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UNIVERSITÀ DI ROMA

Multi-objective optimization for sustainable building design

from schematic design phases to retrofit strategies optimization using genetic algorithms

Adriana Ciardiello

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Symbols and Abbreviations

λ: thermal conductivity [W m^{-1} K^{-1}]
ϱ: density [kg m^{-3}]
cp: specific heat [J kg^{-1} K^{-1}]
aNSGA-II: active-archive Non-dominated Sorting Genetic Algorithm
AEC: Architecture, Engineering and Construction
AS: Active Strategies
BES: Building Energy Simulation
BIM: Building Information Modeling
BPO: Building Performance Optimization
BPS: Building Performance Simulation
BS: Border Shades
CAD: Computer-Aided Design
CO_2: carbon dioxide emissions [kg]
COP: Coefficient Of Performance
DA: Daylight Autonomy [%]
DF: Daylight Factor [%]
EC: Energy Consumption [kWh m^{-2}]
  EC subscript:
  c: cooling
  h: heating
  l: lighting
ECo: Energy Costs [€]
ED: Energy Demand [kWh m^{-2}]
EEA: European Environment Agency
EER: Energy Efficiency Ratio
ENEA: Italian National Agency for New Technologies, Energy and Sustainable Economic Development
EPBD: Energy Performance of Buildings Directive
EU: European Union
EUI: Energy Use Intensity [kWh m^{-2}]
GA: Genetic Algorithm
GH: Grasshopper
GHG: Greenhouse Gas
GWP: Global Warming Potential
HP: Heat Pump
HVAC: Heating Ventilation Air Conditioning
HypE: Hypervolume-based search algorithm
IC: Investment Cost [€]
IPCC: Intergovernmental Panel on Climate Change
jDE: Self-Adaptive Differential Evolution algorithm

L-BFGS-B: Broyden–Fletcher–Goldfarb–Shanno algorithm
LCA: Life Cycle Assessment
LCC: Life Cycle Costs
Low-e: low-emittance
MOGA: Multi-Objective Genetic Algorithm
MOGLS: Multiple-Objective Genetic Local Search
MOO: Multi-Objective Optimization
NSGA: Non-dominated Sorting Genetic Algorithm
nZEB: nearly Zero Energy Buildings
O: orientation [°]
OPT: optimal solution
PAES: Pareto Archived Evolutionary Strategies
PCM: Phase Change Materials
PED: Positive Energy Districts
PMV: Predicted Mean Vote
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PS: Passive Strategies
PSO: Particle Swarm Optimization
PV: Photovoltaic
R: thermal resistance [m^2 K W^{-1}]
RED: Renewable Energy Directive
SC: shape coefficient
sDA: spatial Daylight Autonomy [%]
SHGC: Solar Heat Gain Coefficient
SPEA-2: Strength Pareto Evolutionary Algorithm
SRI: Solar Reflectance Index
t: thickness [m]
vt: visible transmittance
U: thermal transmittance [W m^{-2} K^{-1}]
UDI: Useful Daylight Illuminance [%]
UHI: Urban Heat Island
UTCI: Universal Thermal Comfort Index
WWR: Window-to-Wall Ratio
    WWR subscript:
    N: north façade
    S: south façade
    E: east façade
    W: west façade
ZEB: Zero Emissions Building

Abstract

The intrinsic complexity of the built environment is increasing, due to the intricate interplay of various factors related to environmental, social and economic objectives. Such complexity poses significant challenges in reaching the demanding performances required to buildings today but, at the same time, offers opportunities to innovate the building design process. This doctoral thesis explores the integration of building performance optimization (BPO) methodologies within different design stages, coupling parametric modeling, dynamic simulations and optimization algorithms. The study elaborates on how multi-objective BPO can address complexity in the design process of sustainable and low-energy buildings from the schematic design phase of a new construction up to the retrofit of an existing building. In so doing, it focuses on multi-family residential buildings, as they are a priority in energy efficiency measures at the national and international levels and play a key role in addressing current issues, such as climate change and fuel poverty.

