ANNEX 72

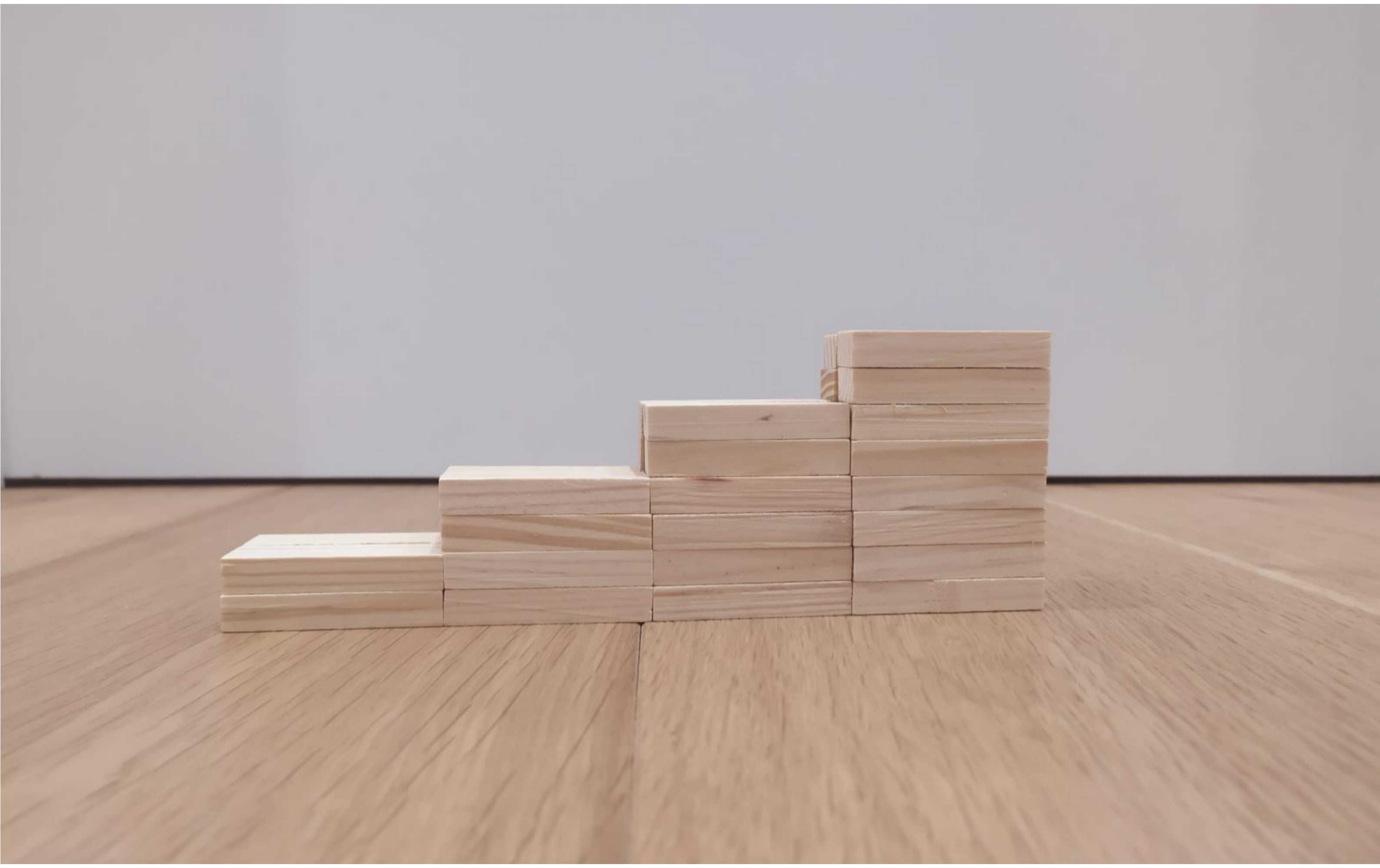
EBC
Energy in Building and Communities Programme

International Energy Agency

Life-cycle optimization of building performance: a collection of case studies

Energy in Buildings and Communities Technology Collaboration Programme

February 2023



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ANNEX 72

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Life-cycle optimization of buildings performance: a collection of case studies

Energy in Buildings and Communities Technology Collaboration Programme

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Picture on front page: Optimization concept; Sonia Longo, © 2023

Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives - The strategic objectives of the EBC TCP are as follows:

- reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
- improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
- the creation of 'low tech', robust and affordable technologies;
- the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;
- the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means - The strategic objectives of the EBC TCP will be achieved by the means listed below:

- the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
- benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
- improving smart control of building services technical installations, including occupant and operator interfaces;
- addressing data issues in buildings, including non-intrusive and secure data collection;
- the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction (*)

Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings
Annex 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems
Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities
Working Group - Building Energy Codes

Summary

Introduction

The building sector is one of the most impacting on the energy demand and on the environment in developed countries, together with industry and transports.
The European Union introduced the topic of nearly zero-energy building (nZEB) and promoted a deep renovations in the existing building stock with the aim of reducing the energy consumption and environmental impacts of the building sector. The design of a nZEB, and in general of a low-energy building, involves different aspects like the economic cost, the comfort indoor, the energy consumption, the life cycle environmental impacts, the different points of view of policy makers, investors and inhabitants. Thus, the adoption of a multicriteria approach is often required in the design process to manage some potential conflicting domains. In detail, one of the most suitable approaches is to integrate the preliminary building design (or renovation) phase in a multi-objective optimization problem, allowing to rapidly compare many alternatives and to identify the most adapt interventions.

Objectives and contents of the report

The purpose of this report is to illustrate the contribution of the International Energy Agency - Energy in Buildings and Communities (IEA EBC) Programme Annex 72 members to the topic of life-cycle multi-objective optimization of buildings performance.
In detail, the purpose of the report is:
- To collect existing case studies developed by the Annex 72 members on optimization techniques applied for finding an environmental-energy-economic "optimum" among different design or retrofitting solutions;
- To examine the collected case studies and compare methodologies, applications and results, and deriving some general conclusions on the topic.

The case studies are intended to be used as a basic knowledge for identifying:
- Optimization techniques to be used for finding the "optimum" among different alternative solutions;
- Solutions to be adopted for reducing both the energy consumption during the operation and the environmental impacts and costs during the whole life cycle and for avoiding that the benefits of a low energy building during operation are offset by the higher impacts due to additional materials/costs and energy required during the other life-cycle stages.

The target groups of this report are scientists and developers and providers of building design tools.

Key messages

The following key messages arise from the analysis of the optimization case studies:
1. Different approaches, software and algorithms, objective functions, variables, constraints and parameters can be used in the optimization processes.
2. A common generic step-by-step procedure can be identified in the examined case studies, starting from the development of the building model and ending with the identification of the optimal solutions. The stakeholders involved in the building life-cycle (e.g. in the design, construction and management) can apply this procedure, time by time adapted to the characteristics of the investigated building, for identifying optimal design or retrofit solutions regarding different aspects of

the whole building life-cycle (e.g. building envelop materials and thicknesses, use of renewable energy technologies in operation, occupancy, useful life, etc.).

3. Some outcomes can be found, focusing on the building envelope, renewable energy systems, climate and occupancy influence. The outcomes, detailed in the following, are valid per each specific case study; they cannot be extended “as is” to a generic building but case-by-case considerations and measurements are needed:
   - Building envelope: given a fixed air-conditioning system, different solutions can be identified for the building envelope, with one case finding as optimal solution the base case envelope (no improvement is preferred) when a heat pump powered by electricity from renewable sources is used for heating. This type of solution is rather common and may challenge the limited availaibility of energy from renewable resources. Thus this type of solution should undergo a stresstest by rolling it out to a relevant share of a national building stock and check the need for the annual operational renewable energy resources against their potential available.
     Furthermore, natural materials (e.g. cellulose) are preferred to synthetic ones (e.g. EPS) for reducing the environmental impacts, while the opposite is obtained by an economic optimization, since natural materials are more expensive.
   - Renewable energy systems: while buildings with a low operational energy efficiency operating with renewable energies may be among the most optimal solutions, such buildings may challenge the available potential of renewable electricity, fuels and other (in particular geothermal) energy sources.
   - Occupancy influence: the variability in occupants’ behaviour influences the identification of the best solutions. One of the exmined studies highlighted that even if some solutions are independent from the households type (e.g. the use of triple-glazing on the North East façade), others are influenced by this aspect, e. g. the equipment features (number of photovoltaic modules or installation of a grey water heat recovery system).
   - Environmental and economic optimisation should be performed using a full life cycle approach, covering the product, construction phase, use and end of life stages of a building. Excluding one or several of these stages may likely lead to suboptimal solutions.

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Acronyms

Abbreviations	Meaning
ADP	Abiotic Depletion Potential
AP	Acidification Potential
BPS	Building Performance Simulation
CED	Cumulative Energy Demand
COP	Coefficient of performance
DHW	Domestic hot water
EP	Eutrophication Potential
EPD$_s$	Environmental Product Declarations
GER	Gross Energy Requirement
GHG$_s$	Greenhouse gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
NRPE	Non-Renewable Primary Energy
nZEB	Nearly Zero (operational) Energy Building
ODP	Ozone Depletion Potential
OF	Objective Function
OSB	Oriented strand board
PE	Primary Energy
POCP	Photochemical Ozone Creation Potential
RPE	Renewable Primary Energy
RTS	Radiant Time Series

1. Introduction

1.1 Life cycle impacts of buildings

In 2019, building construction and operations accounted for 35% of global total final energy consumption: buildings operation on a global scale was responsible of around 30% of total final energy consumption, while the buildings construction industry consumed the remaining 5%. Furthermore, 55% of global electricity consumption took place in buildings during the operation (UNEP, 2020).

The building sector also caused 38% of the total energy-related CO_2 emissions, including both direct ones from the use of fossil fuels for heating purposes and indirect emissions through electricity and/or district heating use. 28% of these emissions was caused during the building use and 10% is from the manufacturing, transportation and use of all construction materials for buildings (UNEP, 2020).

In this context, the reduction of energy consumption,greenhouse gas (GHGs) emissions and other environmental impacts in buildings gained an increasing interest in the last years.

One of the concepts identified to support the transition towards low-energy and low-carbon buildings is the nearly or net zero energy and emission building paradigm (see 1.4 guideline, section on net zero definitions), which is expected to become the primary form of building construction in the future.

The concepts of net zero energy and of net zero emission buildings can be defined in different ways. What most definitions have in common are the following elements: very low energy buildings during operaiton that aim to achieve net zero-energy or zero emissions over the course of a year, where any energy consumed is mainly covered by using renewable sources, usually prioritising production at the building site; in case embodied energy and/or emissions are part of the balance, the 'net zero' achievement often involves use of low emission fuels/energy and use of materials and technologies with low embodied energy/impacts and offsetting of the remaining emissions as real zero emission materials are not yet available.

The European Commission defined a nearly Zero Energy Building (nZEB) as "a building that has a very high energy performance […]. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" (European Union, 2010). A "decarbonised" building stock can be considered as one whose carbon emissions have been reduced to zero, by reducing energy needs and ensuring that remaining needs are met to the extent possible from zero carbon sources (European Commission, 2019).

European and other countries in the world shall develop policies and take measures (new or updated building codes, market regulation, supporting investments in energy efficiency, renewable energy technologies and smart technologies, etc.) in order to stimulate the creation of new buildings and renovated buildings that are nearly zero-energy and zero emission (European Union 2010, 2018).

Focusing on operating energy, it represents 70–90% in the total life cycle energy consumption of a traditional building (Napolitano et al. 2012; Chen et al. 2001; Röck et al., 2020). Conversely, embodied energy of building materials amounts to 10–30% of the life cycle energy consumption. For the above reason, most of the existing policies aim at reducing the energy consumption and related GHGs emissions of a building during the operational phase, neglecting the so-called "embodied" impacts of other stages of the building life-cycle, like the resource extraction, materials and equipment manufacturing, building construction, maintenance, end-of-life.

However, going from traditional constructions to low-energy or net-zero energy buildings, the embodied energy becomes a predominant contribution, or at least non negligible, and the share of operating energy decreases (Dixit et al. 2010; Gustavsson and Joelsson 2010; Ardente et al. 2008, 2011). Similar considerations can be made for the environmental impacts and, in particular, for GHG emissions. Literature case studies describe this phenomenon as "phase shifting", where the interventions for the reduction of use phase impacts cause an embodied impact rising that can nullify each effort in the improvement of building performance (Beccali et al., 2013).

In addition, even if the operating cost of buildings can be reduced thanks to the low energy consumption, an increase in the construction cost can occur. However, buildings should also be cost-efficient. In particular, the European Directive on the energy performance of buildings (EU, 2010) highlights the need of achieving the cost-optimal balance between the investments involved and the energy costs saved throughout the life cycle of the building. The economic point of view is a key issue for the investors and users, aiming at reaching their result with the minimum disbursement.

Furthermore, the building inhabitants would prefer to enjoy a comfortable dwelling, aspect that in some cases can be hardly ensured together with the energy efficiency and the cost-optimality.

Therefore, in order to design or retrofit low-energy or net-zero energy and net zero emission buildings, a holistic approach needs to be adopted, combining life cycle based primary energy and environmental impacts assessment, cost effectiveness, thermal comfort, etc.

This is a complex task: designers often have to assess different solutions and perform dynamic simulations of building performance in order to find the building configuration/s with the lowest energy demand during the operation, life cycle based energy demand, environmental impacts and costs. After, they have to select the “best” performance solutions’ set, dealing with some critical issues:

- The availability of multiple energy efficiency solutions: different commercial solutions are available in the market for increasing the buildings energy efficiency: envelope insulation, thermal mass, renewable energy technologies, etc.;
- The attainment of several objectives: different points of view are often considered in a building design or renovation, e.g. minimum cost, minimum environmental impacts, maximum energy saving or maximum internal comfort, which can be conflicting objectives.
- The presence of conflicting measures: solutions that might produce benefits and disadvantages on the building at the same time. A specific solution can allow for reducing the energy impact and some environmental impacts of the building, but it can cause the increase of other environmental impacts (e.g. the use of electricity from photovoltaic panels instead of electricity from a country-specific grid can allow for reducing greenhouse gas emissions but may cause an increase mineral primary resources);

To deal with the above critical issues and to identify, among a group of solutions (e.g. different thicknesses of insulation or different types of insulation), the optimal one/s (e.g. the optimal thickness of insulation or the best type of insulation) for obtaining an “optimum” among the examined objectives, the mathematical optimization techniques can be applied. In detail, when two or more objectives have to be attained, the search of an optimal technical solution becomes a multi-criteria or a multi-objective optimisation problem.

Multi-objective optimisation is considered an effective technique to evaluate, design and get the optimal compromise solution, since the objectives are usually conflicting. Indeed, the optimization results are sets of solutions being part of the Pareto front (Harkouss, 2018).

In order to compare many alternatives and to identify the most appropriate interventions for buildings considering different objectives, the multi-objective optimisation can be combined with building simulation to examine the energy consumption during operation, with an economic analysis to assess the cost-effectiveness and with an environmental life-cycle assessment to take into account the embodied and operational environmental impacts.

1.2 Purpose of the report

This report illustrates the contribution of the International Energy Agency Energy in Buildings and Communities (IEA EBC) Programme Annex 72 members to the topic of life-cycle multi-objective optimization of buildings performance.

In detail, the purpose of the report is:

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The target groups of this report are scientists and developers and providers of building design tools.

1.3 Structure of the analysis

The first step of the analysis included a preliminary survey of potential case studies on optimized buildings from a life cycle perspective, previously developed by Annex 72 members.

Starting from the results of the preliminary survey, a collection of case studies was carried out. Furthermore, a detailed analysis of the case studies mentioned above was performed, in order to check if they were dealing with the examined topic. At the end of the investigation, thirteen case studies were selected.

Considering the developers of the studies, six of them were performed by the research group of the Bauhaus-University Weimar (Germany) (Hollberg and Ruth 2013, 2014, 2016), (Hollberg et al., 2014), (Klüber et al., 2014), three studies by the group from the University of Palermo (Italy) (Cellura et al. 2019), (Montana 2020), one study by the group of the University of Palermo in collaboration with the group of Aalborg University (Denmark) (Montana et al. 2020), two studies came from the Budapest University of Technology and Economics (Hungary) (Kiss and Szalay, 2020) and the last work was developed by the MINES ParisTech (France) researchers (Recht et al., 2016).

A detailed analysis of the case studies was carried out, allowing to compare methodologies, applications and results, and to derive some general conclusions on the topic, as illustrated in Section 2.

Table 1: Proposed template for "optimization case studies"

Short description of the case study building:	Location (country and region); Type of climate (e.g. continental, tropical); Type of building (e.g. residential, industrial or tertiary; isolated or urban context); Type of action (new design or renovation).
Pictures	If any
Description of the building (before interventions, if it is a renovation case study)	Description of the geometrical and thermo-physical features and of the main elements and energy systems of the building.
Life Cycle Assessment	Goal and scope definition. Description of: functional unit or functional equivalent (according to standard EN 15978:2011); system boundaries (life cycle stages or modules considered); cut-off and allocation rules; selected energy and environmental impact indicators; main parameters (e.g. useful life of the building). Life cycle inventory analysis. Qualitative and quantitative description of primary data (materials, energy sources, outputs, etc.). Description of data quality (e.g. information on secondary data).
Optimization of the life cycle energy and environmental performance	Description of the optimization methodology (single or multi-objective), algorithm, objective functions (e.g. energy consumption, environmental impacts), software used, main variables category (e.g. envelope, heating, ventilation and air-conditioning (HVAC), renewable energy technologies) and constraints. Presentation of the results (e.g. tables and figures).
Lessons learned and conclusions	Description of the main conclusions drawn from the adoption of the solutions.

In order to summarize the results of the case studies, a template was prepared, based on existing literature and on Annex 72 members' experience. Section 3 reports the templates filled in for each case study.
The proposed template is illustrated in Table 1. The information collected through this template includes a description of the case study, of the Life Cycle Assessment (LCA) methodology (including the goal and scope definition and the life cycle inventory), of the optimization methodology (with details on the algorithms, objective functions, software used, main variables categories and constraints), a synthesis of the obtained results, the main conclusions and lesson learned.

2. Review of the Annex 72 case studies

2.1 Introduction

This section synthesizes the results of the Activity 3.3 of Annex 72, regarding the collection and analysis of thirteen case studies on the optimisation of life cycle performance of new or retrofitted buildings.

The above studies were examined in detail, focusing on the methodological approaches and on the obtained results, with the aim to identify a generic methodological framework and to draw conclusions for the scientific community.

The section is organized in three parts: the first one (Section 2.2.) includes a brief description of the optimization approach, of the building simulation process, of the environmental and economic assessment; the second part (Sections 2.3, 2.4, 2.5) summarizes the methodological approaches adopted in the examined case studies; the third one (Section 2.6) describes the methodological framework followed and some solutions identified by the examined case studies.

2.2 Background

2.2.1 The optimization process

Optimization is a branch of the applied mathematics that develops methods to find maximum and minimum points of an Objective Function (OF) by changing the values assumed by variables (Longo et al., 2019). Thus, the objective function is a function of the problem to be minimized or maximized (e.g. operational cost, energy consumption, life cycle based greenhouse gas emissions, life cycle based environmental impacts etc.).

Although in mathematical programming it is not a strict rule, the variables are subject to physical bounds and constraints in most of the engineering optimisation problems. With specific reference to buildings, the annual energy demand may be subject to an upper bound due to legal requirements, while the available rooftop surface may limit the installation of photovoltaic systems. The difference between bounds and constraints is that each variable has a lower and an upper bound on its own, but the values of some variables of the problem may be confined by equality and inequality constraints, identifying the feasibility space.

Depending on the number of objective functions, the optimization problems can be single-objective or multi-objective.

In a single-objective optimization problem the objective function typically has only one optimum value and only one best solution exists (or none, eventually).

In the multi-objective optimization problem more than one objective function is involved and the solution of the optimization problem is a vector of decision variables simultaneously satisfying the constraints and optimising a vector function whose elements represent the objective functions (which usually conflict with each other). The solutions of a multi-objective optimization problem are compromise solutions that can be different from the absolute minimum or maximum of each single objective function. If no preference is expressed for a specific objective function, the obtained solutions of a multi-objective optimization problem represent a set of equally optimal compromise solutions, called Pareto front (Deb, 2001).

In detail, the Pareto front is made up by a set of optimal solutions: it consists of all the points for which there is no point that is better at the same time for all the objective functions considered.

The analysis of a multi-objective optimization study involves introducing decision-making techniques in order to identify the best compromise solution to be actually realised from the Pareto front. Multi-objective optimization algorithms may thus be categorised according to the moment when the selection is performed, distinguishing between a priori or a posteriori methods (Alarcon-Rodriguez et al., 2010). In the a priori methods the decision maker requires specifying a priority among the OFs before the optimisation run, thus a deep knowledge of the problem before performing the optimisation is necessary. A posteriori methods, instead, are oriented to identify the whole Pareto front, in order to obtain diversified solutions that may support and facilitate the decision-making process.

