for about 40% of energy consumption and 36% of CO_2 emissions in the EU. While new buildings generally need fewer than three to five litres of heating oil per square meter per year, older buildings consume about 25 litres on average. Some buildings even require up to 60 litres. Currently, about 35% of the EU's buildings are over 50 years old. Hence, deep energy retrofit and measures regarding the final energy consumptions have become a notable highlight of the Commission's actions. The 2010 Energy Performance of Buildings Directive [1] and the 2012 Energy Efficiency Directive [2] are the EU's main legislative instruments covering the reduction of energy consumption of buildings and completion of the goals related to the building sector, to be analysed in detail below.

1.2 The Energy Union

The Energy Union [3] means making energy more secure, affordable and sustainable. It aims to facilitate the free flow of energy across borders and a secure supply in every EU country, for every European citizen. New technologies and renewed infrastructure will contribute to cutting household bills and creating new jobs and skills, as companies expand exports and boost growth. Its goal is to lead the EU to a sustainable, low carbon and environmentally friendly economy, putting Europe at the forefront of renewable energy production, clean energy technologies, and the fight against global warming.

The Energy Union strategy builds further on the 2030 Framework for Climate and Energy and the European Energy Security Strategy [4]. The Energy Union is made up of five closely related and mutually reinforcing dimensions:

- Security, solidarity and trust: diversifying Europe's sources of energy and ensuring energy security through solidarity and cooperation between EU countries
- A fully integrated internal energy market: enabling the free flow of energy through the EU through adequate infrastructure and without technical or regulatory barriers
- Energy efficiency: improved energy efficiency will reduce dependence on energy imports, lower emissions, and drive jobs and growth
- Decarbonising the economy: the EU is committed to a quick ratification of the Paris Agreement [5] and to retaining its leadership in the area of renewable energy
- Research, innovation and competitiveness: supporting breakthroughs in low-carbon and clean energy technologies by prioritising research and innovation to drive the energy transition and improve competitiveness.

All these priorities imply active engagement of the private investors and end users, among other relevant stakeholders, which calls for more active integration of insights from SSH in the investment behaviour change surge stimulated by the policy and financial support instruments.

1.3 Clean Energy for All Europeans

On 30 November 2016, the European Commission presented a new package of measures with the goal of providing the stable legislative framework needed to facilitate the clean energy transition – and thereby taking a significant step towards the creation of the Energy Union. Aimed at enabling the EU to deliver on its Paris Agreement commitments, the 'Clean Energy for All Europeans' proposals are intended to help the EU energy sector become more stable, more competitive, and more sustainable, and fit for the 21st century. With a view to stimulating investment in the clean energy transition, the package has three main goals: 1) Putting energy efficiency first, 2) Achieving global leadership in renewable energies, and 3) Providing a fair deal for consumers. The package includes 8 different legislative proposals (each with a linked impact assessment) covering Energy Efficiency, Energy Performance in Buildings, Renewable Energy, Governance of the Energy Union, Electricity Market Design (the Electricity Directive, Electricity Regulation, and Risk-Preparedness Regulation), and Rules for the regulator ACER.

Currently, only the amendments to the EPBD have been adopted and entered into force (July 9th, 2018) [6]. They significantly strengthen the requirements to the national building renovation strategies, focusing on attracting private investment and development of advisory tools for building owners and tenants. Special attention is paid to energy poverty, worst performing buildings, specific market failure, which all require serious intervention from experts with pronounced SSH expertise.

The recasts of the EED and the RES directives have both been endorsed by the EP (on November 13th, 2018), being subject to formal approval by the Council. They set new, more ambitious goals to 2030, namely **32,5% improvement of energy efficiency and a binding target of 32% share of RES in the energy mix**, building on the Commission's proposals and setting timeframe for potential further increase. Both policy instruments target increasing investments in energy efficiency and RES projects, most notably by effectively enabling end users to participate in the energy system, by trouble-free production, storage and selling of self-produced energy to the grid, and enabling of the functioning of local energy cooperatives through uninterrupted sharing of the produced energy. This effectively requires streamlined policy efforts to create and sustain the emerging markets, underpinned by the Governance of the Energy Union and Climate Action which puts in place a "simplified, robust and transparent" procedure promoting long-term certainty and predictability for investors. Under the Governance, each Member State will prepare a national energy and climate plan for the period 2021 to 2030, covering all the five dimension of the Energy Union and taking into account the longer-term perspective, presumably putting into work experiences and expertise gained through SSH studies targeting influencing energy positive investor and consumer behaviour.

2. SOCIAL SCIENCES PERSPECTIVE IN THE RELEVANT POLICY DOCUMENTS

There are clear implications for the potential for cooperation between SSH and energy- and climate-related research throughout the EU policy agenda; moreover, there is direct guidance concerning the expected roles and attitudes of the different social units, at different governance levels. The concrete actions are however to be designed at member state and regional/local level, institutionalized in the form of implementation programmes. The goal of this chapter is to outline the specific areas of potential intervention of SSH expertise within the overall policy framework and to provide the basis for the subsequent analysis of the implementation at national/local level.

2.1 The Energy Union

Stating that customers' interests and participation are at the heart of the European energy transition, and assuming that end-user engagement is the key for the sustainable renovation of the building stock, are probably the most notable accents of the importance SSH integration in the energy policies' implementation. As it could be expected by a framework document, these statements are not elaborated into specific actions requiring specific initiatives to influence user behaviour – those should be the detailed at implementation programme level. However, in the third review of the State of the Energy Union, it is declared that "now is the time to mobilise all of society - citizens, cities, rural areas, companies, academia, social partners - to take full ownership of the Energy Union, take it forward and engage in developing the solutions of the future", which relates directly to streamlined engagement activities at community and/or formal social units level – activities, which should become the heart of the public policies in the area of climate and energy.