The research takes its moves from the concept of the built environment as a complex system, emphasizing the necessity of advanced digital tools to deal with such complexity. Indeed, design decision-making phases are characterized by numerous possible combinations of passive strategies which can improve building performance without using extra energy. Such design solutions influence the often conflicting objectives that a sustainable building aims to achieve, towards high conditions of comfort and functionality, without the consequence of excessive energy consumption and emissions.

First, a systematic literature review, carried out in parallel with an online survey distributed to architectural firms, highlights, on the one hand, the great interest in BPO in current research and, on the other, the limited diffusion of both simulation and optimization tools in architectural practice.

Once misalignments between research and professional practice have been analyzed, the thesis then proposes specific methodologies, rooted in the results of

the review, for the use of multi-objective optimization both for new constructions and for existing buildings, demonstrating them by applications on relevant case studies. The optimization carried out during the schematic phase of the project (thus for the case of a new construction) takes into consideration the geometric variables of the building to minimize energy consumption and maximize daylight accessibility. The proposed methodology integrates multi-disciplinary simulations and optimization, in a parametric modeling environment. Results emphasize the critical role of design choices during the early stages, and thus, the necessity of a meticulous optimization of geometric variables. Moreover, in order to analyze the optimization during an advanced and highly detailed phase of the project, the case of a retrofit of an existing building is considered, and a methodology is proposed, testing an advanced algorithm, the active-archive Non-dominated Sorting Genetic Algorithm-II (aNSGA-II). Architecturally-compatible passive retrofit strategies on the building envelope are analyzed and the optimization process is carried out to find an energy- and cost- efficient solution. Furthermore, active strategies and renewable energy are also considered, reflecting on their role in the decarbonization of the building stock and in making inhabitants less subjected to energy price fluctuations.

The thesis concludes by illustrating the answers to the research questions raised in the introduction, emphasizing multi-objective BPO's potential to address and inform design decisions from early phases, aligning with the current necessity of collaborative and multi-disciplinary design process. Therefore, the thesis demonstrates how BPO can be of support in different phases of a building design, showing the significant variables to be analyzed based on the level of detail of the design phase considered and proposing specific methodologies.

The impact of the research here presented extends beyond academia, influencing professionals, software developers, and policymakers in promoting sustainable and low-energy buildings towards the mitigation of climate change and fuel poverty.

Keywords

multi-objective optimization, building performance simulation, schematic design phase, retrofit, genetic algorithm, passive strategies

Sommario

La crescente complessità intrinseca all'ambiente costruito, dovuta alla complessa interazione di vari fattori legati ad obiettivi ambientali, sociali ed economici, pone sfide significative nel raggiungimento delle esigenti prestazioni richieste oggi agli edifici ma, allo stesso tempo, fornisce opportunità per innovarne il processo progettuale. Questa tesi di dottorato esplora l'integrazione di metodologie di ottimizzazione multi-obiettivo della prestazione dell'edificio all'interno di diverse fasi progettuali, combinando modellazione parametrica, simulazione in regime dinamico e algoritmi di ottimizzazione. Lo studio approfondisce come tali metodologie possano affrontare la complessità del processo di progettazione di edifici sostenibili e a basso consumo energetico, dalla fase schematica del progetto di nuova costruzione fino al retrofit di un edificio esistente. A tal fine, si focalizza su edifici residenziali multifamiliari, in quanto rappresentano una priorità nelle politiche di efficientamento energetico a livello nazionale ed internazionale e svolgono un ruolo chiave nell'affrontare problematiche attuali, quali il cambiamento climatico e la povertà energetica.