Another classification of optimisation algorithms consists in the method of exploration of the feasibility space. According to this criterion, algorithms may be classified as deterministic or exact methods and heuristic methods. The deterministic methods are based on mathematical operations that involve derivatives, so that they require the OF to be expressed in a continuous and differentiable analytical form.

When an analytical and continuous expression is not possible, heuristic methods are preferred. This category of algorithms is based on criteria derived from the experience of the analyst, and it generally does not require continuity and differentiability of the OF. The easiest example of heuristic algorithm is a random investigation of the variables and a comparison of the solutions space. The investigation may be stopped setting a maximum number of iterations or through the evaluation of a fitness function (deriving from the OF).

Based on the number of alternatives considered for each iteration, the algorithms are classified as single-point (or local search) or population-based. In detail, single-point algorithms allow the perturbation of the variables one-by-one, while population-based algorithms can manage multiple sets of values of decision variables in each iteration.

2.2.2 Energy performance of buildings

The energy performances of a building are dependent on the principles of building physics, which take into account heat and mass transfer between the indoor and the outdoor environment through the building envelope.

The approach to the optimization of the building performances is oriented to minimize the thermal loads with passive solutions and thereafter to cover the remaining needs of the building through appropriate HVAC systems design.

While the energy performance of buildings in new constructions is improving and the concept of positive operational energy districts and/or net zero operational energy buildings aim to reduce the operational energy use within the built environment, one priority (set of constraints) is to always guarantee the thermal comfort to the occupants, keeping the indoor thermal comfort variables inside a determined range defined as comfort zone (ANSI, 2017), (ISO, 2005).

Different methods are available in literature for the simulation and assessment of the energy performance of buildings (Crawley et al., 2000), (ASHRAE, 2017). Since the energy demand and the environmental impacts related to the operation of buildings became a pressing issue in developed countries, many building simulation approaches were developed for various applications such as the energy efficiency rating or research applications. Nowadays, thermal simulation of buildings became a standard in both research and design fields, also thanks to the growing computational capacity of personal computers.

Building energy modeling and simulation is a discipline within building science, which aims at simulating all energy uses of a building with the required spatial and temporal scale (usually hourly or sub-hourly) for the investigated time span. The models are physics – based and include detailed building geometry descriptions, construction materials, lighting features, passive energy gains (through windows) and waste heat sources (occupants, equipment), heating, cooling and ventilation system requirements. These models also take in consideration users' related features, including occupancy features, plug loads and thermostat settings.

The building energy simulation started being investigated in the '60s, and in about 20 years the foundation theory behind the heat transfer and the main criteria and algorithms for the prediction of heating and cooling loads were developed. For example, in this period, the "Total Equivalent Temperature Differential Method" and the "Z Transfer Function Method" were developed. Although these methods were widely used by designers for decades, modern methods based on fewer simplifications and reducing the required calculations at the same time are available now. A model reduction technique called "Modal Analysis" has been implemented (Peuportier and Blanc Sommereux, 1990) and validated against experimental measurements (e.g. Munaretto et al., 2018). The "Radiant Time Series" (RTS) method was developed to offer a rigorous approach without requiring iterative calculations. This method is suitable for peak design cooling load calculations, but its simplifications prevent its employment for annual energy simulations (ASHRAE, 2017).

Most building energy simulation tools implement the "Heat Balance Method", which formulates energy and moisture balances for the air of the thermal zone and solve the resulting ordinary differential equations. This algorithm is based on the energy balance of the thermal contributions to each envelope component. Starting from the outdoor surface of all building envelope surfaces, the energy balance is performed considering the absorbed solar radiation, the convection with the air and the long-wave radiations. The convection heat transfer between the outdoor and indoor faces of the surface is calculated, and then another balance is evaluated on the indoor surface of a building, considering the convection and radiation with the indoor air and the internal equipment. The indoor air is considered as being fully mixed, thus having a uniform temperature (ASHRAE, 2017). This process is repeated for each surface and each thermal zone, namely rooms or sets of rooms having the same temperature set point whose temperature may be considered uniform and having the same heating system.

Software tools implementing the algorithms to simulate the thermal performance of buildings are collectively known as "Building Performance Simulation" (BPS) tools. "EnergyPlus" and "TRNSYS" are the most widely used BPS tools, both in research and advanced design applications, but there exist other tools that are more widely used at a national level, e.g. "Virtual Environment" in the UK, "IDA" in Sweden, "Pleiades+Comfie" in France, "Enerweb", *Lesosai" and "Thermo" in Switzerland. They implement the heat balance methodology

for the assessment of building performances and energy use, as well as different solutions for the modelling of conduction through walls (Conduction Transfer Function or finite differences) (Crawley et al., 2000), (Delcroix et al., 2012) and use specifically tailored models for natural ventilation (including pressure network applications) and HVAC systems.
Since BPS tools are based on standard meteorological input data and on simplified assumptions of the heat exchange model, in many cases it is not possible to obtain the exact energy use of the building operation from the simulation. Therefore, the model should be fine-tuned to the energy being used by the buildings using information, if available, from energy bills, monitoring devices or surveys among the residents (Sánchez Ramos et al., 2019).

2.2.3 The Life Cycle Assessment

LCA is a standardized methodology that allows for assessing the potential life-cycle environmental impacts of products and services. The life cycle approach takes into account the following stages of a product/process: raw material supply, manufacturing, installation, use and maintenance, end-of-life.
LCA is internationally standardised by ISO 14040 (ISO, 2006), dedicated to the principles and the framework of the methodology, and ISO 14044 (ISO, 2018), describing the requirements and providing guidelines. According to these standards, a LCA study is composed by four phases, each one interacting with others: goal and scope definition, inventory analysis, impact assessment, and interpretation.
Focusing on buildings, a specific LCA methodology framework exists for the evaluation of energy and environmental performance. This methodology is illustrated in the EN 15978 European standard (CEN, 2011) and the international standard ISO 21931 (ISO, 2010). These standards specify the method to assess the environmental performance of a building, based on LCA, and provides a standardised means for the reporting and communication of the outcomes.
In general, the scope, the boundary and the level of detail of a LCA depend on the aim and on the intended use of the study. The results of a LCA are expressed through impact indicators describing a specific phenomenon, which may be further aggregated (weighted) into single score indicators to avoid that an unskilled reader might misunderstand the results, although a single score indicator gives less information than its components. A balance between clarity and readability should thus be found (see Section 4.4.4 of Deliverable B (Lützkendorf et al. 2022).
The life cycle impacts may be split between embodied and operational parts. Although there is not a fixed definition in literature, focusing on buildings the embodied parts may be related to the supply of raw materials and the fabrication of the building materials/equipment, the building construction, the maintenance and end-of-life, while the operational part refers to the energy and water consumption during the building service life (Schwartz et al., 2016), (Tumminia et al., 2018), as described in the A72 methodology report by Lützkendorf et al. (2022). The development of low- operational energy buildings or net zero operational energy buildings gave rise to the investigation of the embodied impacts and embodied primary energy. The embodied part becomes obviously predominant in such buildings because the operational part is very low or even (net) zero.
In LCA literature studies, many indicators are employed to assess the energy and environmental performance (Montana, 2020). Some of the indicators used in the building sector are:

- The emissions of greenhouse gases with the most common substances carbon dioxide, methane and dinitrogen monoxide. The impact of these gases on climate change is expressed with the Global Warming Potential (GWP), which indicates how much heat a greenhouse gas traps in the lower atmosphere. It is determined over a specific time interval, commonly 20 and 100 years. GWP is referred to the equivalent mass of carbon dioxide (CO_2) producing the same effect (IPCC, 2013);
- The emissions of ozone depleting substances, mainly chlorofluorocarbons and halons, quantified with the Ozone Depletion Potential (ODP), which indicates how much the ozone layer in the stratosphere is reduced by the emission of a substance, increasing the ultraviolet radiations in the atmosphere. ODP is referred to the equivalent mass of trichlorofluoromethane (CFC-11) producing the same effect;

- The emissions of acidifying substances, quantified with the Acidification Potential (AP), which expresses the possibility to produce acid emissions or to acidify lands and water. One of the effects of AP is to provoke acid rains, thus reducing the pH of the atmospheric water introducing H+ ions. The most common substances related to this effect are sulphur and nitrogen oxides and ammonia. AP is usually referred to the equivalent mass of sulphur dioxide (SO_2) producing the same effect;
- The emissions of substances contributing to the photochemical smog, quantified with the Photochemical Ozone Creation Potential (POCP), which expresses the airborne substances' potential for forming atmospheric oxidants at ground level as ozone. This effect is mainly due to the presence of volatile organic compounds. POCP is referred to the equivalent mass of ethene (C_2H_4) producing the same effect;
- The emissions of eutrophicing substances, quantified with the Eutrophication Potential (EP), which indicates the reduction of oxygen contained in the bodies of water as a consequence of increased nutrients in water. This effect derives from the excessive growth of algae and plants, disturbing the balance between species. EP is usually referred to the equivalent mass of phosphate ion (PO_4^{3-}) producing the same effect;
- The primary energy demand may be assessed through the Cumulative Energy Demand (CED) or the Primary Energy (PE), which are usually synonyms. It is recommended to report renewable and non renewable primary energy consumption separately and to quantify the amount of energy harvested (Frischknecht et al., 2015).

2.2.4 The economic analysis

The economic analysis of a building can include the economic cost during the building operation or the economic life-cycle cost. In this latter case, the Life Cycle Costing (LCC) methodology can be adopted, a cost accounting method taking into account the cost or cash flows of all the main phases in the life of a product or service, i.e. relevant costs (and income and environmental externalities if included in the agreed scope and if the results of the environmental LCA are not reported separately) arising from raw materials supply through operation to disposal.

In general, the economic analysis can be developed with multiple approaches, by incorporating:

- The investment or both investment and labour cost, thus the initial expense due to the project;
- The investment and operating costs (e.g. electric energy purchase), namely the most common approach;
- The investment, operating and maintenance and/or renovation costs;
- The LCC or the global cost, considering all the costs quantities occurring during the life of the buildings, including costs of decommissoning and end-of-life treatment of construction materials.

The LCC of studies involving buildings or parts of buildings was standardised at international level by the ISO 15686-5 (ISO, 2017). Another international standard, the EN 15459 (CEN, 2007), was published at European level in the set of standards supporting the Energy Performance Building Directive and regulating the energy renovation of buildings. In detail, in order to make the nZEBs diffusion more appealing for the building sector, the accompanying notes to EPBD Recast (EC, 2012) stated that nZEBs should be designed according to the cost-optimal methodology, calculating the global cost (LCC) of several building alternatives and then selecting the one with the best Net Present Value.

2.3 Main features of the examined studies: type of buildings, software, approaches and algorithms

The examined case studies applied the optimization techniques both on early design of new buildings and on the renovation of existing ones. In detail, three studies focused on the early design (Recht et al., 2016) (Kiss and Szalay, 2020) (one of the study aiming at achieving the plus-energy level[1] (Recht et al., 2016)), nine studies examined the renovation process of existing buildings (Cellura et al. 2019), (Hollberg and Ruth 2013, 2014, 2016), (Klübeüber et al., 2014), (Montana 2020), (Montana et al. 2020) and the remaining study focused on the optimal quantity and quality of concrete used in buildings, neglecting the operation stage (Hollberg et al., 2014).

Different software are used to model the building features, to simulate the energy consumption during the operation and to carry out the optimization process (including also economic and environmental variables). Rhinoceros CAD environment (McNeel R. & Associates, 2020) is one of the main used software (Kiss and Szalay, 2020) (Hollberg and Ruth 2013, 2014, 2016), (Hollberg et al., 2014), (Kiss and Szalay, 2020), (Klüber et al., 2014), characterized by a user-friendly framework and allowing the integration of different aspects of the design process of a building thanks to the plug-ins available on its library. SketchUp 3D CAD (Trimble Navigation., 2020) combined with optimizations tools was used in two studies (Cellura et al. 2019), (Montana 2020), one study did not perform a CAD modelling (Montana et al. 2020) and one study applied the Pleiades (Izuba Énergies, 2020) tool able to combine the 3D modelling, the energy simulation, the optimisation and environmental life cycle assessment (Recht et al., 2016). The calculation of the energy demand during the building operation was mainly carried out with a dynamic BPS software. In detail, the software EnergyPlus (U.S. Department of Energy, 2020) is the most used (Hollberg and Ruth 2013, 2014), (Klüber et al., 2014), (Cellura et al. 2019), (Montana 2020), because it can easily be connected with Rhinoceros and SketchUp. Four studies (Hollberg and Ruth 2016), (Montana et al. 2020), (Kiss and Szalay, 2020) based the energy calculations on the quasi-stationary seasonal method described on the European standard EN ISO 13790 (ISO, 2008) or on the German standard DIN V 18599 (DIN, 2011). The optimisation tools and algorithms (Building Performance Optimization – BPO tools) employed are the following: the Galapagos Rhinoceros plug-in used in (Hollberg and Ruth 2013, 2014), (Hollberg et al., 2014); the Octopus Rhinoceros plug-in used in (Klüber et al., 2014) (Kiss and Szalay, 2020); the GOAT Rhinoceros plug-in used in (Klüber et al., 2014), (Hollberg and Ruth, 2016); MOBO Multi Objective Building Optimisation tool (MOBO, 2020), (Palonen et al., 2013) used in (Cellura et al. 2019), (Montana, 2020), (Montana et al. 2020); MATLAB used in (Montana, 2020). The examined case studies indicate the application of different software tools, which can be used alone or in combination. The unique tool that integrates different aspects in the same platform is Pleiades.

Focusing on the optimization process, both the single-objective optimisation approach (six studies) (Hollberg and Ruth 2013, 2014, 2016), (Hollberg et al., 2014), (Klüber et al., 2014), (Kiss and Szalay, 2020) and the multi-objective optimization one (seven studies) (Klüber et al., 2014), (Cellura et al. 2019), (Montana, 2020), (Montana et al. 2020), (Recht et al., 2016) (Kiss and Szalay, 2020) are employed. Some studies integrated the single-objective optimisation with the calculation of life cycle impact indicators, although they were not optimised (Hollberg and Ruth 2013, 2014), (Hollberg et al., 2014).

Most of the examined case studies used heuristic algorithms, in particular genetic algorithms. The application of heuristic and meta-heuristic algorithms is usually preferred due to the non-linear characteristic of most of the optimisation problems in engineering. Two studies implemented a dual step approach and used the "Branch and Bound" algorithm in the second step (Montana, 2020). Some studies applied the single-objective genetic algorithm available on Galapagos tool (Hollberg and Ruth, 2013, 2014), (Hollberg et al., 2014) and the optimisation plug-in of Rhinoceros-Grasshopper modelling environment. Other studies used the CRS2 (Hollberg and Ruth 2016), (Klüber et al., 2014) or HypE (Kiss and Szalay, 2020) algorithms, also working on Rhinoceros. The multi-objective algorithms employed were NSGA II (Cellura et al. 2019), (Recht et al., 2016) that is one of the most popular in the scientific literature (Longo et al., 2019), HypE Kiss and Szalay, 2020) and OmniOptimizer (Montana, 2020), (Montana et al. 2020).

[1] Operational energy only.

Table 2 summarizes the main features of the examined case studies.

Table 2: Summary of the main features of the examined case studies

Reference	Aim	BPS	BPO	Optimization approach	Optimization algorithm
(Recht et al., 2016)	Design of a plus-energy house	Pleiades (COMFIE module)	AMAPOLA (developed in Python)	Multi-objective	NSGA-II genetic algorithm
(Kiss and Szalay, 2019)	Design	Grasshopper. Quasi-steady state approach based on ISO 13790	Octopus plug-in for Grasshopper (Rhinoceros)	Single-objective	HypE genetic algorithm
(Kiss and Szalay, 2019)	Design	Grasshopper. Quasi-steady state Approach based on ISO 13790	Octopus plug-in for Grasshopper (Rhinoceros)	Multi-objective	HypE genetic algorithm
(Hollberg et al., 2014)	Design of a garage	Not performed	Galapagos plug-in for Grasshopper (Rhinoceros)	Single-objective	Evolutionary algorithm
(Hollberg and Ruth, 2013)	Renovation	EnergyPlus	Galapagos plug-in for Grasshopper (Rhinoceros)	Single-objective	Evolutionary algorithm
(Hollberg and Ruth, 2014)	Renovation	EnergyPlus	Galapagos plug-in for Grasshopper (Rhinoceros)	Single-objective	Evolutionary algorithm
(Klüber et al., 2014)	Renovation	EnergyPlus	GOAT plug-in for Grasshopper (Rhinoceros)	Single-objective	CRS2 evolutionary algorithm
(Klüber et al., 2014)	Renovation	EnergyPlus	Octopus plug-in for Grasshopper (Rhinoceros)	Multi-objective	Genetic algorithm
(Hollberg and Ruth, 2016)	Renovation	Grasshopper. Quasi-steady state approach based on DIN V 18599	GOAT plug-in for Grasshopper (Rhinoceros)	Single-objective	CRS2 evolutionary algorithm
(Cellura et al., 2019), (Montana, 2020)	Renovation	EnergyPlus	MOBO; MATLAB	Multi-objective	NSGA-II genetic

					algorithm; Branch and Bound MILP algorithm
(Cellura et al., 2019),(Montana, 2020)	Renovation	EnergyPlus	MOBO; MATLAB	Multi-objective	NSGA-II genetic algorithm; Branch and Bound MILP algorithm
(Montana et al., 2020)	Renovation	Be18 (based on ISO 13790)	MOBO	Multi-objective	Omni-Optimizer genetic algorithm
(Montana, 2020)	Renovation	EnergyPlus	MOBO; MATLAB	Multi-objective	Omni-Optimizer genetic algorithm; Branch and Bound MILP algorithm

2.4 Objective functions and variables

2.4.1 Objective functions

The objective functions of the examined case studies can be grouped in three categories: operation stage energy performance, life cycle based and embodied[2] environmental impacts and economic aspects.
The operation stage energy demand and life cycle based or embodied greenhouse gas emissions are two of the most adopted objective functions, usually dependent each other. Also other LCA based environmental impact indicators are included both in single and multi-objective optimizations. Only one study (Hollberg et al., 2014) regarding the design of a bike garage (with hardly any impacts during the use stage) neglected the use phase and examined only the embodied impacts. In some single-objective optimisations studies (Hollberg and Ruth, 2016), (Kiss and Szalay, 2019) different objective functions are taken into account separately, in order to evaluate the dependency of the optimal interventions on each objective function. Other studies (Montana, 2020) follow a two-step approach, in which the building energy demand during the operation is optimized in a first run, considering only the building envelope components as variables, while in a second run the optimized building envelope is the starting point for optimizing the building equipment able to minimize also operating costs and life-cycle based environmental impacts.
The indicators for the environmental impacts examined in the case studies are among the most commonly used in LCA studies on buildings (Bahramian and Yetilmezsoy, 2020), (Lasvaux et al., 2015): greenhouse gas emissions (taken into account in all the examined studies) ozone depletion potential (Hollberg et al., 2014), (Hollberg and Ruth, 2014, 2016), (Kiss and Szalay, 2019), acidification potential (Hollberg et al., 2014), (Hollberg and Ruth, 2014, 2016), (Kiss and Szalay, 2019), eutrophication potential, abiotic depletion potential (Hollberg et al., 2014), (Hollberg and Ruth, 2016), photochemical ozone creation potential (Hollberg et al., 2014), (Hollberg and Ruth, 2014, 2016), (Kiss and Szalay, 2019), cumulative energy demand (Cellura et al., 2019), (Montana, 2020), (Montana et al., 2020), (Kiss and Szalay, 2019), Renewable Primary Energy (RPE) and Non-Renewable Primary Energy (NRPE) requirement (Hollberg et al., 2014), (Hollberg and Ruth, 2014, 2016).
Seven out of thirteen of the studies assessed the economic aspects of the interventions (Cellura et al., 2019), (Montana, 2020), (Klüber et al., 2014), (Recht et al., 2016), focusing on construction cost (three studies) (Klüber et al., 2014), (Recht et al., 2016), on investment and operating costs (two studies) (Cellura et al., 2019), and on maintenance costs (two studies) (Montana, 2020), (Montana et al., 2020), respectively.
When a multi-objective optimization is applied in the examined case studies, including costs and energy and environmental impacts, some indicators appear to be non-conflicting. For example, Kiss and Szalay (2020) found that CED, life cycle greenhouse gas emissions and POCP tend to the same direction, while in (Cellura et al., 2019), (Montana, 2020) and (Montana et al., 2020) the same relationship is found for embodied energy, GWP and investment cost. In that cases, minimizing costs, CED and GWP led the space of objective functions to become a cloud of solutions with the Pareto Front being concentrated at the base of this cloud, although the proportionality relation between the functions is not exactly linear (Montana et al., 2020). Investment costs and embodied impacts usually conflict with operating energy demand (Cellura et al., 2019), (Montana, 2020), (Montana et al., 2020) and life cycle greenhouse gas emissions (Recht et al., 2016).