Focus on energy poverty

The topic of energy poverty (with measures defined predominantly in the building sector) is the one that most explicitly requests specific action oriented towards end beneficiaries: It is specifically provisioned that an information campaign will highlight the benefits of energy efficiency, and directly involve formal social units as influencers of the user behaviour. It is supported by the Observatory of Energy Poverty, with the goal, among others, to serve as a hub to disseminate good practices to key stakeholders and to be a source of information on energy poverty for the wider public. In a look towards coal and carbon-intensive regions, the Commission states that it "intends to work in partnership with the stakeholders of these regions, to better target European Union support, encouraging exchange of good practices, including discussions on industrial roadmaps and re-skilling needs and promoting synergies / joint cooperation". This example is one of the most detailed declaration on intent to involve SSH insight in the implementation of energy policies; however, specifics on the expected user response to this effort and the tools to reach it are not outlined.

The local level as change driver

Cities are crucial for the modernisation and decarbonisation of the building stock, being a focal point of the action. At the same time, as centres of innovation and growth and engines of economic development, they are also a part of the solution. They are recognized as key players in the effort to decouple greenhouse gas emissions and resource consumption from economic growth and help national economies become more knowledge-based and competitive, which implies direct relation to the social science perspective at macro level, but also implicitly recognizes the feedback loop from individual behaviour and also the influences between different governance levels, respectively different agglomerations of formal social units. The promotion of investment supporting "cross-sectoral, innovative projects that can serve as testbeds for new business models" within the overall context of the EU Urban Agenda [7], is set to be a priority in 2018.

Engagement of all parts of society

In the third report on the state of the Energy Union, it is explicitly stated that "it will only be successful if all segments of society come together and move in the same direction". The Commission declares that it will continue to secure the participation of all levels of society, young people in particular, and create stronger connections between European, national and local efforts. It will also "provide opportunities to launch a transparent and constructive dialogue among all concerned parties on the draft integrated national energy and climate plans which Member States are requested to deliver in early 2018". As specifically addressed, it will strive that "society as a whole and all European, national, regional or local stakeholders concerned to engage actively in the energy transition and contribute to its success". This approach represents proactive behaviour at macro level, but also willingness to foster interactions among stakeholders representing different energy cultures.

2.2 Clean Energy for All Europeans legislative package

The communication on the Clean Energy for All Europeans package is specifically directed to the shifting of the focus towards citizen-centered policies (built around the "energy efficiency first" principle), opening large field for cooperation with SSH expertise. In the case of building renovation – by far the most prominent field of intervention, the expectation for attracting SSHs is explicit: the goals are for "creating the **right market conditions** for increasing the rate and level at which buildings are renovated… a stable framework with a long-term perspective and vision towards the decarbonisation of buildings, which will lead to the transformation of the EU building stock while **creating growth and jobs**." A clear signal to the formal social units, which have to design the right programmes to influence end user behaviour, intensifying the social interactions on the topic at all levels under consideration.

This notion is further developed by the amendment of the **Energy Efficiency Directive** with a clear view to "attracting private investment and supporting the emergence of new market actors", and continued attention to improving metering and billing of energy consumption for the end consumers. Furthermore, the amendment to the **Energy Performance of Buildings Directive** focus on the national long-term building renovation strategies (providing a direct field for interaction with SSHs) and introduction of ICT smart building systems, thus providing opportunities for empowerment of the end-users. Of course, stimulating the market through attracting private finance is in the core of the proposals, exemplified by the "Smart Finance for Smart Buildings" initiative.

2.3 The Energy Efficiency Directive recast

The EED recast of 2018 (as voted by the EP on November 13th, 2018), although at first glance moving away from the building sector through the transition of the former *Article 4 Building renovation* to the EPBD, keeps comparatively stronger relations to the social science perspective, some of which are focused explicitly on building renovation. It is especially interesting that deep energy retrofit becomes a major focus of the investments from the extended Energy Saving Obligation (which is itself one of the major accents in the recast): *"That extension would (...) encourage long-term investments and long-term energy efficiency measures, such as the deep renovation of buildings with the long-term objective of facilitating the cost effective transformation of existing buildings into NZEBs. The energy savings obligation has an important role in the creation of local growth and jobs (...). Cooperation with the private sector is important to assess the conditions on which private investment for energy efficiency projects can be unlocked and to develop new revenue models for innovation in the field of energy efficiency" (Preamble, Par. 10)* [8]. The focus on energy poverty is maintained, specifically stipulating that energy efficiency measures should be proiritarized in the actions for aleviating energy poverty (Preamble, Par. 23-25). Paragraph 26 of the Preamble, however, sets the tone in the relations with SSH, stating that „*It is crucial to raise the awareness of all Union citizens about the benefits of increased energy efficiency and to provide them with accurate information on the ways in which it can be achieved*".

In other areas of the Directive, unchanged since the original 2012 version, the potential for SSH integration is also explicitly mentioned. *Article 5 Exemplary role of public bodies' buildings* suggests that member states may consider cost effective measures as deep renovations and measures **for behavioural change of occupants**, to achieve the required amount of energy savings in eligible buildings owned and occupied by their central government. Member States shall encourage public bodies, including at regional and local level, to demonstrate the exemplary role of government buildings, presumably paving the way for private investment, which is another, very explicit, relation to the formal social unit impact on individual behaviour. In addition, in the Proposal for Amendment cited above, it is specifically stated that "*Local and regional authorities should be given a leading role in the development and design, execution and assessment of the measures laid down in Directive 2012/27/EU, so that they are able properly to address the specific features of their own climate, culture and society*", which once again strengthens the role of the local level of governance, as already indicated in the Energy Union framework document. *Article 16. Availability of qualification, accreditation and certification schemes* assumes that by 31 December 2014, certification and/or accreditation schemes and/or equivalent qualification schemes, including, where necessary, suitable training programmes, become or are available for providers of energy services, energy audits, energy managers and installers of energy-related building elements and member states will ensure that the schemes will provide transparency to consumers. Moreover, Member States shall take appropriate measures to make consumers aware of the availability of qualification and/or certification schemes.