La ricerca prende le mosse dal concetto di ambiente costruito come sistema complesso, enfatizzando la necessità di strumenti digitali avanzati a supporto di tale complessità. Le fasi decisionali del progetto, infatti, sono caratterizzate da numerose possibili combinazioni di strategie passive, le quali permettono di migliorare la prestazione dell'edificio senza l'utilizzo di energia supplementare. Tali soluzioni progettuali influenzano gli obiettivi spesso contrastanti che un edificio sostenibile si propone di raggiungere, verso elevate condizioni di comfort e funzionalità, senza la conseguenza di eccessivi consumi energetici ed emissioni.

In primo luogo, una revisione sistematica della letteratura scientifica, condotta parallelamente ad un questionario online distribuito a studi di architettura, evidenzia da un lato l'attualità del tema nella ricerca, dall'altro la scarsa diffusione di strumenti sia di simulazione che di ottimizzazione nella pratica architettonica. Analizzati i disallineamenti tra ricerca e pratica professionale, la tesi propone

quindi specifiche metodologie, consolidate sui risultati della suddetta revisione, per l'utilizzo dell'ottimizzazione multi-obiettivo sia per nuove costruzioni che per edifici esistenti, dimostrandole attraverso applicazioni su casi studio rilevanti. L'ottimizzazione svolta durante la fase schematica del progetto (e quindi per il caso di nuova costruzione), prende in considerazione le variabili geometriche dell'edificio per minimizzare i consumi energetici e massimizzare l'ingresso di luce naturale al suo interno. La metodologia proposta integra in ambiente di modellazione parametrico, simulazioni multidisciplinari e ottimizzazione. I risultati enfatizzano il ruolo critico delle scelte progettuali durante le fasi iniziali del progetto e quindi la necessità di una attenta ottimizzazione delle variabili geometriche. Inoltre, al fine di analizzare l'ottimizzazione durante una fase del progetto avanzata e più dettagliata, viene considerato il caso di un retrofit di un edificio esistente e viene proposta una metodologia, testando un avanzato algoritmo, l'*active-archive Non-dominated Sorting Genetic Algorithm-II* (aNSGA-II). Sono identificate strategie passive di retrofit sull'involucro edilizio, compatibili da un punto di vista architettonico, e viene eseguito il processo di ottimizzazione per trovare una soluzione efficiente sia dal punto di vista energetico che economico. Inoltre, sono prese in considerazione anche strategie attive e energie rinnovabili, riflettendo sul loro ruolo nella decarbonizzazione del patrimonio edilizio e nel rendere gli abitanti meno soggetti a fluttuazioni di prezzi dell'energia.

La tesi conclude illustrando le risposte alle domande di ricerca sollevate nell'introduzione, sottolineando il potenziale dell'ottimizzazione multi-obiettivo della prestazione dell'edificio nell'indirizzare ed informare le scelte del progettista fin dalle prime fasi, allineandosi con la necessità di un processo di progettazione collaborativo e multidisciplinare. La tesi dimostra quindi come strumenti di simulazione connessi a algoritmi di ottimizzazione possano essere di supporto nelle diverse fasi della progettazione di un edificio, mostrando le variabili significative da analizzare in base al livello di dettaglio della fase progettuale considerata e proponendo metodologie specifiche. L'impatto della ricerca qui presentata si estende oltre il mondo accademico, influenzando professionisti,

sviluppatori di software e *policy-makers* nella promozione di edifici sostenibili e a basso consumo energetico verso la mitigazione del cambiamento climatico e della povertà energetica.

Parole chiave

ottimizzazione multi-obiettivo, simulazione della prestazione dell'edificio, fase schematica di progetto, retrofit, algoritmo genetico, strategie passive

1

Introduction

This chapter provides a general introduction to this doctoral thesis. It aims to give insights into the background and motivation of the research (section 1.1), introducing the main concepts covered in this dissertation, which will then be explored in depth in the following chapters. The gaps and limitations of previous research are illustrated, and the research aims and questions are clearly described in section 1.2, defining the main research question and the related sub-questions that aim to address the challenges previously described. Moreover, in the same section, the potential target audience of this study is delineated. Finally, section 1.3 briefly presents the structure of the thesis and the main methods adopted to answer the questions posed above, with the aim of facilitating the reader's understanding and orientation within this thesis.