2.4.2 Variables categories

Different variables can be selected in the optimization studies of buildings, regarding the building features. The following typology of variables can be identified in the examined case studies:

- Design variables, as the orientation of the building or the number of floors.
  As outlined in the previous sections, most of the studies focused on the building renovation. For this reason, the optimization of the design variables is developed only in three studies: two of them examined

[2] The term "embodied" here refers to the impacts generated during the production step. In some cases, also the impact generated during the end-of-life is included.

the “number of floors” as variable (Kiss and Szalay, 2019) and the remaining one the position of the columns of a garage (Hollberg et al., 2014).

- Envelope components variables, both for the opaque and transparent components. Examples of variables are the thickness and material of the walls for the opaque components and the frame material, surface and type of glass for the transparent components.
  The opaque envelope is included in most of the examined studies, which investigated the optimal material or thickness for envelope components, as insulation or bricks or concrete (Klüber et al., 2014), (Cellura et al., 2019), (Hollberg et al., 2014).
- Variables describing the renewable energy technologies (e.g. surface of solar collectors) and air-conditioning systems (e.g. rated size). In detail, the optimization of these variables is common in the examined studies, particularly the heating system in cold climates, while the analysis of cooling or ventilation is included in selected case studies (Cellura et al., 2019), (Recht et al., 2016), (Kiss and Szalay, 2019).

The assessment of many variables and their interdependency in the optimization of buildings is a difficult task and a different level of detail is required for the different objective functions. For example, the embodied environmental impacts of interventions can be considered linear: the embodied environmental impacts of the insulation doubles if its thickness doubles. On the contrary, the building thermo-physical behaviour has a non-linear trend and the effect of a combination of interventions is different than the sum of the individual effects. In this case, the effect of doubling the thickness of insulation on the building heating and cooling loads needs specific and detailed simulations and calculations.

In some cases, a parametric analysis can be applied to solve the complexity of the computation. In the examined case studies, Hollberg and Ruth (2013, 2014) performed parametric analyses on the optimal insulation thickness by examining different insulation materials, heating systems and time horizons. These parametric analyses help researchers in the selection of a reasonable range of variables in the optimisation studies, thus reducing the computational time and avoiding the risk of assessing useless or non-convenient values of variables.

Table 3 summarizes the main information on objective functions and variables.

Table 3: Summary of the main information on objective functions and variables

Reference	Aim	Objective functions	Variables
(Recht et al., 2016)	Design of a plus-energy house	Construction cost; life-cycle GWP	- Insulation thickness of walls, floor and roof - Windows area and glazing - Ventilation system - PV modules
(Kiss and Szalay, 2019)	Design	Life-cycle GWP; AP; ODP; POCP; EP; PE (indicated as CED in the study)	- Number of storeys - Insulation material and thickness of walls and roof - Window areas - Fixtures shading and glazing type - HVAC system - Number of storeys - Insulation material and thickness of walls and roof - Window areas - Fixtures shading and glazing type - HVAC system
(Hollberg et al., 2014)	Design of a garage	Embodied GWP; PE; NRPE; ODP; AP; EP; POCP; ADP (both mineral and fossil fuels)	- Position of the columns - Slab thickness - Concrete quality
(Hollberg and Ruth, 2014)	Renovation	Life-cycle GWP; RPE; NRPE; ODP; AP; EP; POCP	- Insulation material and thickness. Heating system and energy mix were changed parametrically
(Hollberg and Ruth, 2013)	Renovation	Embodied and operation GWP; NRPE	- Insulation thickness. Service life, heating system and insulation material were changed parametrically
(Klüber et al., 2014)	Renovation	Construction cost; life-cycle and embodied GWP; NRPE	- Insulation material and thickness - Cladding material - Heating system
(Hollberg and Ruth, 2016)	Renovation	RPE; NRPE; life-cycle GWP; ODP; AP; EP; POCP; ADP;	- Insulation material and thickness - Windows glazing - Heating system
(Cellura et al., 2019), (Montana, 2020)	Renovation	Construction, operating and maintenance costs; life cycle and embodied GWP; PE	- Additional insulation material and thickness for each orientation - Additional thermal mass for each orientation - Windows materials glazing and

		(indicated as CED in the study)	frames for each orientation - HVAC system - Electricity production systems - Electricity and thermal storages
(Montana et al., 2020)	Renovation	Construction, operating and maintenance costs; life-cycle GWP; PE (indicated as CED in the study)	- Additional insulation material and thickness - Cladding replacement - Transparent materials glazing and frames - HVAC system - PV modules

2.4.3 Constraints setting and management

The number of solutions found in an optimization process can be limited through the inclusion of constraints in the model. In the space of solutions, they can be identified as lines or planes at the boundary. However, the addition of constraints to an optimization problem can have the effect of making its solving process much more difficult. To manage the above complexity, different approaches can be adopted.

The most common approach is the adoption of penalty functions, which convert the constrained optimization problem into an unconstrained one by introducing an artificial penalty for violating the constraint. In the examined case studies, penalty functions are used to identify a combination of insulation and cladding materials (Klüber et al., 2014) or to set a minimum distance between the supporting concrete columns (Hollberg et al., 2014).

Other approaches are developed to avoid the use of penalty functions: Recht (2016) and Recht et al. (2016) managed the constraint of a positive annual energy balance by considering it as a criterion in the NSGA II selection steps (reproduction and replacement), together with Pareto Front rank of the solution and its Crowding distance as other criteria. Montana (2020) and Montana et al. (2020) developed the optimization process on MOBO, which includes an automatic constraint handling technique for most of the algorithms (Palonen et al., 2013). In these studies (Montana, 2020), (Montana et al., 2020), constraints are used to specify the thermal features of windows (e.g. by fixing the thermal transmittance of window depending on the type of glazing (double or triple)) or to fix the use of only one insulation or cladding material on walls or roof.

2.5 Environmental and economic data

The use of reliable, complete and representative input data is a critical issue in LCA and economic studies, since the results may be influenced by site-specific conditions (Cellura et al., 2011). Thus, the use of specific data characterized by technological, geographical and temporal representativeness for the examined system is suggested.

However, in order to simplify the inclusion of economic and environmental aspects in the optimization problems, especially in the early-design step, and to reduce the effort and time required for the mathematical process, usually secondary economic and environmental data are used, i.e. average data from literature.

The optimization process based on secondary data allows for obtaining generic indications on the problem analysed and the accuracy and representativeness of the results cannot be assured for the specific case study. Then, if needed, the obtained solutions can be verified through more detailed simulations (Pereira et al., 2015) and by using primary input data related to the examined case study.

The examined case studies are based on economic data arising from databases (Montana et al., 2020), (Recht et al., 2016) or market reports (Cellura et al., 2019) and on environmental data taken from LCA databases such as Ecoinvent v2 (Recht et al., 2016), (Kiss and Szalay, 2019), KBOB recommendation 2009/1 (Hollberg and Ruth, 2013), (Klüber et al., 2014), Ökobau (Hollberg and Ruth, 2014, 2016), (Montana et al., 2020), or from the Environmental Product Declarations (EPDs) (EPD, 2020).

2.6 Methodological framework and main design solutions

2.6.1 General framework of the optimization process

The general methodological process adopted in the examined case studies for solving the optimization problems is represented in Figure 1.

The first step focuses on the creation of the geometrical model of the initial building configuration (e.g. existing building, preliminary design) and the description of the envelope components (building materials and layer thickness) and of the building services. Then, auxiliary data as information on the climate and the reference period are defined.

The second step includes the optimization problem setting, that is the definition of variables, objective functions to be optimized, algorithms, parameters constraints, and the collection of data needed for describing the variables (e.g. different layer thicknesses) and for calculating the objective functions (e.g. specific GWP impacts).

The third step regards the run of the optimisation process, to start a loop of iterations, adopting a convergence criterion based on a fitness function. During each run of the optimization process new values of variables are generated and a “new” building is created, e.g. characterized by a specific envelope; then, the simulation of the “new” building energy performance is carried out with the building simulation; finally, the energy, environmental and economic impacts of the “new” building are calculated. The embodied environmental impacts are obtained directly from the variables selected by the optimisation algorithm for each configuration, multiplying the variable quantity (e.g. a specific material with a specific thickness) by its specific environmental impacts per reference unit (e.g. the greenhouse gas emissions due to 1 kg of a specific material). The contribution of the use stage to the impacts may be obtained by multiplying the energy input (e.g. electricity or thermal energy from a specific energy source such as natural gas, light fuel oil or wood) by the specific environmental impacts per reference unit (e.g. the greenhouse gas emissions due to the supply of 1 kWh of electricity, low voltage). The fitness function of each building configuration obtained during the optimization process is examined until the optimisation ends, that is when a convergence criterion is satisfied or when the maximum number of iterations is reached.

During the last step, the obtained results are examined in detail, in order to identify the values of the variables and the optimal solutions to be adopted for the building.

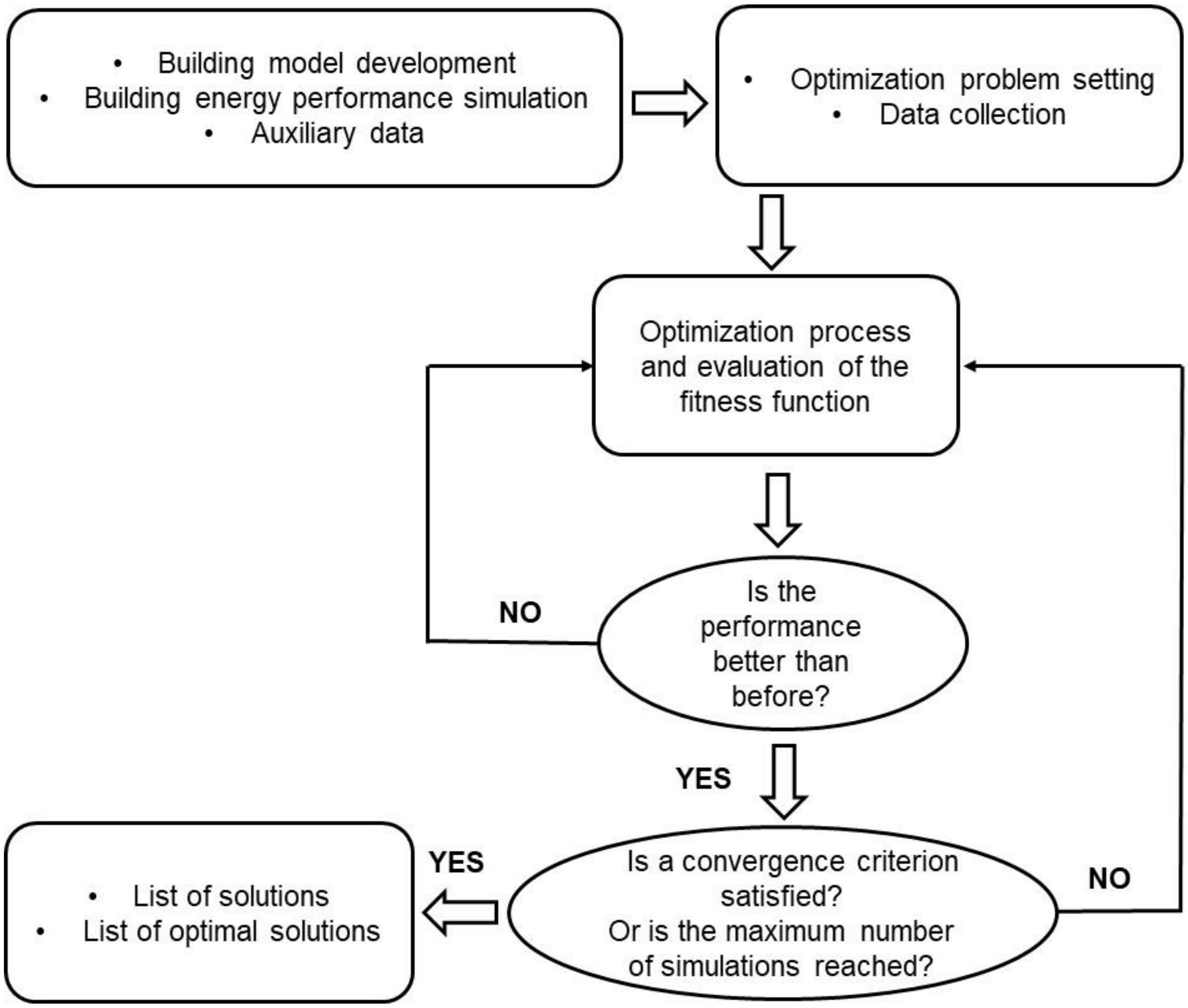

Figure 1: General workflow for the optimisation process of buildings

3. Collected case studies

3.1 Case study 1 (Recht et al., 2016)

This study has been performed in the frame of a research project launched by the French Environment Agency with the goal to design, build and measure "plus energy houses", i.e. renewable energy production should compensate the whole consumption (including heating, hot water, and all electricity uses) on a yearly basis. This was therefore a constraint in the optimisation study.

Short description of the case study building:
- Location: Centre-Val de Loire (France);
- Type of climate: warm temperate climate, without dry season, temperate summer;
- Type of building: single-family house;
- Type of action: design of a plus-energy house.

Pictures (Figure 2):

Figure 2: Case study building

Description of the building:
The house has a wooden structure, mainly composed of certified spruce and oriented strand board (OSB) panels. The walls and the roof are insulated with glass wool, and the floor with extruded polystyrene. Windows consist of frames made of PVC and double glazing and are mainly located on south-east and south-west façades. The house net floor area is 101 m². It has an electrical heating system and a thermodynamic water heater with an outdoor air heat pump. The average coefficient of performance (COP) is 2.77. The photovoltaic modules (1.6 m² each) are made of polycrystalline cells.

Life Cycle Assessment:

- Goal of the study: designing a plus energy building with a positive annual primary energy balance minimising both construction cost and life cycle greenhouse gas emissions (expressed in CO_2 equivalent);
- Functional unit or functional equivalent: the examined building, dwelling for 3 persons over 100 years, considering heating temperature schedules, ventilation, electricity and hot water consumption scenarios corresponding to a statistical model for France;
- System boundaries: construction (A1-A5), use (B6-B7), repair (B3), replacement (B4), demolition (C2-C4) and benefits and loads beyond the system boundary (D) stages;
- Selected impact indicators: construction cost and life-cycle GHG emissions;
- Main parameters: the building's lifetime was assumed to be 100 years, while for some materials and equipment were assumed lifetime values between 10 and 50 years;
- Life cycle inventory analysis: the inventory was built according to Ecoinvent database. In order to take into account the variability of energy production during the year (winter/summer, day/night), a dynamic hourly electricity mix was used.

Optimisation of the life cycle energy and environmental performance:

The software PLEIADES was employed. In detail, the COMFIE module was used for the dynamic building operational energy simulation, while the EQUER model was employed to perform the LCA. A construction cost database was used for the economic analysis. NSGA-II multi-objective and multi-variable genetic algorithm was used to optimise both the construction cost and the environmental impacts (life-cycle GHG emissions) of the building. Table 4 shows the 11 selected design variables, regarding both envelope and technical systems of the building.

Table 4: Design variables list and description

Design variables	Unit	Base value	Lower bound	Upper bound	Number of levels
Thickness of glass wool (walls)	cm	22	15	36	8
Thickness of polystyrene (floor)	cm	22	15	36	8
Thickness of glass wool (roof)	cm	26	12	28	8
Area of window 1 (south-east)	m²	3	2	5	4
Area of window 2 (south-east)	m²	1.46	1.46	2.92	2
Area of window 3 (south-west)	m²	6.88	0	10.50	4
Area of window 4 (south- west)	m²	2.71	2.71	5.42	2
Type of glazing in north-east facade*	-	DG	DG	TG	2
Ventilation system*	-	DF	SF	DF	2
Greywater heat recovery system	-	No	No	Yes	2
Number of photovoltaic modules*	-	12	1	28	16

*DG: double-glazed, TG: triple-glazed, SF: single-flow, DF: dual-flow, PV module surface area: 1.6 m²

As the NSGA-II is a multi-objective algorithm, the results of the optimisation do not provide a unique optimal solution but a set of optimal solutions, representing a compromise between the objectives. In this study, a set of 90 compromise solutions was obtained after 20 generations of individuals, which were very close to the theoretical Pareto Front (4 million calculated combinations), see Figure 3.

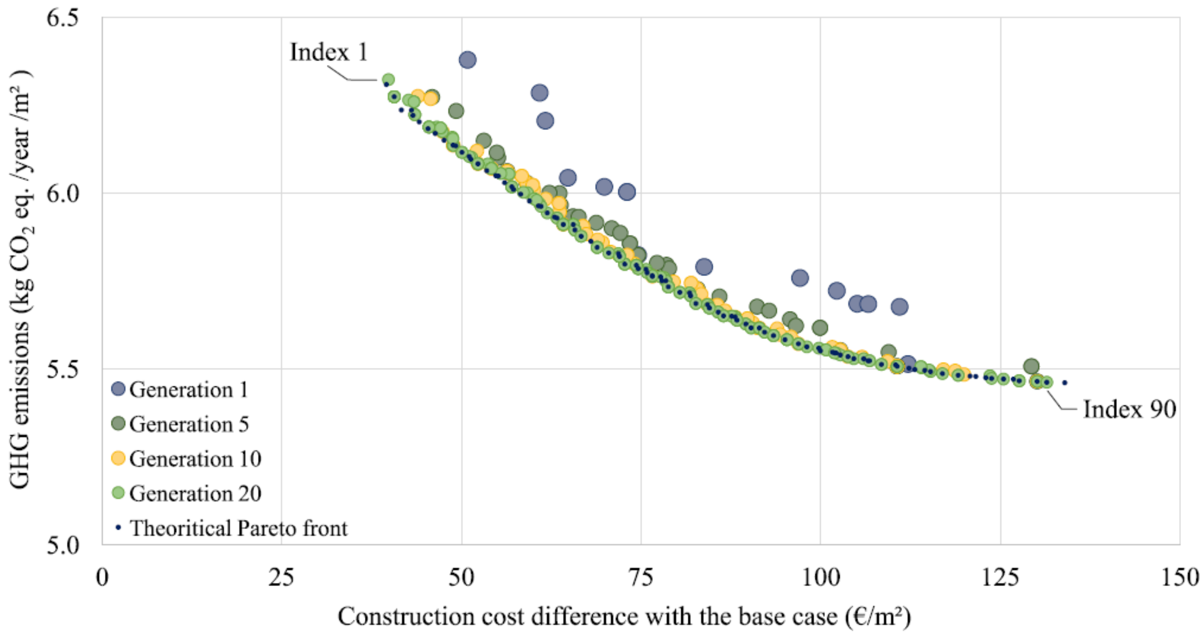

Figure 3: Evolution of the approached Pareto fronts and theoretical Pareto front

A statistical analysis of the 90 optimal solutions highlighted that (Figure 4) considering the type of glazing and the ventilation system variables, only triple-glazed windows on north-east façade and a dual-flow ventilation system with a 80% efficiency heat exchanger were selected in all alternatives, despite the dominated alternatives were sometimes cheaper. Regarding the photovoltaic modules-related variable, starting from 12 modules in the base case, the upper bound (28) was mostly represented, and no solution had less than 22 modules. Approached (coloured bars in Figure 4) and theoretical (white bars) Pareto fronts provide similar trends.

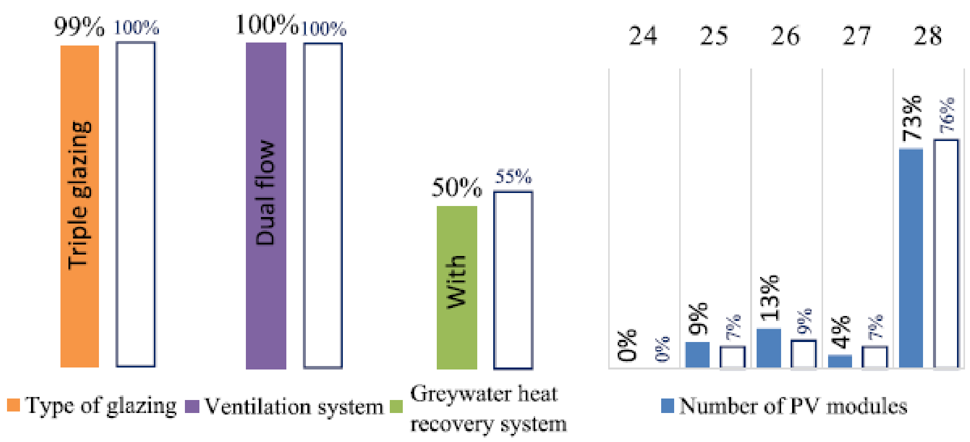

Figure 4: Statistical analysis on 90 optimal solutions: left columns: approached Pareto front right columns: theoretical Pareto front

Another interesting information gained from this study is the identification of the compromise solution for the insulation thickness. As shown in Figure 5, considering the decrease of GHG emissions, the thicknesses firstly increase slowly because the main GHG emissions reduction is due to the increasing number of photovoltaic modules. When the upper bound for photovoltaic modules number is reached, increasing the insulation thicknesses becomes a more pertinent action to implement in order to further reduce GHG emissions.