Specific instruments relevant for the development of **financing stimuli** are also foreseen, including the energy certification of buildings and the promotion of the energy services market. It is especially considered that in the development of energy services the member states should target (a) **disseminating clear and easily accessible information** on: (i) available energy service contracts and clauses that should be included in such contracts to guarantee energy savings and final customers' rights; (ii) financial instruments, incentives, grants and loans to support energy efficiency service projects. In the proposed amendments of Art. 20, it is emphasized (par. 3a) that "In order to mobilise private financing for energy efficiency measures and energy renovation, in accordance with Directive 2010/31/EU, the Commission shall conduct a dialogue with both public and private financial institutions in order to map out possible actions it can take", including mobilising capital investment into energy efficiency by considering the wider impacts of energy savings, most often a subject of interpretation through SSH toolsets.

As for the for the energy certification of buildings, it is assumed that the certificates shall contain information about incentives of a financial or other nature and financing possibilities. A major part of this is the regulation of energy audits, as *Article 8 Energy audits and energy management systems*, promoting the availability to all final customers of high quality cost-effective energy audits. Member States shall also develop programmes to raise awareness among households about the benefits of such audits through appropriate advice services, with the notion of creating "incentive and support schemes for the implementation of recommendations from energy audits and similar measures". The introduction of specific technological solutions for energy efficiency in the building sector is also regulated by the Directive, especially in *Article 14 Promotion of efficiency in heating and cooling.* All these provisions confirm the strong focus of the Directive towards the micro and meso decision making level, promoting generation and distribution of specific data and information and design of specific tools which influence both the small-scale energy collectives and their values and the energy practices and material culture in difference lifestyle patterns.

2.4 The Energy Performance of Buildings Directive recast (30 May 2018)

The practical implementation of the concept of Nearly Zero Energy Buildings (nZEB), as one of the main aspects of the Directive, is generally expected to command a strong focus on social science input. Without streamlined market interventions and behaviour change campaign, it is difficult to assume that such radical change in the current design and construction practice will convincingly win over the stakeholders in the entire value chain in the sector. However, signals of intention to attract inputs from social sciences are somewhat weaker compared to the EED. The major focus is definitely the shift of the national renovation strategy from EED (Art. 4) to EPBD (Art. 2a) and the new requirements, enlarging the scope of the expected social effects, and providing open space for integration with SSH expertise.

The new Art. 2a requires that "*Each Member State shall establish a long-term renovation strategy to support the renovation of the national stock of residential and non-residential buildings, both public and private, into a highly energy efficient and decarbonised building stock by 2050, facilitating the cost-effective transformation of existing buildings into nearly zero-energy buildings".* Among stipulations already known from the previous version, the new one gives provides more direct connections to SSHs, stating that *„Each long-term renovation strategy shall (...) encompass: (d) an overview of policies and actions to target (...), split incentive dilemmas and market failures, and an outline of relevant national actions that contribute to the alleviation of energy poverty; (f) an overview of national initiatives to promote smart technologies and well-connected buildings and communities, as well as skills and education in the construction and energy efficiency sectors; and (g) an evidence-based estimate of expected energy savings and wider benefits, such as those related to health, safety and air quality.* In addition, each Member State *„shall carry out a public consultation on its long-term renovation strategy prior to submitting it to the Commission"*. In terms of requirements for the financial instruments and their coupling with social interventions, the member states are requested to *„facilitate access to appropriate mechanisms for: (...) (b) the* ***reduction of the perceived risk*** *of energy efficiency operations for investors and the private sector; (c) the use of public funding to leverage additional private-sector investment or* ***address specific market failures****; and (e) accessible and transparent advisory tools, such as* ***one-stop-shops for consumers and energy advisory services****, on relevant energy efficiency renovations and financing instruments.*"

In other already existing provisions, *Article 9 Nearly zero-energy buildings* obliges Member States, giving a leading example, to develop policies and take measures such as the setting of targets in order to stimulate the transformation of buildings, and to develop national plans in order to achieve these targets. The national plans should include, among others, information on the policies and financial or other measures for the promotion of nearly zero-energy buildings, including details of national requirements and measures concerning the use of energy from renewable sources in new buildings and existing buildings undergoing major renovation. This, obviously, makes a connection to the formal social unit level of influencing the end user behaviour, leaving vast open space for interpretation by the member states. Additionally, *Article 11 Energy performance certificates*, requiring the establishment of a system of certification of the energy performance of buildings, requires that the energy performance certificate shall provide an indication as to where the owner or tenant can receive more detailed information. Again, Member States are requested to encourage public authorities to take into account the leading role which they should play in the field of energy performance of buildings. A measure with potential for serious social and market impact, the information contained and the targeted use of the Energy performance certificates (EPC) are not defined precisely so the analysis of the implementation and potential input from SSH perspective is again referred to the national level. In the 2018 EPBD recast, this position is somewhat strengthened by the introduction of an optional scheme for building renovation passports (Art. 2a, Par. 1c).

2.5 Cross section 1: Consumer information

Information provision is one of the most important horizontal measures to influence investment behaviour in the building and real estate sector. The provision of high quality and transparent information is specifically targeted by both EED and EPBD, although the focus is on passive provision of information rather than on actual engagement in communication activities. However, these activities stimulate all levels of influence on the behaviour and purchasing decisions of the citizens, which is why they are attracting much of the attention.