1.1 Background and motivation of the research

The built environment is everything humanly made, intended to serve human activities while mediating the overall environment (Bartuska, 2007). It can be considered as a complex system that exists in relationship with other systems, e.g., the closeby natural environment and the people who live in those spaces (Reith & Brajković, 2021). Indeed, particularly when dealing with sustainable design, adopting systemic thinking, i.e. thinking in terms of wholes, is crucial (Voulvoulis et al., 2022). All the components influencing the built environment performance (and being influenced by it) present intricated interrelations, resulting in emergent performances that can not be understood by the analysis of individual parts alone. Moreover, sustainability in the construction sector is no longer a goal to reach but a necessity (Mumovic & Santamouris, 2018). Indeed, buildings are still responsible for approximately 40% of energy consumption and 36% of greenhouse gas emissions in the European Union (EU) (European Parliament, 2018b). Consequently, they represent a threat to worsening environmental issues and the effects of climate change, but, at the same time, they have a great potential for combating these current critical issues. In fact, the construction sector is one of the key sectors in recent European environmental policies towards climate neutrality in 2050, i.e. achieving net zero greenhouse gas emissions for EU countries (European Commission COM/2019/640 final, 2019).

One of the main EU policies pursuing a reduction of the environmental impact of buildings is the Energy Performance of Buildings Directive (EPBD), which was first adopted in 2002 and then revised in 2010 and 2018 (European Parliament, 2002, 2010, 2018a). The EPBD requires that all new buildings must be nearly Zero Energy Buildings (nZEB) and the recent recast proposal (European Parliament, 2021) set more severe standards, the Zero Emission Building (ZEB) standard for all new buildings starting from 2030. Moreover, the European Renovation Wave aims to boost building renovations, starting from public buildings, to achieve cost-effective transformation of existing buildings into nZEBs towards a highly efficient and decarbonized building stock by 2050 (European Commission, 2020). Therefore, the performance required for both new and existing buildings is increasingly stringent and challenging to achieve.

In greater detail, in the construction sector, residential buildings play a key role and are a priority in energy efficiency measures at the national and international levels as they account for a significant part of total energy consumption, more than a quarter of the total (27% in 2021) (Eurostat, n.d.-b). Therefore, significant CO_2 emissions are produced by this sector, as well as high energy expenditure of households, particularly in the last few years where we have witnessed a sharp increase in fuel and energy poverty levels, especially among the most vulnerable population due to low incomes, high energy prices, and poor building performances (European Parliament, 2022). In fact, 22.3% of the European building stock was built before 1946 and around 44% between 1946 and 1980 (Eurostat, n.d.-a). Thus, the majority of the existing building stock is obsolete from an energy performance point of view, as they are older than the first regulations on building energy performance (Rosso et al., 2021). For these reasons, there is a growing interest in energy efficiency in the residential sector, developing strategies and actions both at the EU (European Parliament, 2018a, 2021) and at a national level (DL 34/2020, 2020) to set severe mandatory constraints both for new buildings and retrofit actions (Ascione et al., 2022).

Design choices play a fundamental role in achieving these increasingly high performances, influencing the future behavior of the building since the earliest design phases (Granadeiro et al., 2012). Numerous possible passive strategies, i.e. solutions that do not use extra energy to improve the performance of the building, can be implemented towards more sustainable and low-energy buildings, starting from a good orientation within the construction site to the detailed thermo-physical parameters of the materials used for the building envelope (Cabeza & Chàfer, 2020). All possible alternatives to consider with respect to different objectives and different stakeholders involved can make the design decision phases very difficult to address. Given the amount of effort required to develop and evaluate the most suitable combination of passive strategies, a limited design space is most often considered, compromising the quality of the resulting building performance and also restricting the architects' creative potential (Turrin et al., 2011).