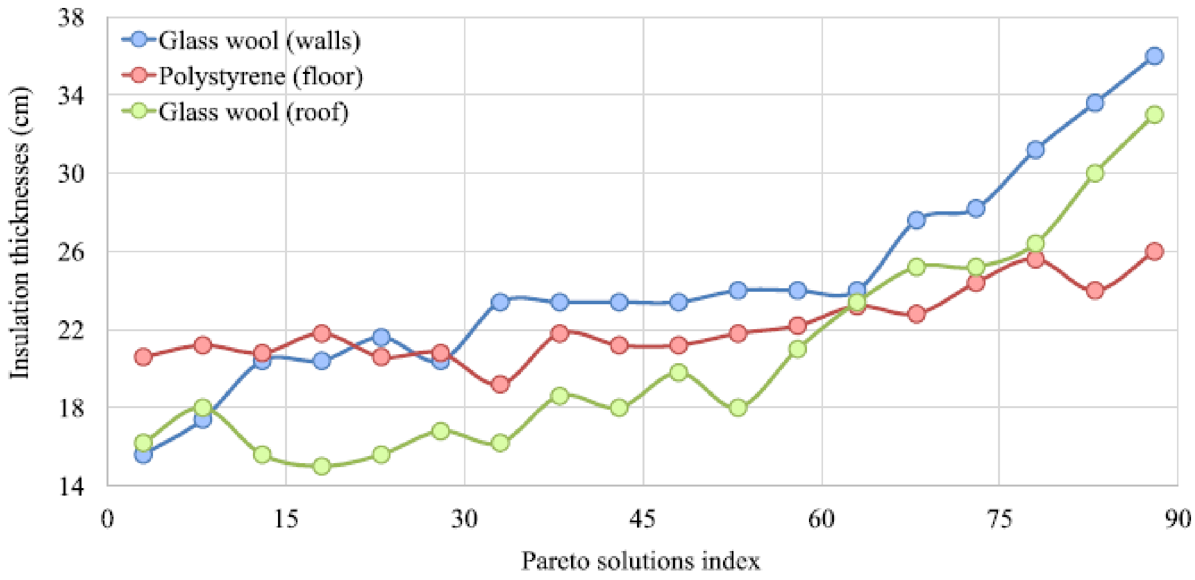

Figure 5: Evolution of the insulation thicknesses for decreasing GHG emissions (Pareto solutions)

<u>Lessons learned and conclusions:</u>

The outcomes of this study allow to state that:

- The construction costs and the life cycle environmental impact (GHG emissions) of a building are conflicting objectives, thus the adoption of a multi-objective approach is necessary for the design and the renovation of buildings;
- The employment of a heuristic population-based optimisation algorithm allows to investigate a great number of solutions and to obtain a set of pseudo-optimal solutions (very close to the theoretical Pareto Front) in a reasonable amount of time. In detail, in this study the pseudo-Pareto front was attained in 2 hours, investigating 8,000 solutions in a search space composed by 4,194,304 combinations;
- The adoption of technologies such as photovoltaic modules, triple glazing windows and heat recovery ventilation systems are able to easily repay their embodied carbon with the operating savings over the use phase of the building life cycle. Moreover, in the context of this case study, the photovoltaic system is preferred to insulation thickness over 20 cm as energy efficiency intervention.

<u>References:</u>

T. Recht, P. Schalbart, B. Peuportier. Ecodesign of a 'plus-energy' house using stochastic occupancy model, life-cycle assessment and multi-objective optimisation. Hamza N AND Underwood C. (Ed) Building simulation and optimisation, third international building performance simulation association IBPSA-England, Sep 2016, Newcastle, United Kingdom. hal-01464310f

3.2 Case studies 2-3 (Kiss and Szalay, 2020)

Note: The study focuses on a single-objective (Case study 2) and on a multi-objective (Case study 3) optimization.

Short description of the case study building:
- Location: Budapest (Hungary);
- Type of climate: continental;
- Type of building: residential multi-storey building;
- Type of action: building design.

Description of the building:
The case study is the early design stage of a middle-sized apartment house with a rectangular shape, flat roof and a heated area of 740 m^2. Since the building is in an early design stage, further details, such as the number of floors, length and width of the building, the insulation level and the window-to-wall ratio, are still to be defined through the optimisation.

Life Cycle Assessment:
- Goal of the study: to support the architectural design process by showing the options with the lowest environmental impact for the whole life cycle;
- Functional unit or functional equivalent: the building;
- System boundaries: product stage (A1–A3), construction process (A4–A5), use stage (B2–B4 and B6 operational energy use), and end-of-life stage (C2–C4);
- Selected impact indicators: the following impact categories, analysed through the CML 2001 method, were optimised: GWP, AP, ODP, POCP, and EP. In addition, NRPE was considered.
- Main parameters: the time horizon of the study is 50 years;
- Life cycle inventory analysis: only secondary data were employed in this study, using the Ecoinvent v2.2 database that, being based on German and Swiss contexts, was adapted to the Hungarian scenario changing the electricity production mix. The operational energy demand for the case study was calculated with the quasi-steady state seasonal method of the EN ISO 13790.

Optimisation of the life cycle energy and environmental performance:
Several optimisation studies were performed, minimizing the LCA impact indicators above described one by one (single-objective) or all together (multi-objective) through the HypE many-objective genetic algorithm, provided by the Octopus plugin for Rhinoceros 3D modeller.
The parameters for the optimisation algorithm are shown in Table 5.

Table 5: Optimisation algorithm parameters

Parameter	Value
Population size	100
Maximum number of generations	20
Elitism	0.5
Mutation probability	0.2
Mutation rate	0.9
Crossover rate	0.8

Three out of four categories of variables were optimised:
- Building envelope: wall and roof insulation type and thickness, window areas;

- Fixtures: shading, glazing type;
- HVAC and equipment: a condensing gas boiler for heating with an air conditioner for cooling, a heat-pump for both heating and cooling or a pellet boiler for heating and an air conditioner for cooling.

In detail, the HVAC systems were excluded from the optimisation, but the optimisation studies were performed three times setting HVAC systems as a parameter.
The results of the single-objective optimisation studies are shown in Tables 6 and 7.

Table 6: Geometrical parameters of the best solution found for each indicator in the single-objective optimisations (energy source for operation: natural gas)

Objective	Number of Floors	Building Width	Length	Width/ length	gizRatioN	gizRatioW	gizRatioS	gizRatioE
CED	7	8	13.21	0.61	0.02	0.02	0.6	0.02
GWP	6	8	15.42	0.52	0.17	0.09	0.56	0.1
AP	4	12	15.42	0.78	0.02	0.09	0.58	0.11
ODP	4	8	23.13	0.35	0.03	0.26	0.58	0.39
POCP	5	10	14.80	0.68	0.05	0.07	0.59	0.04
EP	4	12	15.42	0.78	0.01	0.02	0.59	0.01
Multi Objective (mean±std)	5.11± 0.73	9.84± 1.86	15.21± 1.86	0.67± 0.23	0.24±0.01	0.06±0.02	0.58±0.00	0.20±0.09

Table 7: Construction parameters of the best solution found for each indicator in the single-objective optimisations (energy source for operation: natural gas)

Objective	wallIns Thick	wallIns Mat	roofIns Thick	roofIns Mat	glazingN	glazingEW	glazingS	shading
CED	0.46	Cellulose	0.33	Glass wool	Triple	Triple	Triple	Yes
GWP	0.39	Cellulose	0.16	PUR	Triple	Triple	Triple	Yes
AP	0.15	PUR	0.37	Cellulose	Double	Triple	Double	Yes
ODP	0.47	PUR	0.5	PUR	Triple	Triple	Triple	Yes
POCP	0.49	Cellulose	0.32	Cellulose	Triple	Triple	Double	Yes
EP	0.2	Cellulose	0.21	Cellulose	Triple	Triple	Double	Yes
Multi Objective (mean±std)	0.24±0.13	PUR (79%)	0.26± 0.05	PUR (100%)	Triple (79%)	Double (79%)	Double (95%)	Yes

In general terms, a mid-rise building of 4-7 storeys and a relatively compact shape is found to be optimal. Regarding the glazed area in the façade, the results confirm the principle of energy efficient design: large glazed areas of close to 60% ratio to the south (intensive solar gain), and low glazed area to the north (more insulation). The ratio on the west and east façade is 2–10% except for ODP where higher ratios are allowed. Triple glazing tends to be more favourable on the north, east and west façade, and double or triple on the south façade depending on the indicator. It is important to mention that the optimization concluded that shading must be applied to the windows in all cases to reduce the cooling demand.
The results of the multi-objective optimisation are provided graphically in Figure 6, where the advancement of the objectives with the generations and a comparison with the singe-objective optimisation results are also shown.

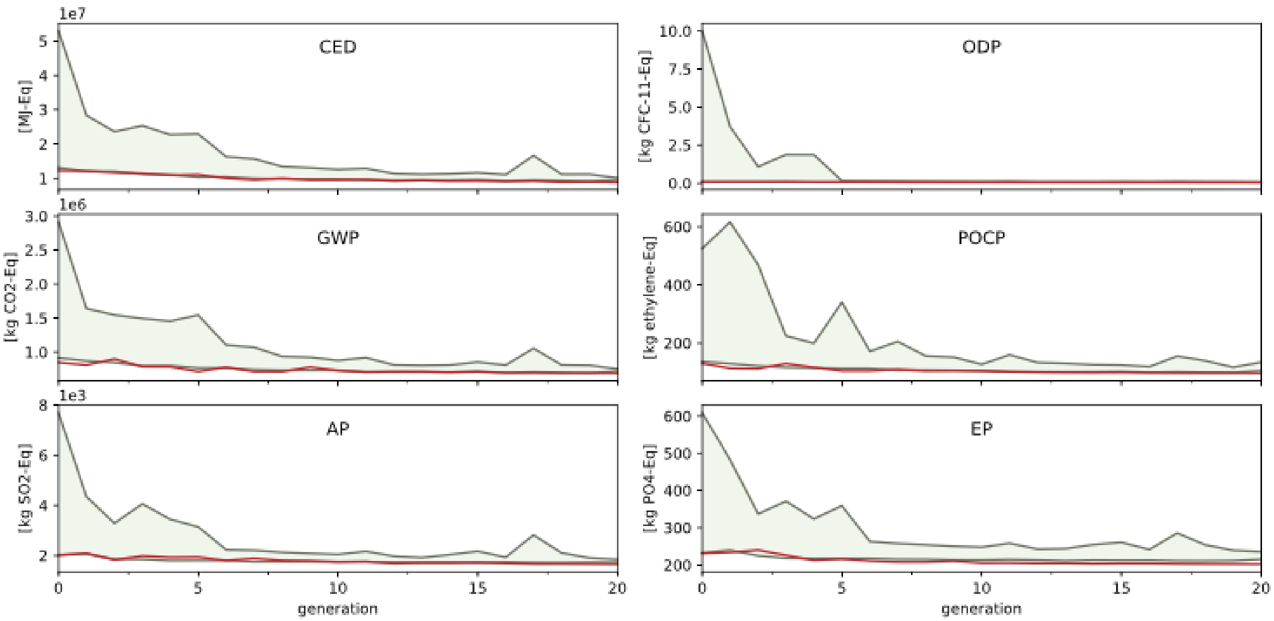

Figure 6: Improvement of the objectives (minimum and maximum values) throughout the generations in the multi-objective optimization (green), and the minimum values from the single-objective optimization (red), if the energy carrier for building operation is natural gas

Comparing the achieved optima with those of the single-objective optimization, they are barely worse for each objective (within 5%), and it is possible to see that no major improvement was reached after the 15th generation.

The results of the multi-objective optimisation indicate similar parameters for the building as the results of the single-objective optimisation in terms of geometrical parameters: a close-to-cubic shape with a somewhat larger façade to the south (see Table 6); large glazed areas to the south, and low glazing to the north. The level of insulation is very high in this case too (25–30 cm for the roof, and 15–45 cm for the wall). A strong split can be observed for the insulation thickness on the walls, which either means extremely thick insulation (35–45 cm) or a rather reasonable but still very high insulation (15–25 cm) (Figure 7).

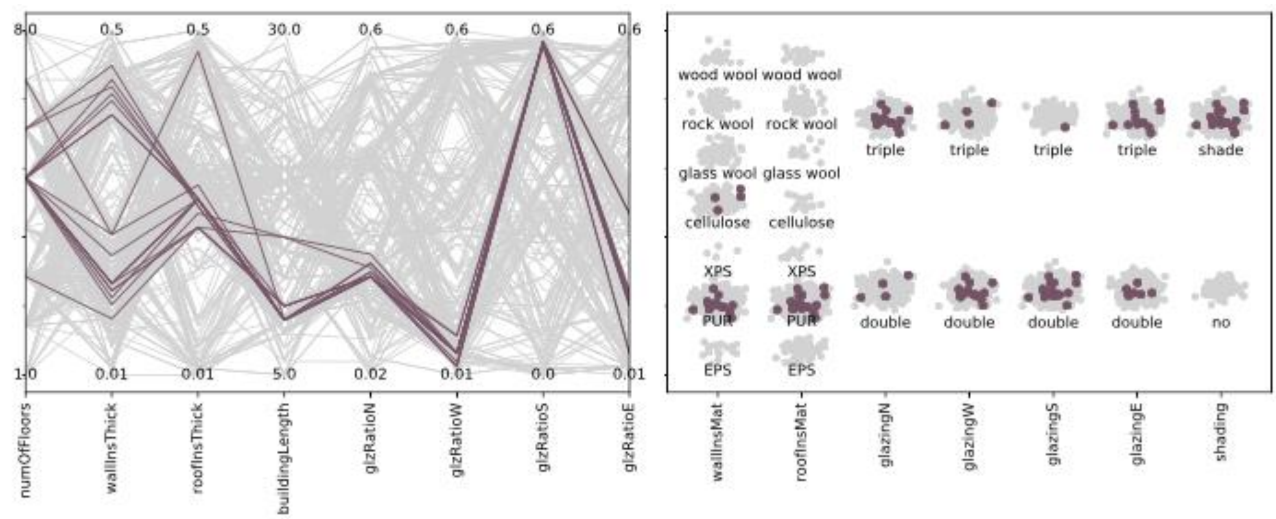

Figure 7: Optimal values of variables in the multi-objective optimisation study

A further optimisation study was performed, focusing only on CED (non renewable plus renewable), comparing the single objective optimisation of only embodied or operational energy with the multi-objective optimisation of both of them. The results, shown in Figure 8, indicate how these two quantities are conflicting, and a further analysis prove that the share of the operational impact is about one third of the total impact, highlighting that a life cycle approach should be applied in the optimisation of building energy performance.

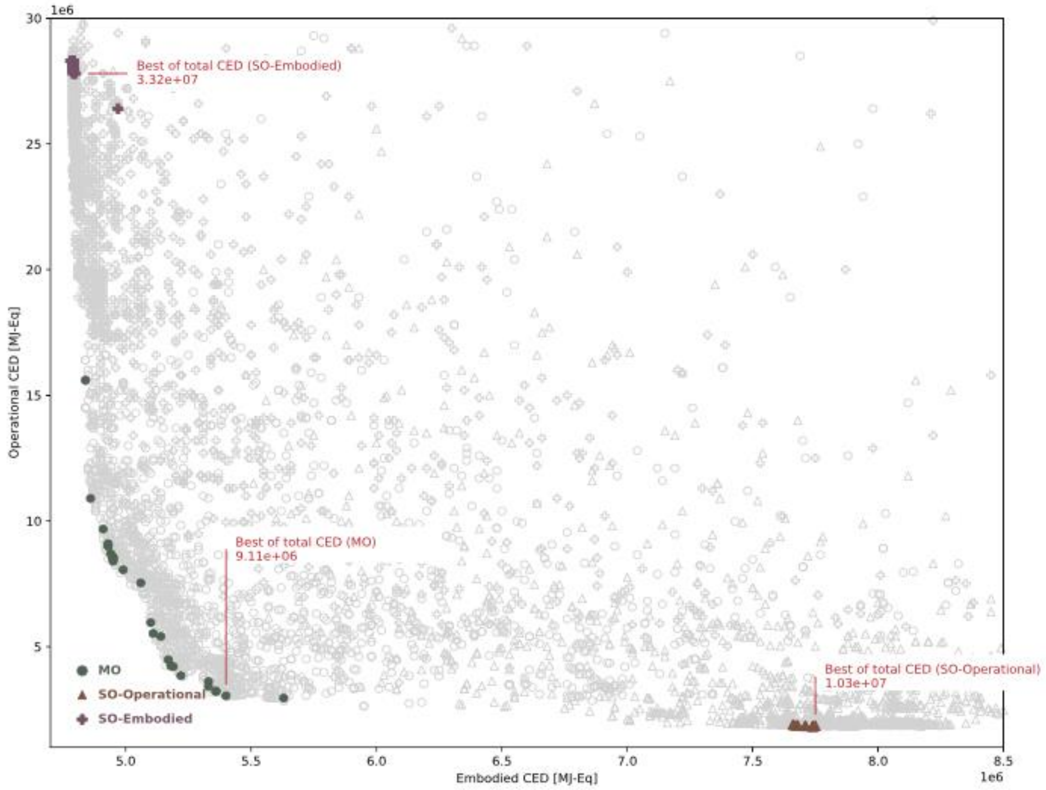

Figure 8: Results of the multi- (MO - green dot) and single-objective (SO-operational - red triangle, SO-embodied - purple cross) optimizations on the objective space for CED (heating energy carrier: natural gas)

Lessons learned and conclusions:

The case study showed that single-objective optimisation leads to different optima for different environmental indicators, which makes it difficult for the designer to decide between the options without explicitly assigning a weighting to the indicators. To overcome this issue, a multi-objective optimization should be applied, so the optimised options guarantee that no indicator will be neglected.

In all the studies, the optimisation achieved very significant environmental savings of 60–80% compared to the initial design options, proving the importance of the optimisation studies in this field.

The analysis showed that CED – GHG emissions, CED – POCP and GHG emissions – POCP are non-conflicting objectives in this case. This means that it may be sufficient to include only one of the three indicators as an objective in the optimization, which would reduce the computation time in the results evaluation phase.

References:

Kiss B, Szalay Z, Modular approach to multi-objective environmental optimization of buildings. Automation in Construction, 111, 103044, 2020.

3.3 Case study 4 (Hollberg and Ruth, 2013)

Short description of the case study building:

- Location: not specified;
- Type of climate: not indicated, but it is known that Germany's climate is continental or oceanic;
- Type of building: residential;
- Type of action: renovation.

Description of the building:

The building is that it is a single-family house built in the '50s. This is a hypothetical case study showing the application of a parametric LCA approach in the early design stage. Thus, no further detail on the building is provided.

Life Cycle Assessment:

- Goal of the study: identifying the interventions minimising the life cycle impacts of the building;
- Functional unit or functional equivalent: the retrofitted building;
- System boundaries: embodied and operational environmental impacts were assessed;
- Selected impact indicators: GHG emissions and non-renewable primary energy, which is assessed but not optimised;
- Main parameters: energy efficiency of the heating system (a gas-fired boiler and three heat pumps with different COP), expected service life of the insulation materials and heating system;
- Life cycle inventory analysis: only secondary data were employed for the present study. KBOB Swiss database was employed for the impacts while service life of components was drawn from the Information portal Nachhaltiges Bauen, Schweiz.

Optimisation of the life cycle energy and environmental performance:

In this study, the GHG emissions related to the life cycle of a building were minimised using *Grasshopper*, a parametric design software, and *DIVA for Rhino*, a plug-in that links *Grasshopper* to *EnergyPlus*. *Galapagos* plug-in was employed for the optimisation through a single-objective evolutionary algorithm. Several scenarios with different variables related to envelope and equipment were performed:

1. Optimal insulation thickness depending on service life. This scenario was aimed at identifying the optimal insulation thickness for external walls, ceiling and roof considering different time horizons (5, 10, 20 and 30 years), showing that the optimal thickness is highly dependent also on this parameter, with optimal values increasing for higher service life (Figure 9). A gas-fired boiler heating system was assumed to be installed in this scenario. Rock wool insulation was adopted for ceiling and roof and EPS for walls.