Again, the EED is more elaborate in terms of requesting specific information services to the end users. Articles 9 to 11 of, and Annex VII to, Directive 2012/27/EU are amended to require provision of frequent and enhanced feedback on energy consumption. *Article 12 Consumer information and empowering* requires that Member States shall take appropriate measures to promote and facilitate an efficient use of energy by small energy customers, including domestic customers. These measures shall include one or more of the elements listed under point (a) or (b): (a) a range of instruments and policies **to promote behavioural change**: (i) fiscal incentives; (ii) access to finance, grants or subsidies; **(iii) information provision; (iv) exemplary projects; (v) workplace activities**; and (b) **ways and means to engage consumers and consumer organisations** during the possible roll-out of smart meters. Being implemented at national level, these requirements provide open field to stimulate social activities.

Concerning the interventions to stimulate the exchange within different stakeholders' groups, according *Art. 17 Information and training*, Member States must ensure that information on available energy efficiency mechanisms and financial and legal frameworks is transparent and widely disseminated to all relevant market actors. *Article 18 Energy services* adds up to the topic, insisting on disseminating clear and easily accessible information on available energy service contracts and financial instruments, incentives, grants and loans. Member States shall support the proper functioning of the energy services market, where appropriate, by identifying and publicising point(s) of contact where final customers can obtain information; taking, if necessary, measures to remove the regulatory and non-regulatory barriers; enabling independent market intermediaries to play a role in stimulating market development on the demand and supply sides.

The EPBD also tackles the information needs and delivery through a specific article (*Article 20 Information*), which stipulates that Member States will take measures to inform the owners or tenants of the different methods and practices to enhance energy performance, provide information on energy performance certificates and inspection reports, and on cost-effective ways to improve the energy performance of the building and on available financial instruments. Specific requests for provision of information are developed in relation to energy performance certificates (*Article 11*), including in regard to the cost-effectiveness of the recommendations for renovation measures. The 2018 recast is further strengthened in this direction, introducing new text in Article 20(2), stating that *"Member States shall in particular provide information to the owners or tenants of buildings on energy performance certificates, including their purpose and objectives, on cost-effective measures and, where appropriate, financial instruments, to improve the energy performance of the building, and on replacing fossil fuel boilers with more sustainable alternatives. Member States shall provide the information through accessible and transparent advisory tools such as renovation advice and one-stop-*

shops". Additionally, the role of information availability is justified in relation to the newly introduced smartness readiness indicator, directly relating also to the new moments in the proposal for recast of the RES Directive related to empowering of prosumer behaviour.

2.6 Cross section 2: Training and education

An often underestimated topic with significant relevance to social sciences input, training and education are understandably regarded as important part of the energy transition and specifically addressed in the discussed policy documents. In the EED, the already mentioned *Art. 17 Information and training* commits the Commission to review the impact of its measures to support the development of information platforms. Member States are requested to involve local and regional authorities, promote suitable information, awareness-raising and training initiatives to inform citizens of the benefits and practicalities of taking energy efficiency improvement measures. Specifically, Member States should encourage training programmes for the qualification of energy auditors (*Article 8*) and provide that "where necessary, suitable training programmes, become or are available for providers of energy services, energy audits, energy managers and installers of energy-related building elements" (*Article 16*), which again leads directly to support of the decision making process.

In the proposal for amendment of the EED, the subject is introduced in the Preamble (Par. 34), stating that *"Member States should take into account the fact that the successful implementation of new technologies for measuring energy consumption requires enhanced investment in education and skills for both users and energy suppliers"*.

As regards the EPBD, in *Article 20 Information of the EPBD*, Member States are requested to *"ensure that guidance and training are made available for those responsible for implementing this Directive"*. Such guidance and training shall address the importance of improving energy performance, and shall enable consideration of the optimal combination of improvements in energy efficiency, use of energy from renewable sources and use of district heating and cooling when planning, designing, building and renovating industrial or residential areas. The 2018 recast significantly strengthens this message, stating that *"Member States should take into account the need for a clear link between their long-term renovation strategies and pertinent initiatives to promote skills development and education in the construction and energy efficiency sectors*" *(Preamble, Par. 10)*, and that long-term renovation strategies should provide *"an overview of national initiatives to promote smart technologies and well-connected buildings and communities, as well as skills and education in the construction and energy efficiency sectors"* (Art. 2a, Par. 1f).

3. CONCLUSIONS

Energy efficiency in the building sector commands a strong focus in the EU agenda setting and policies, as serious attention is paid to the development of strategic, regulatory and financial framework for the transformation of the sector. Consumer behaviour change towards a more active role in the building renovation market is recognized at EU level as key for the energy transition, which implies systematic using of input from social sciences and humanities in the programming documents at all levels of governance. In some areas of the reviewed policies, there are very specific and detailed guidance notes, which is definitely a strong point and a major stimulus for development of further collaboration efforts in a pronounced multidisciplinary mode. This notion is also strengthened in the new legislative acts under the Clean Energy for All European package, recognizing the central role of the consumer in the energy system. However, at the same time, there are still some significant deficiencies: the process is rather one-directional, based on passive provision of information rather than on active engagement and interactions with the relevant stakeholders (a gap which is partially covered through the introduction of obligatory stakeholders' consultations in 2018 EPBD recast). There is no guidance on strategic planning of the marketing and communication activities using the potential of SSH, and unfortunately there is no institutional basis to sustain such cooperation. The programming of the policy support tools, where these interaction should find their collaboration interface, is designed at national level of governance, but there are no coherent quality criteria or institutionalized quality assurance mechanisms for monitoring of the outcomes. However, there are notable signs for improvements in this area in the agreement between the Council and the EU Parliament on the Regulation of the Governance of the Energy Union and Climate Action [9] with detailed monitoring reports on the building renovation strategies, but how these provisions would be addressed at national level remains to be seen.