Advanced digital tools can manage this increasing complexity of the project and can offer us opportunities for approaching the design of buildings in new ways (Naboni et al., 2013). Indeed, simulation tools can provide accurate analysis of different aspects of building performance, increasing the awareness of the designer's choices and the understanding of the influence of a design solution on the future performance of the building (Han et al., 2018). Moreover, using parametric modeling, different alternatives can be easily generated and optimization algorithms can be used to search in the wide solution space effectively, instead of considering just a few combinations of passive strategies (Kheiri, 2018). Optimal solutions can be found in relation to different objectives, often conflicting with each others. For example, the achievement of high energy performance of a building often brings about an increase in investment costs, i.e. the initial cost for the implementation of the strategies. Indeed, taking into account real applications, more than one objective is usually considered in the optimization process, and a multi-objective optimization should be carried out to account for all the conflicting objectives.

Moreover, design choices made during the schematic design phases are those that most influence the performance of the building and furthermore, these can be implemented in a phase in which the project is more flexible to changes without significantly increasing costs (MacLeamy, 2010). Architects have a key role in those phases and make crucial decisions early in the design process, such as determining the building form, orientation, and window layout, often without much assistance from simulation software. However, achieving such high building performance is challenging, and given the increasing complexity of the built environment, it cannot be addressed with intuition or experience alone.

While building energy simulations can effectively predict performance and compare design options, they are commonly employed too late in the traditional design process (Østergård et al., 2016). Indeed, performance simulations are primarily conducted for equipment size and code compliance after the architectural design has been finalized. This is also motivated by the fact that significant challenges lie in the required detailed data for simulations and interoperability issues with the design tools. Thus, particular attention should be paid to simulation models adapting to the different phases of the design process and the corresponding level of detail. Indeed, even if the distinction between phases in the design process has blurred in recent years due to digital developments, the level of detail increases as the design proceeds. For example, during the schematic design phase, massing, spatial relationships, and the overall form of the building are explored, and several design alternatives are developed and compared, following the requirements and constraints of the project (Mankins, 2013).

When numerous variables and different conflicting objectives are involved, recent research has focused on multi-objective building performance optimization (BPO) techniques and different methodologies have been developed, both for new constructions (Ascione et al., 2019; Negendahl & Nielsen, 2015) and existing buildings (Panagiotidou, 2020; Rosso et al., 2020). However, it seems that this kind of design approach is still not widespread among professionals (Attia et al., 2013; Wortmann et al., 2022), especially in architectural practice (Kistelegdi et al., 2022; Shi et al., 2016). This is an issue that should not be underestimated, as architects are typically responsible for making crucial decisions during the early stages of design. Thus, the topic still demands methodologies and tools supporting different aspects of BPO and its introduction into common practice, focusing on their applicability and their efficacy in solving real problems. Furthermore, updated information on the actual diffusion of building performance simulation and optimization in practice and needs of potential users should be collected to develop practice-oriented methodologies.

The above-mentioned BPS and BPO gaps are further exacerbated in the residential sector, which is a crucial sector as illustrated at the beginning of this text. Indeed, due to COVID-19, many people are spending more time at home (Balest & Stawinoga, 2022) and this behavior is likely to continue as working from home is having diverse benefits to the workers and society as a whole (Hook et al., 2020). Residential buildings, as a consequence, have the dual function of houses and offices most often, and the trend is likely to increase (Hu, 2020). Therefore, addressing not only energy aspects but integrating also comfort metrics, such as visual comfort (Carlucci et al., 2015), is of utmost importance for building more energy-efficient, comfortable, and healthy spaces to live/work in, and more generally, to spend time in. However, while daylight performance has been extensively studied in BPO works related to office or educational buildings during schematic design phases (Fang & Cho, 2019; Noorzai et al., 2022), little research has been conducted in residential ones (Dogan & Park, 2017), which appears as a limitation due to the newly acquired office function of residential spaces.