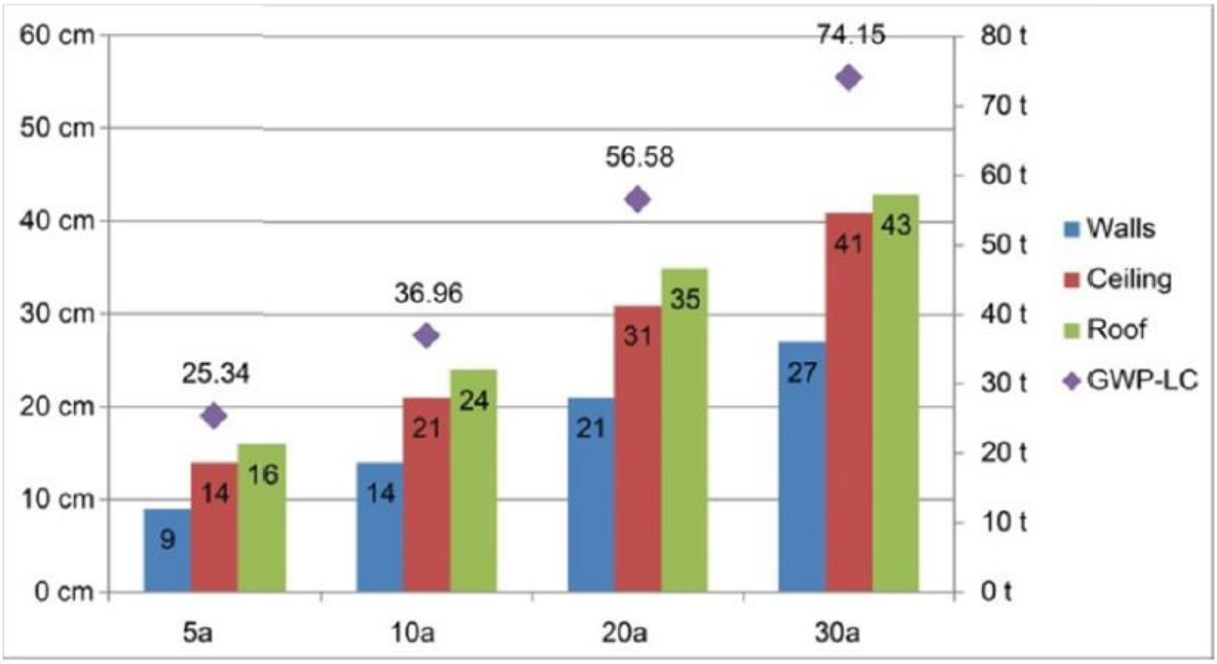

Figure 9: Optimal insulation thickness for each envelope component and life cycle GHG emissions depending on service life

2. Optimal insulation thickness depending on heating system. This scenario was aimed at identifying the optimal insulation thickness for external walls, ceiling and roof considering different heating systems (a gas-fired boiler and three heat pumps with different COP).

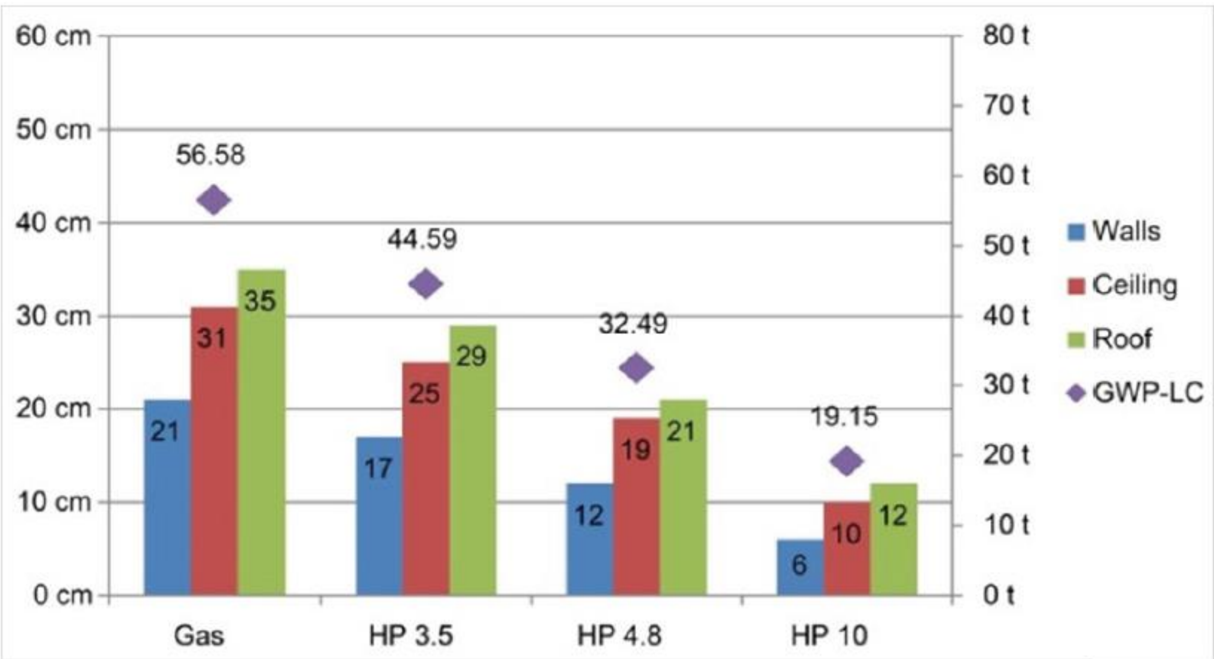

Figure 10: Optimal insulation thickness for each envelope component and life cycle GHG emissions depending on heating system; insulation material: ceiling and roof: rock wool; walls: EPS; service life: 20 years

With higher system efficiency, thus lower operating GHG emissions related to the heating production, the optimal thickness rapidly decreases (Figure 10). A service life of 20 years was assumed in this scenario. Rock wool insulation was adopted for ceiling and roof and EPS for walls.

3. Optimal insulation thickness depending on insulation material. This scenario was aimed at identifying the optimal insulation thickness for external walls, ceiling and roof considering different insulation materials (EPS, glass wool, rock wool and wood fibre). The outcome is that natural materials allow lower GHG emissions although higher thickness values are selected (Figure 11). A gas-fired boiler heating system was assumed to be installed in this scenario. A service life of 20 years was assumed in this scenario.

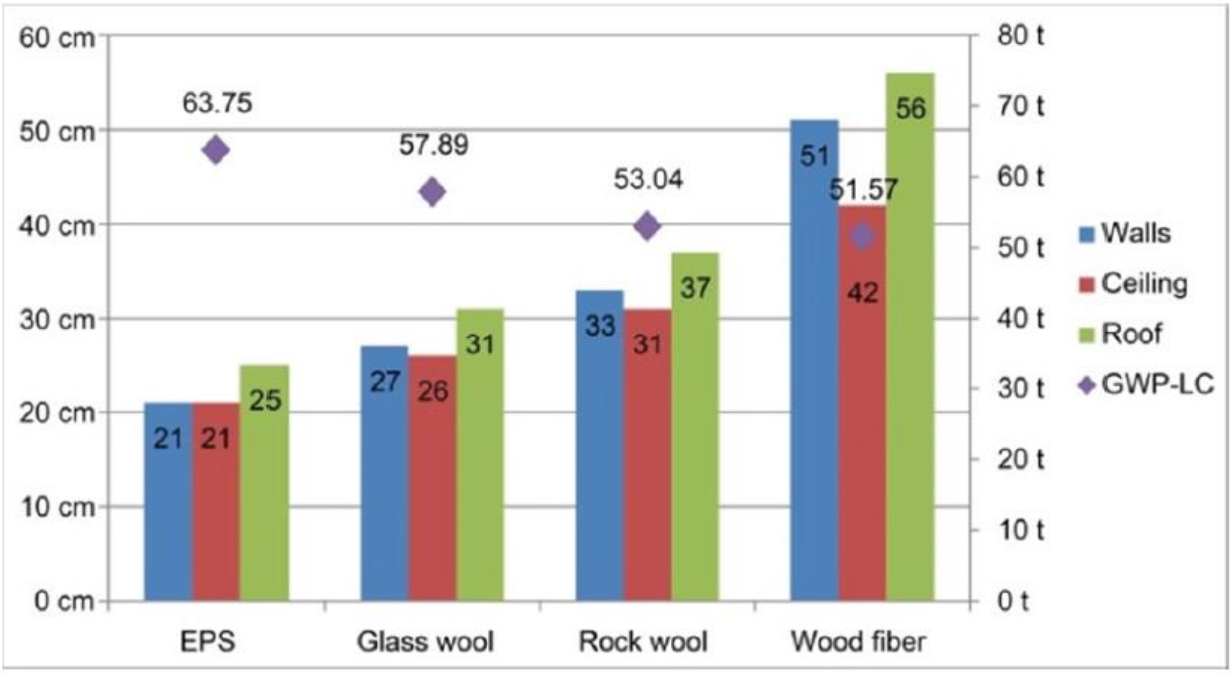

Figure 11: Optimal insulation thickness for each envelope component and life cycle GHG emissions depending on insulation material; gas fired boiler; service life of heating system and insulation: 20 years.

4. Optimal insulation thickness depending on insulation material and on heating system. This scenario was aimed at identifying the optimal insulation thickness for external walls, ceiling and roof considering different insulation materials and different heating systems (the same examined in the previous scenarios). The outcome of this optimisation is that the maximum thickness was obtained combining a heating system with high GHG emissions during operation, such as a gas boiler, with a low impact material, such as wood fibre, implying that a very high energy saving on the envelope is required to balance the impact of the heating system (Figure 12). No information on how the GHG emissions are influenced by these combinations is provided. A service life of 20 years was assumed in this scenario.

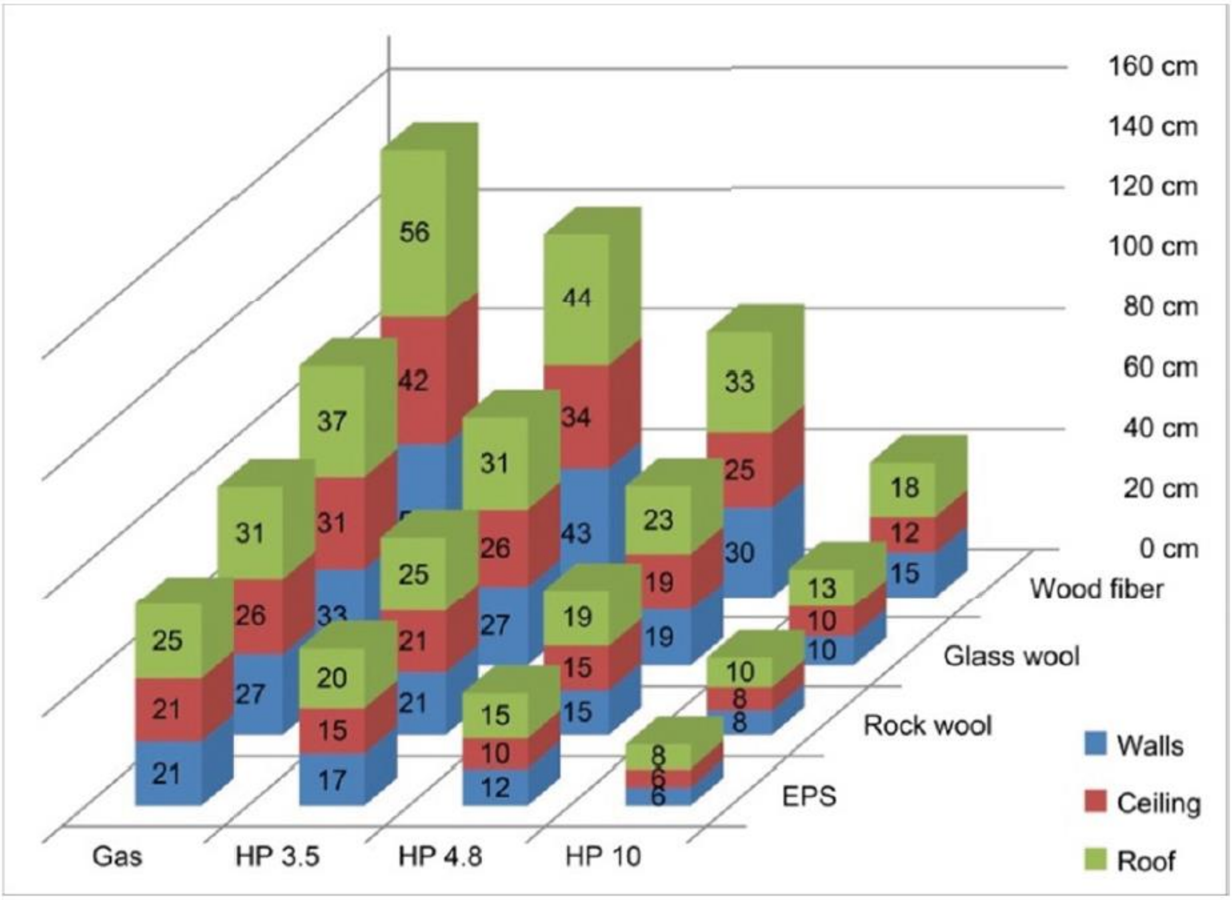

Figure 12: Optimal insulation thicknesses for each envelope component depending on heating system and insulation material; service life: 20 years.

Lessons learned and conclusions:

In this study, a deep investigation on the GHG emissions related to the life cycle of a building was performed, showing that many factors should be considered when a building is insulated, also including the expected service life of the building elements under assessment. The study highlighted that the lower is the lifetime the lower should be the thickness, since the embodied impact related to more insulation material would not be recovered in a few years. Furthermore, natural materials should always be preferred to synthetic insulation materials such as EPS or glass wool, since their lower embodied impact can easily balance a higher thickness required because of their higher specific thermal transmittance.

References:

Hollberg A, Ruth J, Parametric performance evaluation and optimization based on life cycle demands. 8th Energy Forum Adv. Build. Ski., Bressanone, Italy, 2013.

3.4 Case studies 5-6-7 (Hollberg and Ruth, 2014; Klüber et al., 2014)

Note: Three studies are developed for the same building: two single-objective optimizations (Case study 5 and Case study 6) and one multi-objective optimization (Case study 7).

Short description of the case study building:

- Location: Würzburg (Germany);
- Type of climate: continental;
- Type of building: typical single-family home in Germany from the 1960s;
- Type of action: renovation.

Pictures (Figure 13):

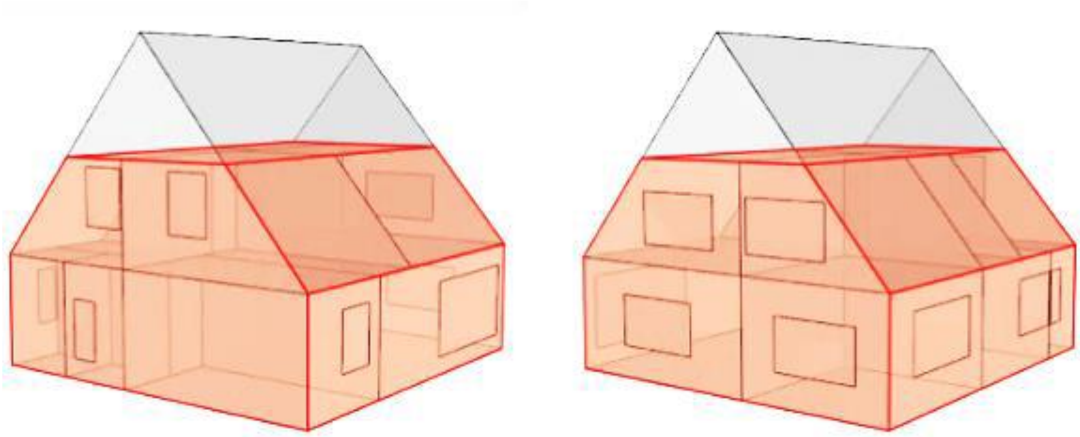

Figure 13: 3D model of the case study

Description of the building:

The case study is a single family house built in the 1960ies with very low insulation level. It was estimated that all buildings of this kind (age and energy efficiency level) account for the 47% of building sector final energy demand in Germany. The heated area of this house is 120 m^2, with a total heat exchange surface of 318 m^2 and a volume of 374 m^3. The external walls transmittance is 0.27 W/m^2 K, the roof transmittance is 0.19 W/m^2 K and the windows transmittance is equal to 1.3 W/m^2 K. The heating system is based on a gas-fired boiler, with heating set point equal to 20 °C during the day and 16 °C by night.

Life Cycle Assessment:

- Goal of the study: identifying the interventions to minimize the life cycle impacts of the building. In the first and second studies, external walls insulation materials and thicknesses were used as variables, although they were analysed with several heating systems, while in the third study the heating system and the external cladding were additionally optimised;
- Functional unit or functional equivalent: the retrofitted building;
- System boundaries: In the first and second studies, a cradle to grave approach was adopted, also including the end of life, thus production stage (modules A1-A3), operational energy use (B6) and the waste processing at the end-of-life (C3) were taken into account while module D (benefits and loads beyond the system boundary) was neglected because of the excessive uncertainty regarding far future material replacements and environmental impacts of primary material production. No details were provided for the third study;
- Selected energy and environmental impact indicators: in the first and second studies, GHG emissions were optimised but other six impact indicators were assessed: renewable and non-renewable primary energy, EP, AP, ODP, POCP. In the third study, the ratio of investment cost and life cycle GHG emissions were assessed and optimised;

- Main parameters: the reference study period was set equal to 30 years, assumed as the average useful life of insulation materials;
- Life cycle inventory analysis: in the first and second studies, embodied impacts for building materials and for energy vectors were derived from German Ökobau database 2013 when available (since it complies with standard EN ISO 15804) and 2011 for other parameters, while the operational heating energy demand was estimated with four different building performance simulation programs with similar results. For the third study, data from Swiss KBOB recommendation 2009/1, which are based on Ecoinvent data v2.2, were preferred for the impacts assessment of the building materials, while average market values were employed for the economic analysis.

Optimisation of the life cycle energy and environmental performance:
The building was subject of many parametric and optimisation studies. A simulation-based optimisation approach was employed combining *EnergyPlus* building performance simulation program with *Rhinoceros* 3D modeller through *ArchSim* plug-in. The studies can be summarized as follows:

1. Single-objective single-variable parametric analysis. This study was aimed at identifying the optimal external walls insulation thickness (ranging between 0 and 60 cm) of 8 insulation materials (EPS, XPS, PUR, glass wool, rock wool, foam glass, wood fibre, cellulose), thus optimising only the building envelope. The objective function was the life cycle GHG emissions, assessed for many different heating systems (gas-fired boiler or heat pump with 3 different COP values) and energy vector mixes (natural gas, German average electricity mix or electricity from wind energy). Results are shown in Figure 14 and Figure 15.

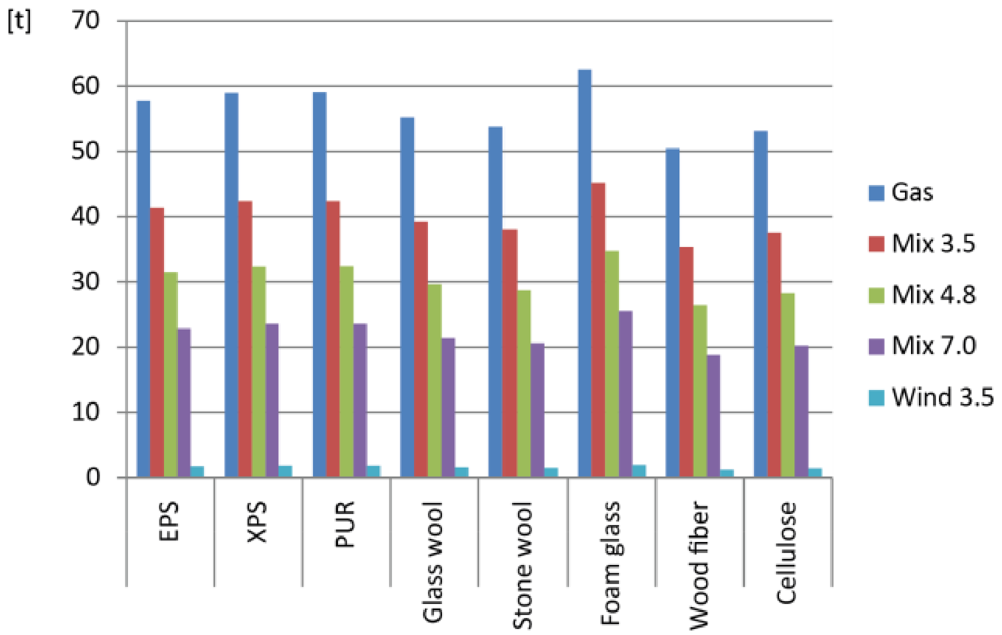

Figure 14: Minimal GHG emissions depending on the material and heating system

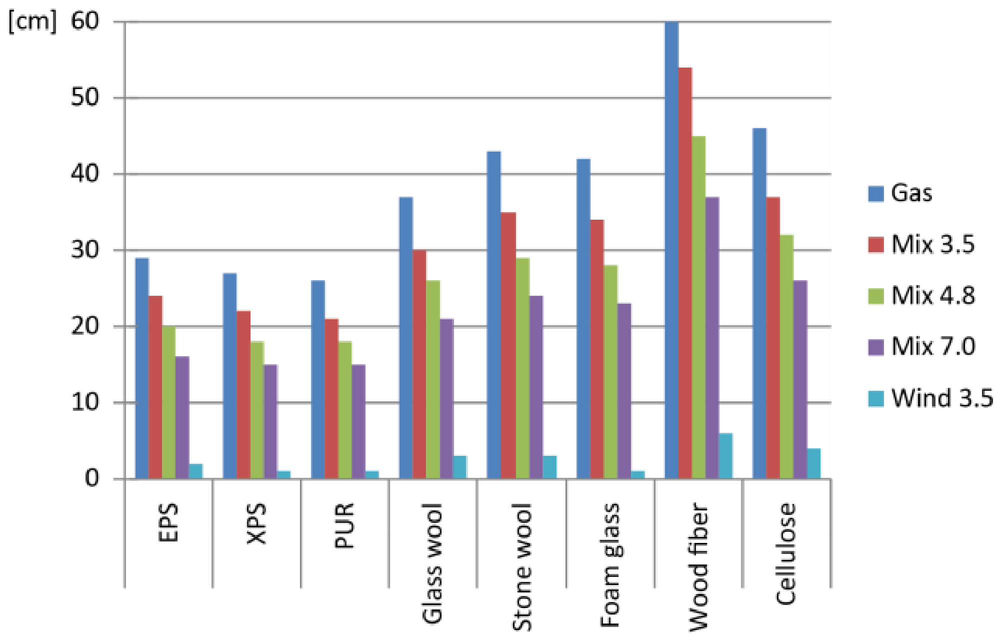

Figure 15: Thickness for minimal GHG emissions depending on the heating system

2. Single-objective optimisation through an evolutionary algorithm available in *Galapagos* plug-in. This study was aimed at identifying the optimal insulation thickness (ranging between 0 and 60 cm) of 8 insulation materials (EPS, XPS, PUR, glass wool, rock wool, foam glass, wood fibre, cellulose) to be installed on external walls, roof, ceiling and slab, minimising GHG emissions for a given heating system (gas-fired boiler or heat pump with 3 different COP values) and energy vector mix (natural gas, German average electricity mix or electricity from wind energy). The results are shown in Figure 16 and Figure 17.