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INNOVATIVE TRAINING SCHEMES FOR RETROFITTING TO NZEB-LEVELS

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Abstract

One important barrier that hampers the development of Nearly Zero-Energy Buildings (nZEBs) and effective deep energy renovations (DERs) is the lack of adequate construction competences. Improving the competences of middle- and senior-level building professionals, including various trade professionals (construction workers) in sustainable energy efficient construction is therefore of key importance.

Besides the fact that the lack of quality is often caused by the lack of competences, building professions also need to be aware of new and upcoming challenges relating to nZEBs. These include new materials and products, the integration of renewable energy sources, new systems or processes, and the use of Building Information Modelling (BIM) tools.

This leads to the conclusion that upskilling towards energy efficiency and nZEBs should be done throughout the entire buildings sector value chain (including designers, architects, engineers, building managers, technicians, installers and workers).

The EU countries are all trying to upgrade professional competences in nZEB design and construction, thus increasing the experts' capacity to tackle nZEB implementation in actual building stock. The efforts are continued on developing new competences for DER through the Horizon 2020 projects developing multi-country qualification and training schemes such as Fit-to-nZEB (Innovative training schemes for retrofitting to nZEB-levels).

Keywords: Fit-to-nZEB, NZEB, professional competences, upskilling, training schemes

1. INTRODUCTION

European Commission (EC) is focused on improving the energy performance of the existing building stock in order to reach 2020, 2030 and 2050´s targets on energy demand reduction [1]. In 2010, the Recast of the Energy Performance Building Directive (EPBD) brought into the EU legislation the notion of Nearly Zero Energy Buildings (NZEB) [2]. According to [2], Member

States (MS) shall ensure that by 31 December 2020, all new buildings are nZEBs; and after 31 December 2018, new buildings occupied and owned by public authorities are nZEBs.

It is well known that, buildings have a central role to play in the energy transition of the EU since our buildings are responsible for about 40% of primary energy consumption in the EU and about 36% of energy-related CO_2 emissions while at the same time around 75% of the building stock is energy inefficient [3]. On the other hand, BPIE [4] has found that just 3% of buildings in the EU are assessed as highly energy efficient in 2017 (with an Energy Performance Certificate (EPC) A-label or better), leaving the other 97% in need of energy renovation in order to achieve the 2050 decarbonisation vision. The gap between the two figures (75% versus 97 % of inefficient building stock) is explained by the general assumption that all buildings built before 1990 (and any EU building regulations) are inefficient and all built after are efficient, determining the efficiency level of the EU building stock based on its age [4].

The IEA [5] has pointed out that in the EU, energy efficiency can deliver 76% of energy savings needed to achieve Paris Agreement objectives. IEA shows that despite a near-tripling of the world economy and a global population increase by 2.3 billion, end-use energy efficiency alone can deliver 35% of the cumulative CO_2 savings through 2050 required to meet global climate goals. Since 75- 90 % of current buildings will still stand in 2050 [4], [6], a faster and deeper (in terms of energy savings) renovation rate is crucial for Europe to achieve its commitment to the Paris Agreement.

To date, however, renovation rates in the EU are low and renovating the existing building stock in terms of energy efficiency remains a challenge, even more so when considering the ambitious levels set by the EPBD which aim at NZEBs. One of main results of the changes implemented in Amended EPBD [7] is that it requires MS to focus more on the energy renovation of their building stock in order to transform it into a highly energy efficient and decarbonized stock by 2050, facilitating its cost-effective transformation towards nZEB.

From the existing experience of the authors both construction of nZEBs and DER proved to be a complex process for construction industry in general. It demands a change of business as usual procedures of everybody involved, including architects, civil and mechanical engineers, site managers as well as construction workers (craftsmen). The complexity of the energy efficiency renovation process is also evident from the fact that only 0.4-1.2% (depending on the country) of the building stock is renovated each year [8].

Looking at the construction sector, experience has shown that a number of challenges still exist and endanger the policy goals of the EC. The construction industry needs to be able to deliver DER as well as newly build nZEBs using innovative technologies which are key in addressing new approaches for energy efficient buildings [9]. On the other hand, there is a lack of qualified and skilled workforce which would deliver high quality nZEBs in which occupants would have healthy living conditions [9], without any construction faults occurring in use, and delivering designed energy consumption. Improving the competences of middle- and senior-level building professionals, including various trade professionals (construction workers) in sustainable energy efficient construction is therefore of key importance.

Besides the fact that the lack of quality is often caused by the lack of competences, building professions also need to be aware of new and upcoming challenges relating to nZEBs. These include new materials and products, the integration of renewable energy sources, new systems or processes, and the use of BIM tools. This leads to the conclusion that upskilling towards energy efficiency and nZEBs should be done throughout the entire buildings sector value chain (designers, architects, engineers, building managers, technicians, installers and workers).

It is envisioned that increasing the knowledge and skills of craftsmen about new technologies, cross-crafting good practices as well as worst practices will result with a higher level of energy performance in buildings, as well as avoiding inadequacies caused by poor practices [10]. Additionally, objectives and consequently up-skilling is regarded as an upstream measure, as outlined by a respective recent European study [11]

Among other things, the lack of qualified and certified building professionals was implemented into the Amended (EPBD) [7] where in Article 10, paragraph 6 the following states: "*6. Member States shall link their financial measures for energy efficiency improvements in the renovation of buildings to the targeted or achieved energy savings, as determined by one or more of the following criteria:*

(a) the energy performance of the equipment or material used for the renovation; in which case, the equipment or material used for the renovation is to be installed by an installer with the relevant level of certification or qualification;"

The above-mentioned article does give the MS the possibility to introduce the knowledgeable and skilled workers when considering financial measures with energy renovation of buildings. It still has to be seen how specific MS will tackle this article during the Amended EPBD implementation, but at least now there is a possibility to promote competent workforce in order to achieve quality DERs.