Additionally, the cost of energy has significantly increased, thus becoming a heavier burden for those who live and work at home, and to the most vulnerable residents, i.e., elderly people or disadvantaged residents. Thus, the focus on social housing - also evidenced as a priority by the European Union - and its energy retrofit is even more pressing today that the prices of energy resources are characterized by strong uncertainty and fuel poverty is significantly increasing.

1.2 Research aims and questions

Given the above panorama, the research aims to address the challenges and gaps described in the previous section, through an in-depth analysis of multi-objective BPO of passive design strategies for sustainable and low-energy residential buildings for the optimization of geometric variables and envelope characteristics using genetic algorithms.

In greater detail, the research aim is to propose effective multi-objective methodologies for achieving sustainable residential buildings at the different design stages, while dealing with the decisions on geometric variables from the schematic design phase, considering energy and daylight objectives (new construction) to the detailed development phase, considering the envelope proprieties with respect to energy, emissions, and costs (retrofit of existing buildings).

Thus, the main Research Question of this thesis is the following:

RQ1. How can multi-objective BPO address complexity in the design process of sustainable and low-energy buildings from the schematic design phases up to retrofit strategies, and how to increase its applicability?

To answer the main research question, this dissertation aims to address in the different chapters five sub-questions, as follows:

RQ2. How does sustainability increase complexity in building design and which advanced digital tools can deal with such complexity? (Chapter 2)

RQ3. What is the state of the art of multi-objective BPO in schematic design phases both in scientific literature and in practice, and what are the challenges to integrating BPO into the design process? (Chapter 3)

RQ4. How can multi-objective BPO be applied to the schematic design phase of a new building while dealing with the decisions on geometric variables? (Chapter 4)
RQ5. How can multi-objective BPO be applied to retrofit strategies on existing buildings while dealing with a large number of building envelope variables? (Chapter 5)

RQ2 and RQ3 question the theory behind the topics covered in the thesis and want to analyze the state of the art. Instead, the last two questions (RQ4 and RQ5) aim to guide the investigation through practical applications, not only helping in the identification of challenges associated with the utilization of BPO in different design stages but also facilitating an understanding of its implications in the architects' design practice. Thus, the goal is to empower architects and engineers to make well-informed design decisions with a high awareness of the multiple facets of building performance, especially when dealing with a complex design problem with a large number of design parameters. For this reason, common problems in the applicability of computational workflows into the practice, e.g. required detailed data for simulations and interoperability issues with the design tools, are addressed while proposing the multi-objective methodologies applied in Chapters 4 and 5.

Therefore, this thesis targets both researchers and practitioners interested in sustainable building design, performance simulation, and optimization techniques to enhance their ability to address decision-making phases. Indeed, the thesis can stimulate researchers' interests because it focuses on a field of research that has been particularly active in recent years and applies it to current problems, such as the trade-off between energy and daylight in residential buildings, an issue even more important today that our habits have changed spending more time in our homes, or the optimization of the retrofit strategies of a social housing building to respond to the recent growth in fuel poverty. Moreover, the thesis targets practitioners too, involved in both new and existing buildings. Indeed, some barriers to the application of BPO in practice are addressed here, and a more collaborative and multi-disciplinary design process could be carried out using the proposed methodologies. Furthermore, the research may also be of interest to AEC software developers, collecting useful information from the survey to enhance usability and select appropriate functions for new software. Additionally, this research can benefit policymakers by informing strategies for the green and digital transition of the construction sector.

To facilitate the reading of this dissertation, the following section presents the structure of the thesis and the methods adopted.

1.3 Thesis structure and methods

This section provides an overview of the structure of the thesis and the methods used to answer the research questions previously described. Figure 1 represents a summary diagram of the structure of this dissertation which is explained in more detail in the following paragraphs.