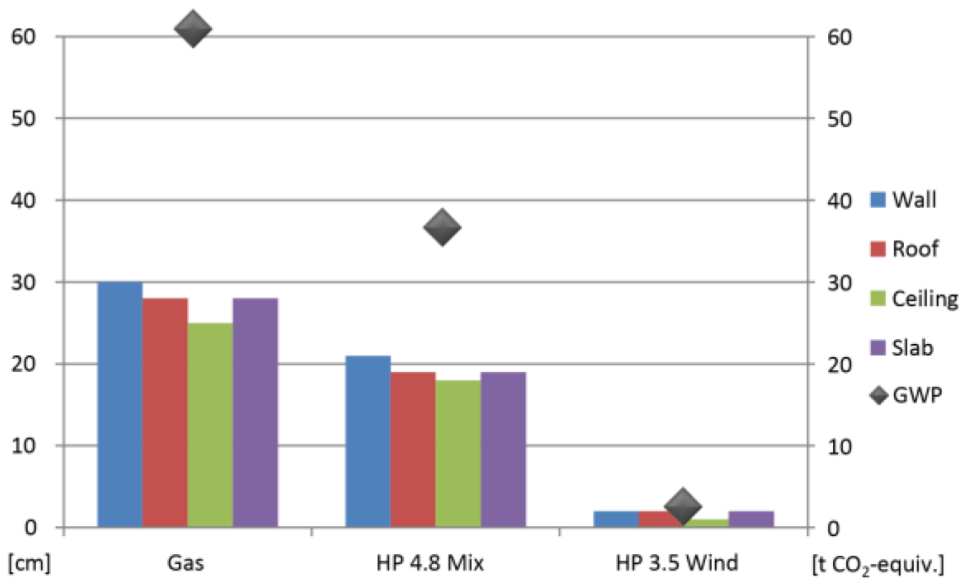

Figure 16: Optimal thicknesses of EPS depending on the heating system and on building envelope components minimising GHG emissions

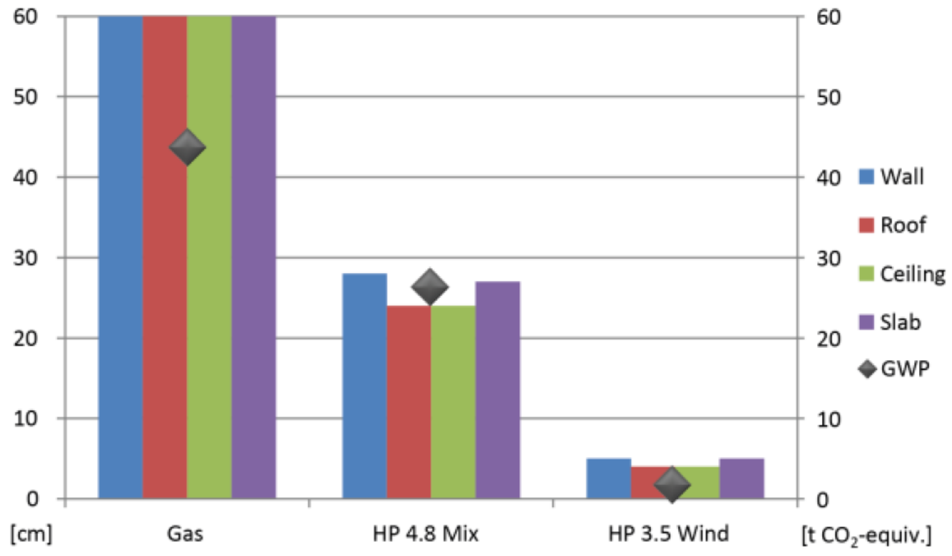

Figure 17: Optimal thicknesses of wood fibre depending on the heating system and on building envelope components minimising GHG emissions

3. Multi-objective optimisation through an evolutionary algorithm available in *Octopus* plug-in. This study was aimed at identifying the optimal combination between 19 insulation materials, their thicknesses (ranging between 0 and 70 cm) and the cladding material (6 options) for the external walls, and heating system (gas-fired boiler or heat pump with 3 different COP values) to be installed to minimise the GHG emissions and the installation cost. Constraints were included to describe the available combinations of insulation and cladding materials, and were handled through penalty functions. The results are shown in Figure 18.

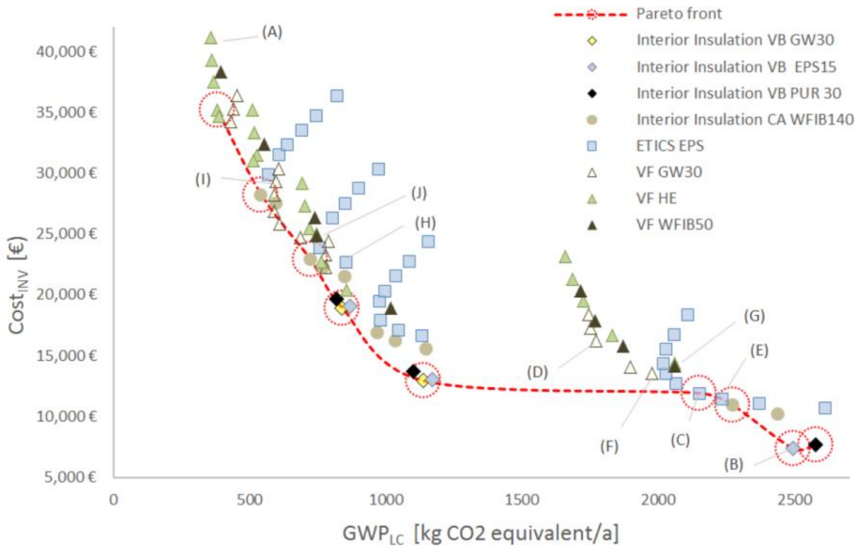

Figure 18: Pareto front of the multi-objective optimisation study comparing investment costs against life cycle GHG emissions

Lessons learned and conclusions:

1. Single objective single-variable parametric analysis and 2. Single-objective optimisation:

- With higher heating system efficiency (from gas system to heat pump fed by renewable electricity) the operational impact decreases rapidly, allowing a lower insulation thickness, thus reducing also the embodied impact;
- Insulations with natural materials (e.g. wood fibre and cellulose) allow lower GHG emissions although thicknesses are more than the double with respect of synthetic materials (e.g. EPS);
- Fixing the materials' thickness to 20 cm and assessing other environmental impact indicators, each material had good and bad performance according to the indicator, without an optimal insulation material being identified. The best results were obtained with the heat pump as heating system with electricity from renewable energy (in this case wind energy), thus with a very low related impact. With this system, very low insulation level or no insulation was sometimes the best solution.

3. Multi-objective optimisation:

- The optimum highly depends on the optimisation criterion: the environmental optimisation suggests the installation of renewable-based insulation materials, while the economic criterion disregards them;
- The range of optimal thicknesses of synthetic insulation materials is limited, thus suggesting that for harsh climates characterized by high insulation standards requiring greater thicknesses renewable materials should be preferred.

References:

Hollberg A, Ruth J, A Parametric Life Cycle Assessment Model for Façade Optimization. Build. Simul. Optim., 2014.

Klüber N, Hollberg A, Ruth J. Life cycle optimized application of renewable raw materials for retrofitting measures. World Sustain. Build. 2014, Barcelona, Spain, p. 1–7, 2014.

3.5 Case study 8 (Hollberg and Ruth, 2016)

Short description of the case study building:

- Location: Potsdam (Germany);
- Type of climate: continental;
- Type of building: residential;
- Type of action: renovation.

Description of the building:

The case study is a typical single-family house from the 1960s. This is a hypothetical case study showing the application of a parametric LCA approach. Thus, no further detail on the building is provided.

Life Cycle Assessment:

- Goal of the study: identify the optimum insulation material and optimum insulation thickness, taking into consideration the heating system, the energy carrier and the location, finding a trade-off between embodied and operational environmental impacts;
- Functional unit or functional equivalent: the renovated building;
- System boundaries: the product stage (A1–A3 modules) was considered, while modules A4 and A5 were neglected because of difficulties in finding this kind of data for generic designers. Further, replacement of products/components within the use of the building (B4), operational energy demand (B6), waste processing (C3) and disposal (C4) were included;
- Selected impact indicators: RPE, NRPE, GHG emissions, ODP, AP, EP, POCP, ADP (or ADPE);
- Main parameters: the reference service life of components is taken from data provided by the German Federal Institute for Research on Building, Urban Affairs, and Spatial Development, while the reference service period for the building is 50 years;
- Life cycle inventory analysis: only secondary data were employed for this study, drawn from Ökobau database and EPDs. The use phase energy demand was assessed through a quasi-steady state approach based on DIN V 18599 standard.

Optimisation of the life cycle energy and environmental performance:

For the optimization, a plugin for Grasshopper3D called GOAT was used. The evolutionary single-objective CRS2 algorithm was employed. Although it is not clearly stated in the text, each of the eight impact indicators was optimised, with the optimal values and the corresponding interventions being reported in Figure 19.
As variables, nine different insulation materials were compared, which can be varied in thickness from 0 to 60 cm in steps of 1 cm in combination with seven different heating systems and three window glazings. For simplicity, it was assumed that all building components that comprise the thermal envelope, e.g., basement ceiling, outer walls, roof, and uppermost ceiling, are insulated with the same material and the same thickness. Thus, the search space is made up of 9 × 61 × 7 × 3 = 11,529 possible solutions.

Lessons learned and conclusions:

The results of the optimisation study show a great variability in optimal insulation thickness depending on the heating system and insulation material, suggesting the importance of considering boundary conditions such as the heating system in the life cycle optimisations of buildings, although they are related only to the envelope.
The results also show a great divergence among the different indicators, making difficult the decision on which insulation material and thickness should be employed. This highlights the need of a single score indicator that facilitates the communication of the results to the architect/designer or the clients.

Figure 19: Results for minimum life cycle impact depending on heating system and indicator: eight single objective functions: environmental indicators indicated in the respective plot

Regarding the computational time, the adoption of a quasi-steady state approach allowed a huge reduction in comparison with a dynamic approach, since the same building was optimised in previous studies using *EnergyPlus* building performance simulator. This does not imply that a dynamic simulation should be disregarded in optimisation studies, but that the approximations in quasi-steady state methods seems adequate for the level of detail that is usually adopted for optimisations of residential buildings in Central Europe, since simplified models are often adopted.

References:

Hollberg A, Ruth J, LCA in architectural design—a parametric approach. Int J Life Cycle Assess 21: 943–60, 2016.

3.6 Case study 9 (Hollberg et al., 2014)

Short description of the case study building:

- Location: Germany;
- Type of climate: not relevant for the study;
- Type of building: garage;
- Type of action: design.

Description of the building:

This study is related to the minimization of the GHG emissions of the concrete slab for a bike garage. Since the garage is not conditioned and the lighting energy was neglected, operational energy performance was not assessed and only the embodied impacts were minimized.

Life Cycle Assessment:

- Goal of the study: minimising the embodied GHG emissions of the garage;
- Functional unit or functional equivalent: a bike garage with a concrete slab 15×30 m used as covering;
- System boundaries: in this study the following modules from the EN 15978:2011 standard were taken into account: A1-A3 modules, representing the cradle-to-gate phase; the transportation to the building site (A4); installation at the site (module A5); C1-C3, including the demolition, transport to the reprocessing plant and the crushing of concrete; module D, i.e. the loads and potential benefits for the concrete recycling beyond the system boundary, usually employed for the construction of roads. B module (use phase) and C4 module (disposal) were neglected;
- Selected impact indicators: the embodied GHG emissions were minimised, additionally other eight indicators were assessed: PE; NRPE; ODP; AP; EP; POCP; abiotic resources depletion potential (both mineral and fossil fuels);
- Main parameters: no additional parameters were employed for the study;
- Life cycle inventory analysis: only secondary data were used for the present study, drawn from EPDs developed by the German Institute of Building and Environment.

Optimisation of the life cycle energy and environmental performance:

The optimisation study was developed integrating *Karamba3D* finite element tool into *Grasshopper* 3D modeller and using *Galapagos* plug-in for the single-objective optimisation, employing the evolutionary algorithm available in *Galapagos*. *Karamba3D* assessed the static parameters such as deformation or utilization of the components. The variables are the position of the columns, the slab thickness and the concrete quality. Three constraints limiting the deformation and utilisation of the slab and setting a minimal distance between columns were handled through penalty functions. The optimisation process took 17 minutes on a standard PC in 2016. The optimum was found using C20/25 concrete and a slab thickness of 16 cm, with 12 supporting columns, while the standard solution has a regular grid of 15 columns with a spacing of 7.5 m and a thickness of 20 cm, as shown in Figure 20. Compared to the standard solution, the optimised solution needs less material for slab and columns and emits 3.2 tons $CO_{2\text{-eq}}$ less.

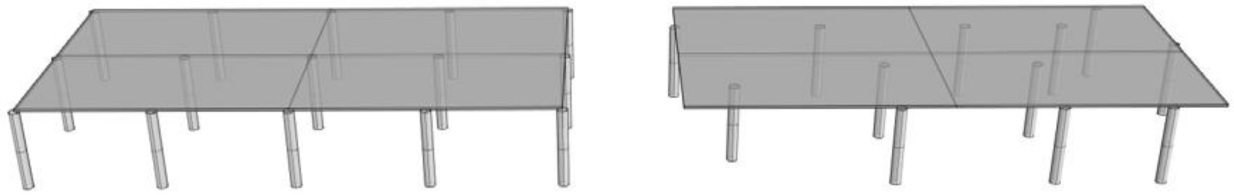

Figure 20: Standard (left) and optimised (right) garage configuration

Lessons learned and conclusions:

According to the results of this study, the main conclusion is that, from a life cycle point of view, it is better to choose a higher slab thickness and thus use more material of lower strength and environmental impact than to reduce the thickness by employing a high-performance concrete. The second important conclusion is that evolutionary algorithms are suitable to identify adequate solutions in small amounts of time and without any detailed background knowledge on the algorithm.

References:

Hollberg A, Heidenreich C, Ruth J, Hartung R, Herzog S. Using evolutionary optimization for low-impact solid constructions. World Sustain. Build. 2014, Barcelona, Spain, 2014.

3.7 Case studies 10-11 (Cellura et al., 2019)

Short description of the case study building:

- Location: Palermo (Italy) and Copenhagen (Denmark);
- Type of climate: Mediterranean (Palermo) and continental (Copenhagen);
- Type of building: residential;
- Type of action: renovation.

Pictures (Figure 21):

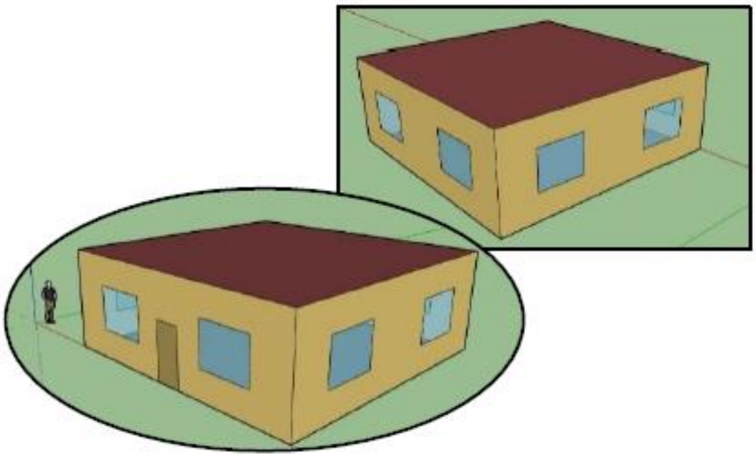

Figure 21: The examined building

Description of the building:

Simplified cuboid-shaped single-family building with a concrete-based structure, a single floor, where only external walls are slightly insulated while both walls and roof have a ventilated air cavity. Set-point temperatures are equal to 20 °C for space heating and 26 °C for space cooling. Lighting, ventilation and domestic hot water energy demands were neglected. Because of the dimensions, the building was assumed to be a unique thermal zone.

Life Cycle Assessment:

- Goal of the study: identifying the envelope retrofit actions minimising the life cycle environmental impacts and costs of the building;
- Functional unit or functional equivalent: the retrofitted building;
- System boundaries: The construction (module A) and use phase stages were taken into account (replacements (B4) excluded). The use phase was examined only for calculating the optimization of final energy consumption, it was not included in the impact calculation;
- Selected impact indicators: Construction cost, embodied GHG emissions, embodied primary energy consumption and final energy demand;
- Main parameters: the building's lifetime was assumed to be 60 years;
- Life cycle inventory analysis: specific embodied impacts were drawn from EPDs, while costs were derived from a market analysis on European context.

Optimisation of the life cycle energy and environmental performance:

The optimisation problem was solved through NSGA II multi-objective genetic algorithm, using a population size of 16 individuals and 126 generations (2016 buildings assessed over 259,308,000 configurations), a mutation rate equal to 0.1 and a crossover rate of 0.9. Four objective functions were considered: use phase final energy demand, embodied primary energy consumption, embodied GHG emissions and investment cost. Variables were all related to the envelope, consisting in additional insulation material and thickness and

cladding replacement. The optimisation software employed for this study was *MOBO*, which was linked to *EnergyPlus* building performance simulator.
The 10 optimal building retrofit composing the Pareto Front for the Mediterranean climate case study always exclude external walls insulation, since they were already insulated, while only glass wool was selected as optimal material for roof insulation, adopting the lowest available thickness (0.025 m), as shown in Figure 22. Regarding the external walls thermal mass materials, brick layer was never adopted, preferring small amounts of concrete (between 0 and 0.012 m[3]). The optimal solutions provide very low values of the four objective functions, as shown in Table 8, where the values of the four objective functions for the extreme solutions are reported, compared with the range of the objective functions among the 2016 buildings assessed.