The increase of the number of qualified construction specialists at all levels is directly related to the accessibility and quality of the training and educational programmes and the inclusion of training on intelligent energy efficiency and RES solutions in building renovation.

According to the Amended EPBD [7], Member States should design consistent mixtures of policy instruments (policy packages) to provide the required long-term stability to investors in efficient buildings, including DERs. In respond to this explicit, requirement, the Fit-to-nZEB project aims to increasing competence and skills of the building professionals in the field of DER in the target countries (Czech Republic, Romania, Bulgaria, Italy, Croatia, Ireland and Greece) through the unique educational programmes developed by the consortium, which will contribute to both the quality and the scale of the deep energy building renovations.

This paper presents an innovative European Qualification Framework (EQF) level 3-7 training schemes for retrofitting buildings up to nZEB-levels, implemented under Fit-to-nZEB Horizon 2020 project framework. The training programs have been organized in different countries across Europe with common structure, learning outcomes and competences. Courses are delivered by Universities, professional high schools and colleges, vocational training centres (VTCs) as well as through on-the-job training and validation programmes.

2. DAMAGE CAUSED BY LACK OF COMPETENCES

Suffering a severe employment crisis, especially in terms of qualified construction specialists looking for better-paid jobs abroad, the need for training of the current workforce is much stronger, as is well recognized the countries involved in the project. In 2012 a Communication on a "Strategy for the sustainable competitiveness of the construction sector and its enterprises" [12] was published, focusing on the human capital in the sector. The Energy Efficiency Plan [13] also recognises the importance of training and urges MS to develop strategies and schemes to satisfy training needs. It is evident that the biggest impact on the quality of buildings in terms of energy efficiency has the building's envelope, and not only its calculated thermal transmittance or the materials used, but also detailing and the quality of works performed. There are numerous examples (Figure 1) where implementation of energy efficiency measures caused damage and/or poor performance due to the lack of competences of designers, construction workers and/or supervising engineers.

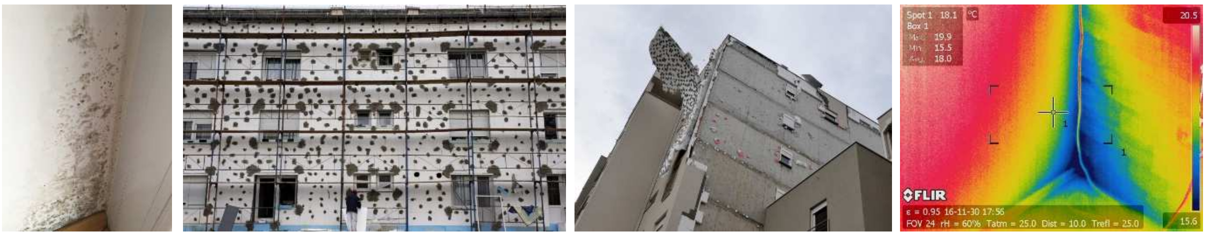


Figure 1: Examples of poor energy renovation in Croatia

3. COMPENDIUM OF COMPETENCES FOR DEEP ENERGY RENOVATION

3.1 Analysis of existing training programmes

Prior to the development of the compendium of competences, an analysis of existing training programmes for DER in the partner countries was performed with identification of gaps and deficiencies. The main aim of the analysis of existing programmes was the identification of learning outcomes of the programmes available in each target country, identification of the existing gaps and recommendations for further development or modification of the system of education in DER field. In all target countries, a tangible lack of integration of the topic in the professional secondary, high and higher education and vocational training programmes was identified. The observation shows that the allocation of the identified programmes within the EQF system is quite broad and unstructured, and it is very difficult to harmonize and compare the results of the analysis at national level - as related to both the professional education and the vocational training system. In the secondary and high education (EQF 3-5) system, principles of DER are not included in official training programmes. In higher education (EQF 6-7), there are some fragments of the topic represented by certain subjects that are studied separately from each other. That is why the lack of qualification is filled in most cases by vocational education. Vocational trainings can be divided into two large parts according to the target group, for construction workers (EQF 4-5) and supervising professionals (EQF 6-7), these trainings are however not harmonised and do not provide official DER qualification in their national qualification frameworks.

It could be however stated that in most of the target countries, the certified passive house designer/tradesperson courses are mentioned as a well-structured uniform (and sometimes the only one existing) programme that can be used as a basis for the development of detailed programmes in different EQF levels. Additionally, MEnS project [1] developed a novel EQF level 7 Building Educational Program with the objective to upgrade professional skills in nZEB design and construction. The analysis of the Fit-to-nZEB project showed the necessity to develop each EQF level programme for DER implementation in each target country.

3.2 Compendium of competences for deep energy renovation

A compendium (systematically organized collection of requirements) of competences for DER was derived from all relevant professions.

The following definitions for competences (knowledge, skills, autonomy and responsibilities), introduced in the Council recommendation [14] are being used in this paper:

"**Knowledge**" means the outcome of the assimilation of information through learning. Knowledge is the body of facts, principles, theories and practices that is related to a field of work or study. In the context of the EQF, knowledge is described as theoretical and/or factual; "**Skills**" means the ability to apply knowledge and use know-how to complete tasks and solve problems. In the context of the EQF, skills are described as cognitive (involving the use of logical, intuitive and creative thinking) or practical (involving manual dexterity and the use of methods, materials, tools and instruments); "**Responsibility**" and autonomy' means the ability of the learner to apply knowledge and skills autonomously and with responsibility.