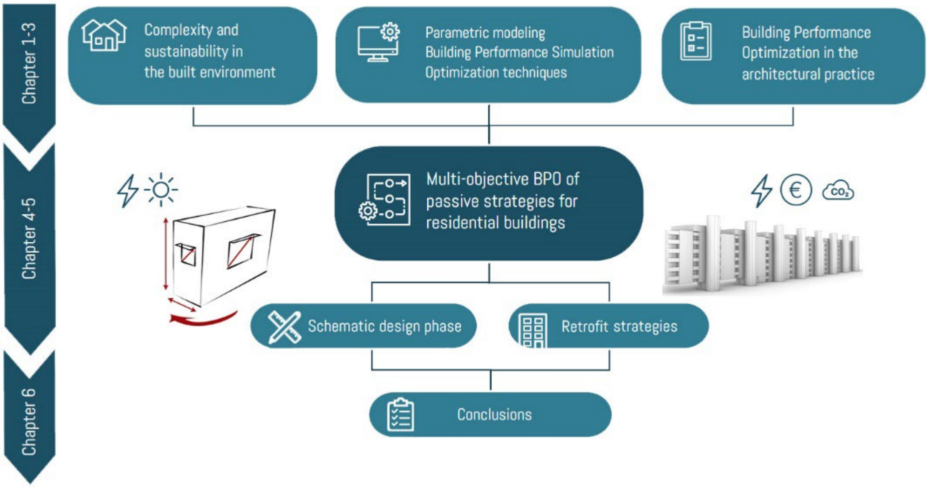

Figure 1. Structure of the thesis.

The first part of the research is a review of the state of the art on sustainability and complexity within the built environment, regulations and strategies. Then, parametric modeling, energy and daylight simulations and optimization techniques are analyzed, introducing the theoretical principles behind them and the main tools whose integration leads to BPO methods (Chapter 2). Indeed, in Chapter 3, the research aims to gather specific information on BPO during schematic design phases in both literature and practice. Towards this aim, a systematic literature review is carried out, and an online survey is distributed to architectural firms, as they have a fundamental role in early design phases. Thus, the online and anonymous survey has the goal to understand knowledge and diffusion of BPO in the practice and opportunities and barriers concerning the potential adoption in the professional world. Indeed, this review in research and practice looks at academic articles to extract what resonates and does not resonate in research but also what matches and does not match with needs in practice and vice versa. The work described in Chapter 3 was carried out during the visiting research period abroad at TU Delft, with the help and supervision of prof. Sevil Sariyildiz and prof. Michela Turrin.

Based on the results of the review, Chapter 4 focuses on the methodological framework for the geometric variables optimization during the schematic design phase with respect to the energy performance and the accessibility of daylight in a new residential building. Indeed, energy and daylight are two fundamental components in sustainable residential building design and, particularly in Mediterranean climates, they are two conflicting objectives. To verify the proposed methodology, an application on a new construction apartment block located in Rome is carried out, focusing on the integration of modeling, multidisciplinary simulation and optimization in the same parametric environment.

Instead, Chapter 5 deals with the methodological framework related to envelope optimization, considering energy and economic aspects. For this reason, a retrofit of a significant case study pertaining to the social housing buildings in Rome is chosen, addressing energy efficiency measures feasible from an architectural and economic perspective. Given the complexity of the project, an in-house aNSGA-II, which is a recent optimization algorithm still not widely diffused, is developed and tested, thanks to the collaboration with the Department of Astronautical, Electrical and Energy Engineering in Sapienza University of Roma. Moreover, since the case study is a social housing building, an analysis of the energy price increase between 2019 and 2022 due to geopolitical instabilities is carried out, evaluating the benefits of the modification of the HVAC system and implementation of renewable energy on the fuel poverty issue.

Finally, Chapter 6 draws conclusions, highlighting the contribution of the research and introducing the limitations and future developments.

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