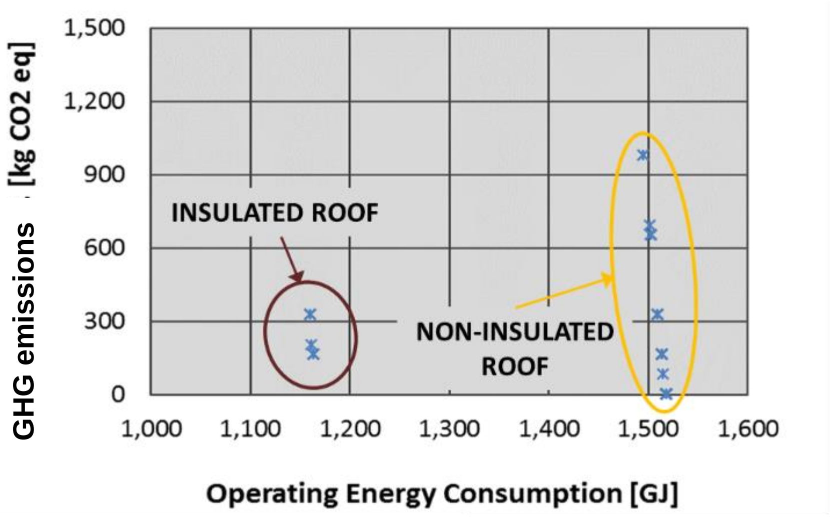

Figure 22: Embodied GHG emissions against Final Operating Energy Consumption of the 10 optimal solutions in Mediterranean climate

Table 8: Values of the objective functions for the extreme solutions in Mediterranean climate

	Operating Energy Consumption [GJ]	Embodied GHG emissions [kg CO_{2eq}]	Embodied primary energy [MJ]	Investment Cost [€]
Operating Energy Consumption extreme solution	1.160	329	6.115	253
GHG emissions, Embodied PE, and Investment Cost extreme solution	1.518	0	0	0
Range for all the buildings assessed	724 – 1.518	0 – 80.205	0 – 1.5 × 106	0 – 19.200

The Pareto Front for the Continental climate case study is made up of 28 optimal building retrofit solutions. The optimisation preferred glass wool as optimal material for roof insulation and concrete layers for external walls, setting all the other variables to zero. In detail, up to 3 insulation layers were considered as optimal, with optimal thickness values ranging between 0 and 0.075 m (single layer thickness is 0.025 m), while the

[3] This is a theoretical result obtained from the optimization process. The technical feasibility of this solution should be evaluated in practice.

highest additional concrete thickness is equal to 0.018 m. Also in this case, a strong reduction of all the objectives was obtained (Table 9).

Table 9: **Values of the objective functions for the extreme solutions in Continental climate**

	Operating Energy Consumption [GJ]	Embodied GHG emissions [kg CO_{2eq}]	Embodied primary energy [MJ]	Investment Cost [€]
Operating Energy Consumption extreme solution	1.768	900	17.350	746
GHG emissions, Embodied PE, and Investment Cost extreme solution	3.024	0	0	0
Range for all the buildings assessed	857 – 3.024	0 – 78.315	0 – 1.4 × 106	0 – 19.903

In both case studies, the embodied impacts and the investment cost are not really conflicting, since increasing one of them means increasing all of the three objectives, while they are all conflicting with the operating energy demand. This aspect can be seen in Figure 23 and 24 for the Mediterranean climate.

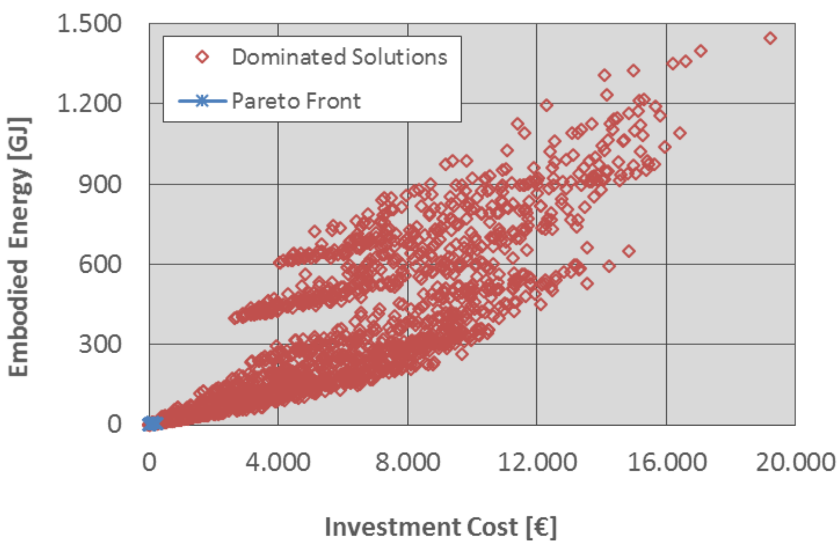

Figure 23: Values of the embodied PE and investment cost objective functions for the 2016 assessed buildings (red circles) and for the optimal solutions in the Pareto front (blue crosses) in Mediterranean climate

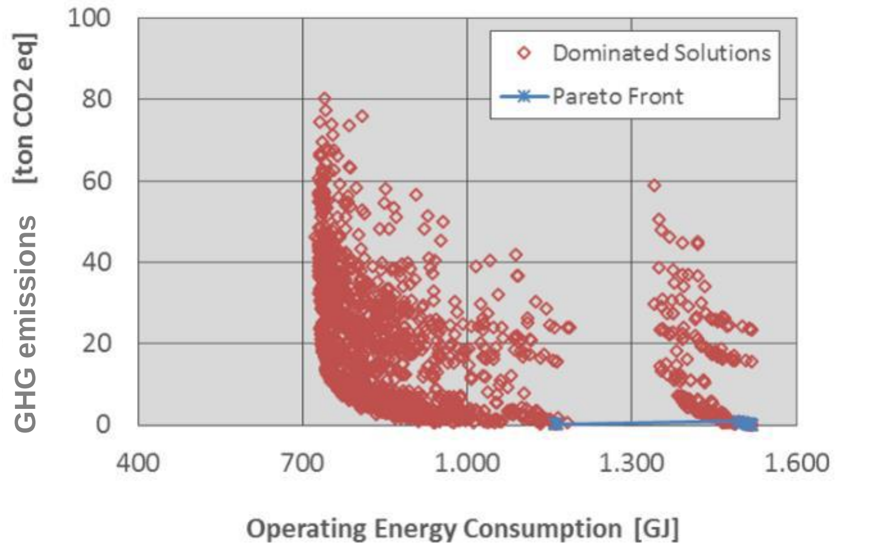

Figure 24: Values of the embodied GHG emissions and operating energy consumption objective functions for the 2016 assessed buildings (red circles) and for the optimal solutions in the Pareto front (blue crosses) in Mediterranean climate

<u>Lessons learned and conclusions:</u>

From this study, one of the main results is that the differences in optimal retrofits in these two climates is limited, with the same materials being adopted and a higher walls insulation in Continental climate being preferred. Nevertheless, the building in the continental climate already had a high thermal performance, so the retrofit measures are limited.

Another conclusion that can be drawn, since the search space of this study was quite large, is that a preliminary assessment of the base case before retrofit may help reducing the number of interventions to compare, and thus the computational time for the optimisation. Similar consideration may be done for the objective functions. In detail, by comparing the embodied energy against the embodied GHG emissions of the building retrofits (Figure 25), it is possible to identify a linear trend, although it does not perfectly fit all the data.

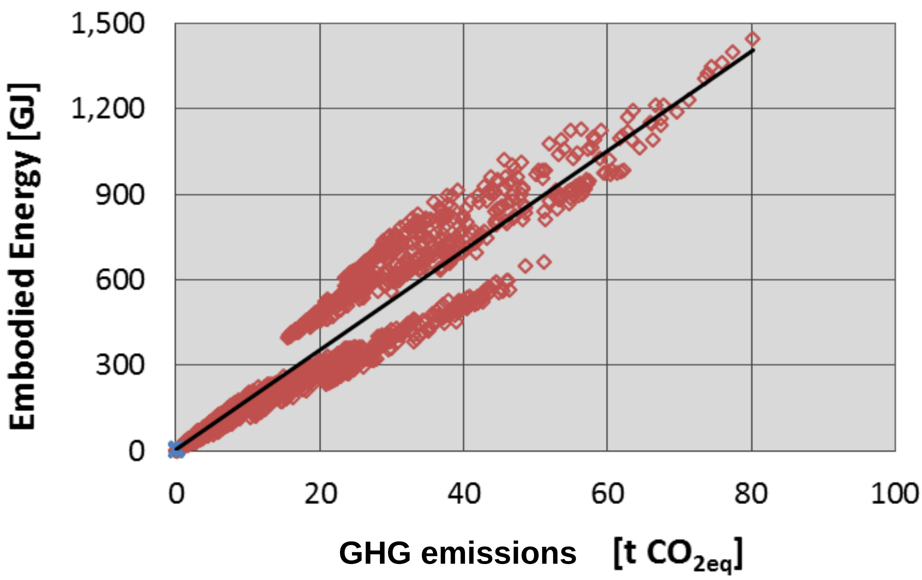

Figure 25: Values of embodied energy against embodied GHG emissions for the assessed buildings in Mediterranean climate

This means that only one of these two functions may be minimised also reducing the other one. Nevertheless, evolutionary algorithms proved to be very flexible and to allow a comprehensive comparison of alternatives identifying the optimal solutions in a very large search space.

References:

Cellura M, Longo S, Montana F, Riva Sanseverino E, Multi-Objective Building Envelope Optimization through a Life Cycle Assessment Approach. 2019 IEEE Int. Conf. Environ. Electr. Eng. 2019 IEEE Ind. Commer. Power Syst. Eur. (EEEIC / I&CPS Eur., Genoa, Italy: Institute of Electrical and Electronics Engineers (IEEE), p. 1–6, 2019.

3.8 Case study 12 (Montana et al., 2020)

Short description of the case study building:

- Location: Hvalsø (Denmark);
- Type of climate: continental;
- Type of building: residential;
- Type of action: renovation.

Pictures (Figure 26):

Figure 26: North (left) and South (right) facades of the case study

Description of the building:

The selected building is a 3-storeys residential building, being part of a complex of buildings collectively known as Traneparken. The building analysed in this study has a heated floor area of 2047.86 m^2, with a total of 24 flats and a heated basement area of 730.80 m^2; it is made up of prefabricated reinforced concrete sandwich elements with insulation material. The roof is composed by a fibrecement board and is insulated, while the basement floor has a concrete layer and an insulation layer. Further details on the building envelope are provided in Table 10. The building space heating and requirements are fulfilled through a 55 kW district heating heat exchanger, with three 300 l tanks for domestic hot water (DHW) storage. No space cooling system is installed. There are energy-saving light bulbs in all indoor lamps on the stairways, equipped with automatic switch-off controls based on presence sensors. Outdoor lighting has automatic daylight switch-off.

Table 10: Building envelope components details

Component	Features	Area [m²]	U [W/m²K]
Exterior concrete walls	Concrete sandwich, 50 mm mineral wool insulation	1047.67	0.66
Exterior light walls	Light board with 45 mm insulation	330.55	0.70
Basement walls	Concrete walls	363.84	1.00
Roof	14 degree tilt, fibrocement board cladding, 185 mm insulated ceiling	682.62	0.20
Basement floor	100 mm lightweight expanded clay aggregate insulation	730.8	0.40
North windows	2-layer glazing	101.4	2.40
South windows	2-layer glazing	196.87	2.40
Staircase windows	2-layer glazing	85.83	2.40

Life Cycle Assessment:

- Goal of the study: identifying the interventions minimising the life cycle impacts and life cycle costs of the building. In a first scenario, only envelope-related features were considered, while both envelope and equipment (heating system and renewables) are optimised in a second scenario;
- Functional unit or functional equivalent: the retrofit actions of the building;
- System boundaries: product stage (modules A1-A3), construction stage (module A5), replacements (B4) and operational energy use (B6) were considered for all the minimisation criteria, while the waste processing at the end-of-life (C3) was taken into account only for environmental impact indicators, since no reliable data was available for costs;
- Selected energy and environmental impact indicators: life-cycle and embodied GHG emissions and primary energy consumption were minimised. In addition, the costs for investment, operation and replacement over the life cycle were also optimised;
- Main parameters: the reference study period was set equal to 50 years starting from the beginning of the renovation, while the useful life of the glazed material is assumed equal to 25 years (1 replacement) and the equipment are assumed to operate for 30 years (1 replacement). The economic analysis was conducted assuming a discount rate equal to 5% and an inflation rate of 2% for equipment and 4% for energy carriers and building materials;
- Life cycle inventory analysis: embodied impacts for retrofit materials and for energy vectors were derived from the German *Ökobau* database 2016 and adapted to the Danish context (see LCAbyg tool), while costs related to building components were based on the Danish building price database Molio.

Optimisation of the life cycle energy and environmental performance:

The building was subject to two multi-objective optimisation scenarios. A simulation-based optimisation approach was employed combining *Be18* building energy rating tool with *MOBO* building performance optimisation software.

1. The first scenario aims at reducing the building energy demand identifying the best combination of envelope materials; in detail, the variables deal with walls and roof insulation and cladding materials and thermal features of glazed components. The objective functions were the GHG emissions, the primary energy consumption, the investment cost of the retrofit materials and the final operating energy consumption. Some of the results are shown in Figure 27, Figure 28 and Figure 29.

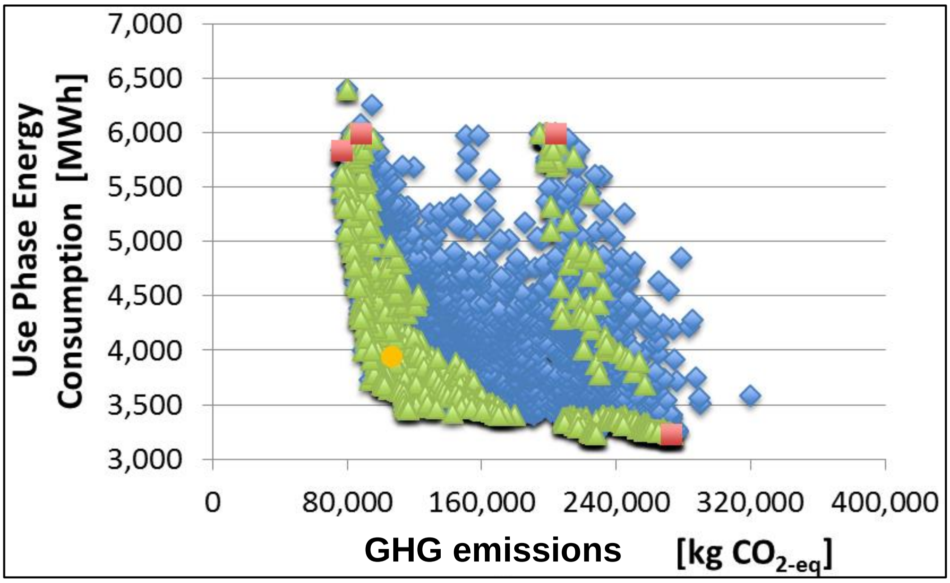

Figure 27: Combination of the objective functions showing all the solutions assessed (blue rhombi), the Pareto fronts (green triangles), the solutions minimising each objective function (red squares) and the best compromise solution (yellow circle): use phase energy consumption versus GHG emissions

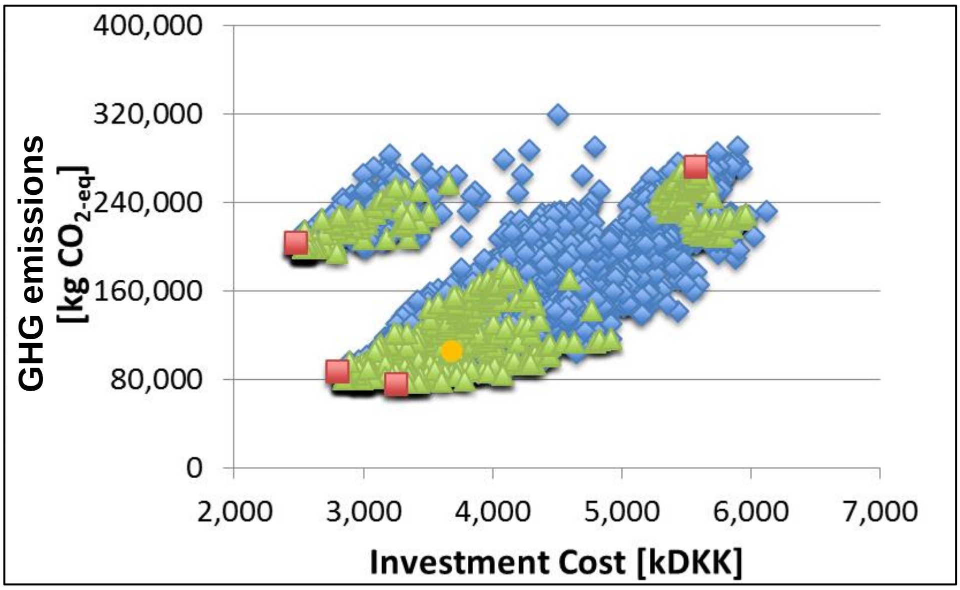

Figure 28: Combination of the objective functions showing all the solutions assessed (blue rhombi), the Pareto fronts (green triangles), the solutions minimising each objective function (red squares) and the best compromise solution (yellow circle): GHG emissions versus investment cost

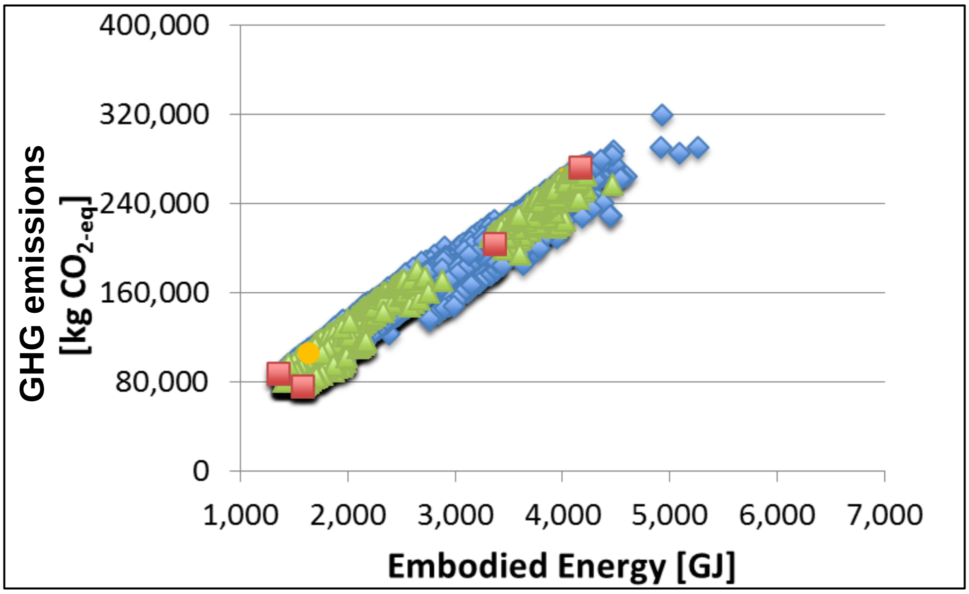

Figure 29: Combination of the objective functions showing all the solutions assessed (blue rhombi), the Pareto fronts (green triangles), the solutions minimising each objective function (red squares) and the best compromise solution (yellow circle): GHG emissions versus embodied PE

2. The second scenario aims at minimising the building impacts and costs through a whole building optimisation, employing variables related to both the envelope materials and the service equipment. In addition to the previous scenario, the variables deal with the technology and the rated size of the space heating generation system and of the solar renewable systems. The objective functions were the life cycle GHG emissions, the life cycle primary energy consumption and the costs for the investment, operation and replacement of components. Some of the results are shown in Figure 30.

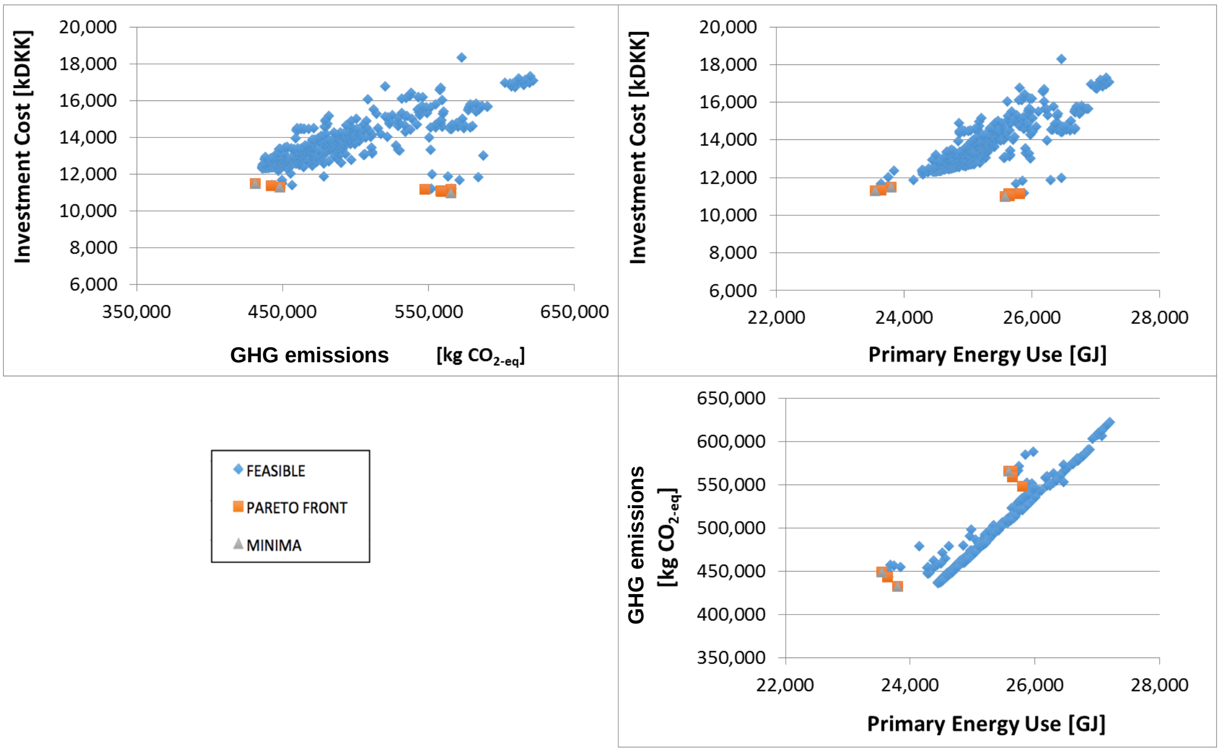

Figure 30: Combination of the objective functions showing all the solutions assessed, the Pareto fronts and the solutions minimising each objective function (the best compromise solution is the one minimising GHG emissions)

<u>Lessons learned and conclusions:</u>

1. Multi-objective building envelope optimisation:

- Low impact materials such as cellulose should be preferred for insulation material;
- Double-glazing was considered enough for staircase and apartment windows in both orientations (North and South);
- A linear correlation can be identified between embodied primary energy consumption and embodied GHG emissions; thus, only one of these functions might be employed in future works, reducing computational time;

2. Multi-objective whole building optimisation:

- District heating, which is the predominant heating technology in Danish urban areas, is preferred to other alternatives, also with respect to solar heating;
- Since the building is not a Net Zero nor low operational Energy Building, the impacts and costs related to the building operation are predominant to the embodied impacts / investment costs, although these impacts/costs are not negligible;
- A linear correlation can be identified between both embodied and life-cycle primary energy consumption and life cycle based GHG emissions; thus, only one of these functions might be employed in future works, reducing computational time;
- The number of alternatives should be kept low in order to avoid problems in the optimisation process.