Catalogue of Learning Outcomes includes compendium of knowledge, skills and responsibilities that the learner is supposed to possess after finishing DER training programme at different EQF levels. The catalogue is structured according to 17 topics, (Table 1). Topics were developed in order to cover all fields of DER issues and to take into account local conditions of the involved countries. The order of the topics in the Catalogue is not connected with their importance or relevance to the field of DER. It has to be emphasised that each country-program includes all major aspects related to nZEBs, as well as national particularities. Each of 17 topics, chosen as most relevant for DER, contains requirements to the knowledge, skills and responsibilities of the learner according to levels EQF 3, EQF 4 - 5 and EQF 6 – 7 which could not be listed in this paper due to the length limitation but is freely available in [15]. Common topics included in all country education programs include (Table 1):

Table 1: Developed topics for DER with short descriptions

Topic and subtopic	
1. Basics of building physics	1.1. Passive house principles
Basics of building physics needed to understand the interrelations of the major principles in DER. Introduction to the passive house principles and how they work together	
2. Optimal solar gains	
Situation and sizes of openings / shading and natural ventilation	
3. Building Envelope 3.1. Thermal insulation	3.2. Minimizing thermal bridges 3.3. Highly efficient windows
Building envelope exterior and interior insulation. Thermal bridges through structural building elements, windows and doors, through cracks and gaps in building envelope. Use of highly efficient window frames / insulating doors / positioning of windows and doors	
4. NZEB Neighbourhoods 4.1. Energy cooperatives	4.2. Distributed energy production systems and energy management
Understanding the nZEB Neighbourhood. Energy cooperatives as isolated business or connected to a local smart grid or to the national grid. Distributed energy sources. Microgrid solutions. District level distribution grids. Impacts and benefits of the grid integration of the distributed energy production. Energy Management Systems (EMS). Assessment of the extended built boundary and energy balance of the bounded area.	
5. Airtightness, vapour and moisture movement, wind tightness	
Infiltration and/or exfiltration heat losses, quality assurance and blower door test. Vapour movement through the construction fabric, relevant properties of different materials	

6. Building Services 6.1. MVHR; 6.2. Heating and Cooling	6.3. DHW 6.4. Automation – Regulation 6.5. Lighting
Emerging technologies in building services for high performance residential projects	
7. Conservation of historic building fabric	
Different levels of conservation, concept of authenticity, technical concerns in DER of buildings of historic value – suitable materials and techniques	
8. RES in building renovation	8.1. Long and short term energy storage
Installation of RES systems in DER without interfering with nZEB principles and requirements. Possibilities of long and short-term storage of energy in the building.	
9. Cost effectiveness	
Provision of solutions with proven cost effectiveness within the whole life cycle of the building, economic efficiency of a package of measures.	
10. Planning and design instruments	
Nationally recognized software tools / other available software planning tools. BIM tools.	
11. Comfort, health and safety requirements in buildings, incl. indoor air quality 11.1.Summer comfort/ passive cooling	11.2.Fire protection
Comfort, health and safety requirements in buildings, indoor air quality, condensation, humidity and mould appearance, CO_2 levels, draught elimination, productivity and health impact, light, acoustic. Fire protection issues. Summer comfort.	
12. Step-by-step retrofit plans	
Economic assessment, energy audit, design and implementation issues. Step-by-step strategies as well as suitable component and alternative solutions	
13. Energy efficiency and building renovation policies	
National and EU strategic goals; financing schemes and opportunities; relevant legislation acts in nZEB construction and DER.	
14. Achieving measurable results	
Energy audits; required parameters of the building components; energy performance certificates (EPC). Monitoring and evaluation of the results of the retrofit projects. International retrofitting standards (e.g. EnerPHit).	
15. Engaging stakeholders	
Benefits of energy efficiency to different target groups – energy and financial savings, increased comfort, sanitary and health conditions, better indoor air quality, ecological and climate change mitigation, broader economic and social benefits, energy security, etc.	
16. Project management	16.1.Quality assurance
Introducing basic principles – Initiating; Planning; Executing; Monitoring; Controlling of project. Increase knowledge of investment efficiency, multicriteria assessment, life cycle assessment, energy efficiency legislation used for project management and evaluation.	
17. Ecology and sustainability	
Ecology as a starting point for energy efficiency in building; climate change and CO_2 levels; building materials	

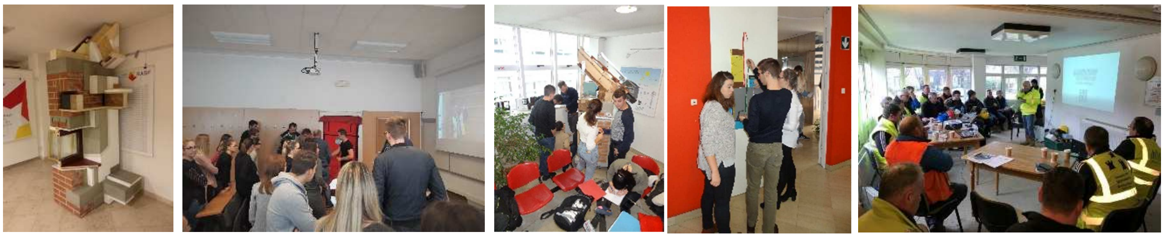
3.3 Training programmes

New training programmes target at all professional groups involved in the retrofit process. Based on the compendium, training programmes for the following EQF levels were developed:

EQF level 6-7: A design-focused training programmes on DER for higher education, 60 hours of training (*30 theoretical hours and 30 practical hours*), with all necessary requisites.

EQF level 3-5: A training programme to be included in the professional high schools in training plans and programmes for the tradesperson professions in "Construction", consisting of *24 theoretical hours and 36 hours of practical training*. Training content for professions in "Electrical engineering and energy sector" professional direction was also developed, consisting of *24 hours of theoretical and 18 hours of practical training*.

EQF level 3-4: Two training programmes for acquiring qualification on part of profession (specialization, or similar qualification according to each national qualification framework), to be used by the VTCs, *16 hours of theoretical and 24 hours of practical training*. A comprehensive scheme for validating competences acquired at the workplace, consisting of entry level tests, with theoretical and practical trainings (*8-12 hours*) and evaluation scheme.



a) b) c) d)

Figure 2: a) example of the training models, b) execution of the university training – blower door, c) university training – minimizing thermal bridges, d) on the job training in Ireland

In order to create hands-on and practical training demonstration, training models were designed and developed (Figure 2 a), c)). Visualization by means of models during training programmes is an essential method for better assimilation of the programme content. These training models are being used by the training centres, specifically serving the goal of providing close-to-real training environment regarding the retrofitting process.

The models also provide the trainees with an insight into small-scale RES systems (PV, solar thermal, mini-wind, biomass, thermal pumps) in close-to real environment, bridging the skills between the different crafts and professional occupations involved in the process. Additionally, the MVHR units are installed in rooms within/besides the model itself. The rooms and measuring devices for testing the ventilation equipment and wind tightness of building envelope are available for practicing at the premises (Figure 2 b).

4. CONCLUSIONS

The Fit-to-nZEB project delivered all necessary requisites for the introduction of educational content on DER of buildings in the curricula at all levels of the educational and training system in South-eastern Europe. The process was guided by the understanding of the complex nature of building retrofit, combining various building disciplines and allowing integrated design and cross-craft understanding with special focus on practical exercises and demonstrations. End users of the developed compendium of competences are developers of new training programmes on DER and nZEB renovations, as well as decision makers, involved into educational system, and the trainers. The elaborated learning outcomes can be applied to development of wide range of training programmes of vocational or specialised education for construction specialists. They represent the fullest collection of new competences related to DER in the involved countries.

The next step would be an essential element for the sustainability of the Fit-to-nZEB project, and that is the creation and deployment of certification schemes and accreditation procedures corresponding to the EQF. It has to also be emphasised that additional efforts need to be invested in communicating professionals the importance of their role in this new nZEB challenge and expected benefits in their professional careers.

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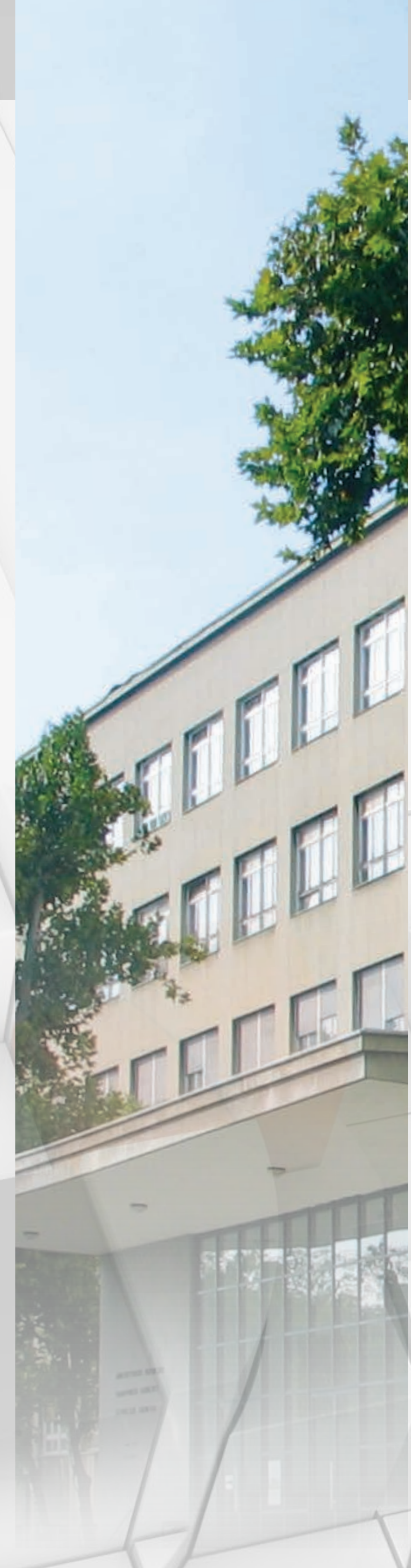
- founding individual study programmes in the English language, and organising life-long learning and non-formal education in the English language
- development and modernisation, and certification of laboratories
- increasing spatial and personnel capacities for teaching and research needs
- further ties with the business sector and searching for adequate organisational forms



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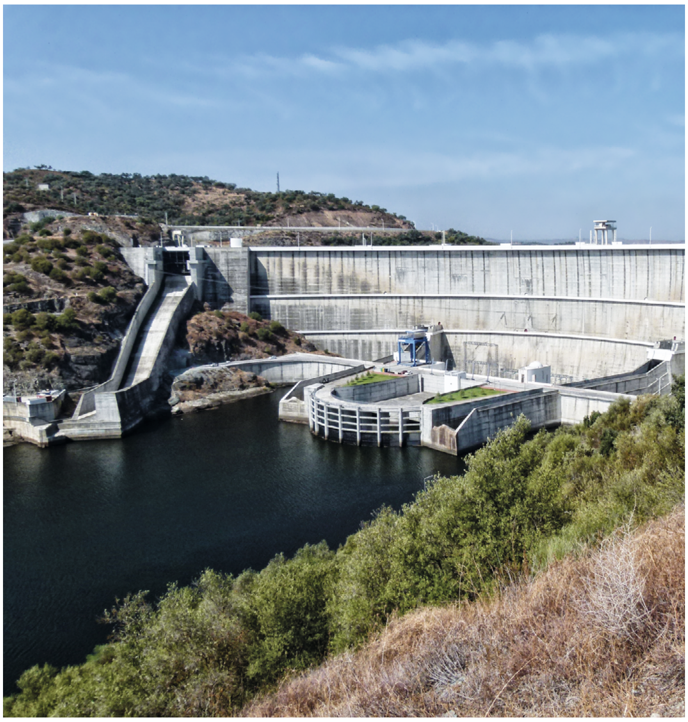

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