<u>References:</u>

Montana F, Kanafani K, Wittchen KB, Birgisdottir H, Longo S, Cellura M, Riva Sanseverino E, Multi-objective optimization of building life cycle performance. A housing renovation case study in Northern Europe. Sustainability, 12(18) 7807, 2020.

3.9 Case study 13 (Montana, 2020)

<u>Short description of the case study building:</u>

- Location: Palermo (Italy);
- Type of climate: Mediterranean;
- Type of building: residential;
- Type of action: renovation.

<u>Pictures (Figure 31, Figure 32, Figure 33):</u>

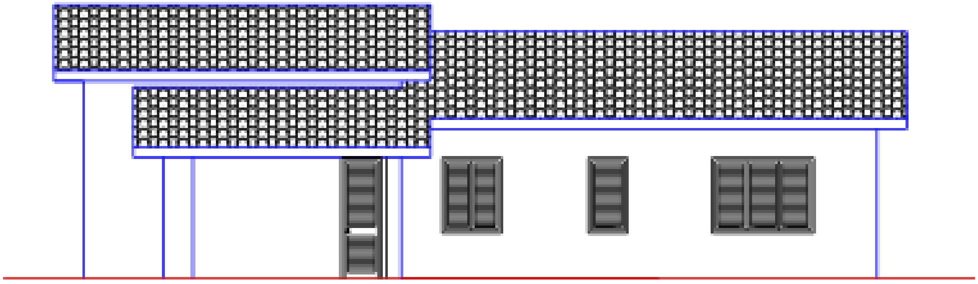

Figure 31: Sketch of the South-West oriented facade of the case study

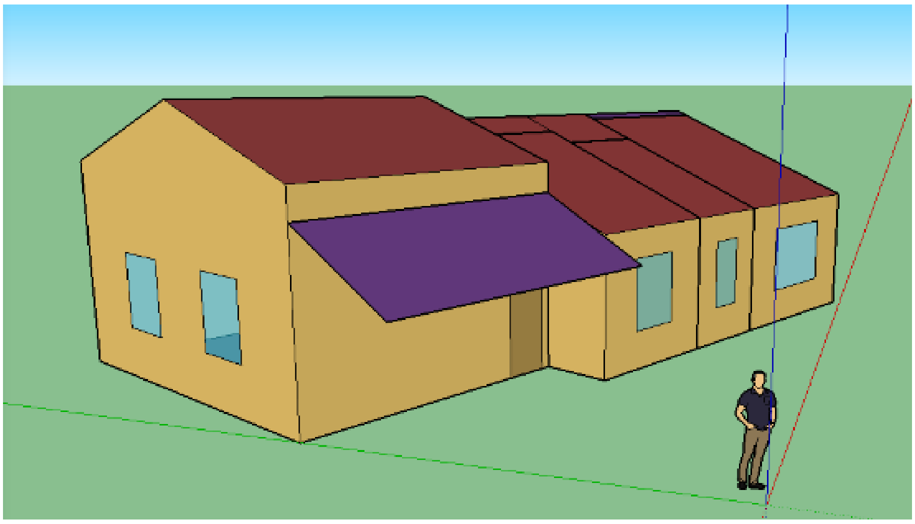

Figure 32: Simulation model of the South-West oriented facade of the case study

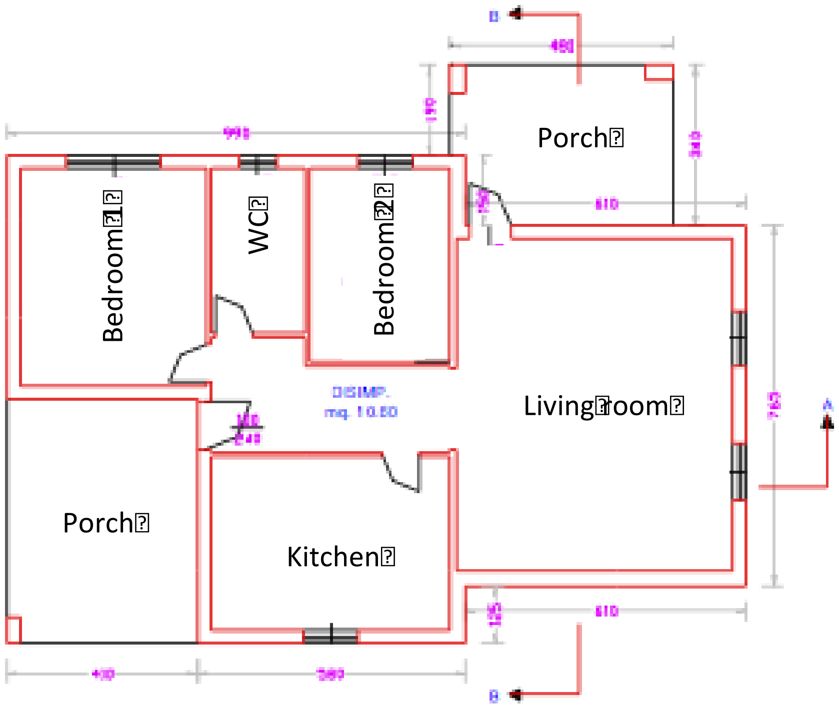

Figure 33: Floor plan of the case study

Description of the building:

The building is an existing single-floor, single-family detached house, with a base area of 119.80 m^2 and including two bedrooms, one bathroom, a kitchen and a living room. The living room is newer and higher than the rest of the building, with 4.2 m high against 2.9 m for the other rooms. There are six windows and two doors, and both of the two entrances of the house communicate with a porch. Further details on the building envelope are provided in Table 11. The space heating and DHW production are provided through an LPG-fired boiler, while the space-cooling requirement is fulfilled with an electric air conditioner.

Life Cycle Assessment:

- Goal of the study: identifying the interventions minimising the life cycle environmental impacts and costs of the building;
- Functional unit or functional equivalent: the retrofit actions of the building;
- System boundaries: product stage (modules A1-A3) and construction stage (module A5) for the retrofit actions, operational energy use (B6) post retrofit; the waste processing at the end-of-life (C3) was neglected since no reliable data was available. Replacement step (B4) was disregarded because it does not influence the optimization process. In fact, assuming that the useful life of a specific component/material used in the retrofit is the same independently on the material typology and quantity, the replacement process does not change for the different examined solutions;
- Selected energy and environmental impact indicators: GHG emissions and primary energy consumption were minimised. In addition, the costs for investment, operation and replacement over life cycle were also optimised;
- Main parameters: the reference study period was set equal to 60 years starting from the beginning of the renovation, the infiltration rate was set equal to 0.1 air changes per hour;
- Life cycle inventory analysis: Life cycle specific environmental impacts were drawn from EPDs, while costs were derived from a market analysis on the European context.

Table 11: Building envelope components details

Component	Layer 1 (outside)	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
Exterior Walls	Lime mortar plaster	Perforated bricks	Foam vermiculite	Air cavity	Perforated bricks	Lime mortar plaster
Interior Walls	Lime mortar plaster	Perforated bricks	Lime mortar plaster	-	-	-
Roof	Clay roof tiles cover	Wooden structure	Air cavity	Light concrete block	Lime mortar plaster	-
Floor	Ventilated air cavity	Reinforced concrete	Plasters	-	-	-
Exterior Doors	Metal surface	Insulation board	-	-	-	-
Windows	Clear glass	Air gap	Clear glass	-	-	-

Optimisation of the life cycle energy and environmental performance:

The building was subject to a two-step multi-objective optimisation, the first one aimed at identify the best envelope configuration and the second one selecting the optimal equipment combination.

For the first step, a simulation-based optimisation approach was employed combining *EnergyPlus* dynamic building simulation tool with *MOBO* building performance optimisation software. The optimisation problem was solved through Omni-Optimizer multi-objective genetic algorithm. Eleven optimisation runs were performed using a population size of 16 individuals and 50 or 126 generations (800 or 2016 building simulations), in order to investigate the sensitivity of the problem to this parameter. The mutation rate was set equal to 0.00893 (calculated using the Mühlenbein formula (Mühlenbein, 1992)) and the crossover rate to 0.9. Four objective functions were considered: use phase final energy demand, primary energy consumption, GHG emissions and investment cost. Variables were all related to the envelope, consisting in additional insulation materials and thickness, additional concrete layers to increase the thermal mass and replacement of windows.

The feasible solutions from the eleven runs were combined, identifying 31 solutions in the Pareto front. These solutions had limited or null envelope insulation, apart from the East-oriented walls, while the additional thermal mass was mainly installed on the West oriented walls. All the solutions have the same window features, although each orientation has glazing level and frame different from each other. The solutions were ranked according to the utopia point criterion (*i.e.* minimum Euclidean distance from the origin of axes) to identify two optimal building envelope configurations that were used for the second step.

The buildings final energy demand with hourly detail was assessed through EnergyPlus and then used as an input for a MATLAB script based on an *energy hub* model and optimised through the MATLAB MILP algorithm *intlinprog*. In this way, optimal technologies and rated sizes for HVAC, solar energy technologies and storage systems were identified. These systems, installed on the optimal building envelope configurations, are aimed at minimising the objective functions. The Pareto fronts of the second step is shown in Figure 34.

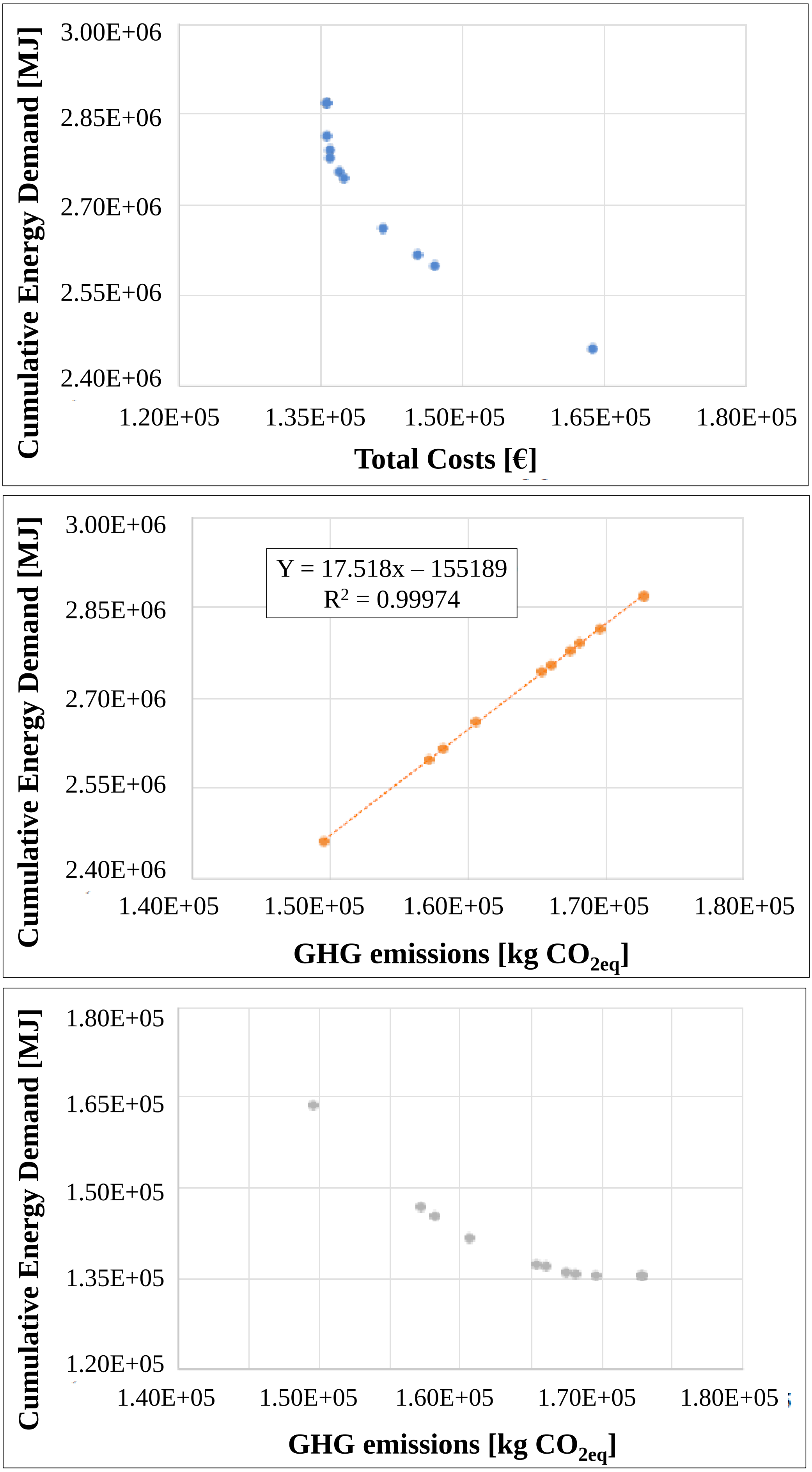

Figure 34: Bi-dimensional Pareto fronts of the second step

The best compromise solution was selected using the utopia point criterion. It involves the maximum exploitation of solar renewables system allowed by the roof surface, 5.3 kW_{cool} for the air conditioner and no electrical storage. The thermal storage capacity, to be used for space heating and DHW, was equal to a massive value of 40 m^3; this value is more of theoretical rather than technical interest. The life cycle performance and payback times of this building configuration are shown in Table 12, highlighting the high attractiveness of the approach adopted in this case study.

Table 12: Optimal values of the objective functions and payback times

	Cost (€)	CED (MJ)	GHG emissions (kg CO_{2eq})
Operating term in the AS-IS scenario (over 60 years)	1,814.766	15,989.122	495.435
Embodied term - Envelope retrofit	4.516	31.935	2.410
Embodied term - Equipment retrofit	97.793	337.426	19.685
Operating term in the TO-BE scenario (over 60 years)	44.730	2,229.222	135.033
TOT	147.039	2,598.582	157.128
Payback Time	3.47 years	1.61 years	3.68 years

Lessons learned and conclusions:

1. Multi-objective building envelope optimisation:

- As was already known in building physics, the results suggests that limited insulation level and medium-high thermal mass materials should be adopted in Mediterranean climate, somehow validating the soundness of the optimisation results;
- A linear correlation can be identified between primary energy consumption and GHG emissions; thus, only one of these functions might be employed in future works, reducing computational time;

2. Multi-objective building equipment optimisation:

- Solar energy technologies are highly profitable and should be massively adopted;
- Seasonal thermal energy storage is recommended;
- Since the building is not a Net Zero nor a low operational Energy Building, the impacts and costs related to the building operation are predominant to the embodied impacts / investment costs, although they are not negligible;
- A linear correlation can be identified between primary energy consumption and GHG emissions; thus, only one of these functions might be employed in future works, reducing computational time;
- Although some literature studies disregard the adoption of a stepwise optimisation process, the study has shown very profitable results.

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3.10 Design solutions

Starting from the results of the examined case studies, some outcomes can be found, focusing on the building envelope, renewable energy systems, climate and occupancy influence. The outcomes, detailed in the following, are valid per each specific case study; they cannot be extended “as is” to a generic building but case-by-case considerations and measurements are needed:

- Building envelope: given a fixed air-conditioning system, different solutions are identified for the building envelope, with one case (Hollberg and Ruth, 2014) finding as optimal solution the base case envelope (no improvement is preferred) when a heat pump powered by electricity from renewable sources is used for heating. This type of solution is rather common and may challenge the limited availaibility of energy from renewable resources. Thus this type of solution should undergo a stresstest by rolling it out to a relevant share of a national building stock and check the need for the annual operational renewable energy resources against their potential available.

  Natural materials (e.g. cellulose) are preferred to synthetic ones (e.g. EPS) for reducing the environmental impacts, while the opposite is obtained by an economic optimization, since natural materials are more expensive (Klüber et al., 2014).
- Renewable energy systems: few studies investigated this type of systems. Recht et al. (2016) pointed out that the insulation of the building envelope with an optimal thickness should be coupled with the installation of photovoltaic panels for optimizing both installation costs and GHG emissions. Montana et al. (2020) investigated the installation of a rooftop photovoltaic system and solar thermal collectors in a large residential building; the optimization process preferred the connection to a district heating system instead of the solar collectors for hot water production. This result was based only on the energy provided by the different sources and the embodied impacts of the systems (solar collectors vs. heat pump or district heating); costs and environmental impacts for piping used for connecting the building with the district-heating network are not included, since these components were already in place in case of the selected building.
- It is important to outline that while buildings with a low operational energy efficiency operating with renewable energies may be among the most optimal solutions, such buildings may challenge the available potential of renewable electricity, fuels and other (in particular geothermal) energy sources.
- Climate: focusing on the location, one study was developed in Northern France (Recht et al., 2016), six in Germany (Hollberg and Ruth, 2013, 2014, 2016), (Klüber et al., 2014), two in Denmark (Cellura et al., 2019), (Montana et al., 2020), two in Southern Italy (Cellura et al., 2019), (Montana, 2020), and two in Hungary (Kiss and Szalay, 2019). Thus, most of the examined studies are developed in continental or oceanic climate cities, while only two studies deal with mild climate, with one of them being a comparison of the performance of the same building in Mediterranean and oceanic climate. This last study highlighted that the same insulation materials are optimal in both climates, with higher thicknesses being preferable in cold climates.
- Occupancy influence: the variability in occupants’ behaviour also influences the identification of the best solutions. Recht (2016) and Recht et al. (2016) compared different households typologies: single person, a retired couple and a young working couple with a child. The results highlighted that even if some solutions are independent from the households type (e.g. the use of triple-glazing on the North East façade), others are influenced by this aspect, e. g. the equipment features (number of photovoltaic modules or installation of a grey water heat recovery system).
- Environmental and economic optimisation should be performed using a full life cycle approach, covering the product, construction phase, use and end of life stages of a building. Excluding one or several of these stages may likely lead to suboptimal solutions.

4. Conclusions

This report described the research experience of IEA EBC Annex 72 members on the application of optimization processes for selecting design or retrofit actions most suitable for improving different aspects (energy, environmental, economic performance, etc.) of buildings in a life cycle perspective.

Thirteen case studies were identified and examined, in order to describe the different optimization approaches used and to provide useful information to building designers and decision-makers.

The analysis of the case studies pointed out that different approaches, software and algorithms, objective functions, variables, constraints and parameters are suited and used in the optimization processes. This makes it difficult to draw generic guidelines on the optimisation of life cycle primary energy, greenhouse gas emissions, environmental and economic performance of buildings. Futhermore, this result highlighted the need of further researches in this field, by developing case studies exploring all the optimization possibilities. This will allow to identify, for each approach, the strength and weakness points and the range of results that can be obtained.

However, a common generic step-by-step procedure can be identified in the examined case studies (see Figure 1), starting from the development of the building model and ending with the identification of the optimal solutions.

The stakeholders involved in the building life-cycle (e.g. in the design, construction and management) can apply this procedure, time by time adapted to the characteristics of the investigated building, for identifying optimal design or retrofit solutions regarding different aspects of the whole building life-cycle (e.g. building envelop materials and thicknesses, use of renewable energy technologies in operation, occupancy, useful life, etc.).

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ANNEX 72

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