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Technological Imagination in the Green and Digital Transition

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Editors

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Editors
Eugenio Arbizzani
Dipartimento di Architettura e Progetto
Sapienza University of Rome
Rome, Italy

Eliana Cangelli
Dipartimento di Architettura e Progetto
Sapienza University of Rome
Rome, Italy

Carola Clemente
Dipartimento di Architettura e Progetto
Sapienza University of Rome
Rome, Italy

Fabrizio Cumo
Dipartimento Pianificazione, Design, Tecnologia dell'Architettura
Sapienza University of Rome
Rome, Italy

Francesca Giofrè
Dipartimento di Architettura e Progetto
Sapienza University of Rome
Rome, Italy

Anna Maria Giovenale
Dipartimento di Architettura e Progetto
Sapienza University of Rome
Rome, Italy

Massimo Palme
Departamento de Arquitectura
Universidad Técnica Federico Santa Maria
Antofagasta, Chile

Spartaco Paris
Dipartimento di Ingegneria Strutturale e Geotecnica
Sapienza University of Rome
Rome, Italy

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Contributors

Sofia Agostinelli Sapienza University of Rome, Rome, Italy

Hosam Al-Siah Sapienza University of Rome, Rome, Italy

Davide Allegri Polytechnic University of Milan, Milan, Italy

Maria Beatrice Andreucci Sapienza University of Rome, Rome, Italy

Eugenio Arbizzani Sapienza University of Rome, Rome, Italy

Marianna Arcieri Polytechnic University of Milan, Milan, Italy

Maria Vittoria Arnetoli University of Florence, Florence, Italy

Stefano Arruzzoli Polytechnic University of Milan, Milan, Italy

Davide Astiaso Garcia Sapienza University of Rome, Rome, Italy

Nazly Atta Polytechnic University of Milan, Milan, Italy

Gigliola Ausiello University of Naples Federico II, Naples, Italy

Maria Azzalin Mediterranean University of Reggio Calabria, Reggio Calabria, Italy

Meri Batakoja Ss. Cyril and Methodius University, Skopje, North Macedonia

Silvia Battaglia Polytechnic University of Milan, Milan, Italy

Oscar Eugenio Bellini Polytechnic University of Milan, Milan, Italy

Carla Álvarez Benito European University Foundation (EUF), Brussels, Belgium

Roberto Bianchi Mercatorum University, Rome, Italy

Leonardo Binni Polytechnic University of Marche, Ancona, Italy

Martina Bocci Polytechnic University of Turin, Turin, Italy

Andrea Bocco Polytechnic University of Turin, Turin, Italy

Arthur Bohn Polytechnic University of Turin, Turin, Italy

Roberto Bologna University of Florence, Florence, Italy

Steven Boon Housing Anywhere, Rotterdam, Netherlands

Martina Bosone Research Institute on Innovation and Services for Development of the Italian National Research Council (CNR-IRISS), Naples, Italy

Andrea Brambilla Polytechnic University of Milan, Milan, Italy

Timothy Daniel Brownlee University of Camerino, Camerino, Italy

Erica Brusamolin Polytechnic University of Milan, Milan, Italy

Maddalena Buffoli Polytechnic University of Milan, Milan, Italy

Francesca Caffari ENEA, Rome, Italy

Nicolandrea Calabrese ENEA, Rome, Italy

Gisella Calcagno University of Florence, Florence, Italy

Guido Callegari Polytechnic University of Turin, Turin, Italy

Maria Canepa University of Genoa, Genoa, Italy

Eliana Cangelli Sapienza University of Rome, Rome, Italy

Monica Cannaviello University of Campania "L. Vanvitelli", Aversa, Italy

Stefano Capolongo Polytechnic University of Milan, Milan, Italy

Cheren Cappello University of Sassari, Sassari, Italy

Barbara Cardone University of Roma Tre, Rome, Italy

Tecla Caroli Polytechnic University of Milan, Milan, Italy

Giovanni Castaldo Polytechnic University of Milan, Milan, Italy

Giulia Centi ENEA, Rome, Italy

Francesca Ciampa University of Naples Federico II, Naples, Italy

Andrea Ciaramella Polytechnic University of Milan, Milan, Italy

Adriana Ciardiello Sapienza University of Rome, Rome, Italy

Federico Cinquepalmi Sapienza University of Rome, Rome, Italy

Carola Clemente Sapienza University of Rome, Rome, Italy

Marta Cognigni Polytechnic University of Milan, Milan, Italy

Raffaella Colombo Istituto Comprensivo Rinnovata Pizzigoni, Milan, Italy

Alessandra Corneli Polytechnic University of Marche, Ancona, Italy

Nataša Ćuković-Ignjatović University of Belgrade, Belgrade, Serbia

Fabrizio Cumo Sapienza University of Rome, Rome, Italy

Laura Daglio Polytechnic University of Milan, Milan, Italy

Anna Dalla Valle Polytechnic University of Milan, Milan, Italy

Francesca Daprà Polytechnic University of Milan, Milan, Italy

Roberto D'Autilia University of Roma Tre, Rome, Italy

Alberto De Capua Mediterranea University of Reggio Calabria, Reggio Calabria, Italy

Jacopo Dell'Olmo Sapienza University of Rome, Rome, Italy

Valentina Dessì Polytechnic University of Milan, Milan, Italy

Raffaela De Martino University of Campania L. Vanvitelli, Aversa, Italy

Stefania De Medici University of Catania, Catania, Italy

Maria Giovanna Di Bitonto Polytechnic University of Milan, Milan, Italy

Marco Di Ludovico University of Naples Federico II, Naples, Italy

Mohamed Eledeisy Sapienza University of Rome, Rome, Italy

Lidia Errante Mediterranea University of Reggio Calabria, Reggio Calabria, Italy

Daniele Fanzini Polytechnic University of Milan, Milan, Italy

Emilio Faroldi Polytechnic University of Milan, Milan, Italy

Marco Ferrero Sapienza University of Rome, Rome, Italy

Maria Fianchini Polytechnic University of Milan, Milan, Italy

Irene Fiesoli University of Florence, Florence, Italy

Maria F. Figueira International Union of Property Owners (UIPI), Brussels, Belgium

Antonio Fioravanti Sapienza University of Rome, Rome, Italy

Rossella Franchino University of Campania L. Vanvitelli, Aversa, Italy

Caterina Frettoloso University of Campania L. Vanvitelli, Aversa, Italy

Valentina Frighi University of Ferrara, Ferrara, Italy

Matteo Gambaro Polytechnic University of Milan, Milan, Italy

Pablo Garrido Torres Universitat Politécnica de Catalunya, Barcelona, Spain

Vincenzo Gattulli Sapienza University of Rome, Rome, Italy

Marko Gavrilović University of Belgrade, Belgrade, Serbia

Giuliana Nardi University of Roma Tre, Rome, Italy

Ludovica Nasca University of Catania, Catania, Italy

Benedetto Nastasi Sapienza University of Rome, Rome, Italy

Berardo Naticchia Polytechnic University of Marche, Ancona, Italy

Maicol Negrello Polytechnic University of Turin, Turin, Italy

Aleksandra Nenadović University of Belgrade, Belgrade, Serbia

Antonio Novellino ETT SpA, Genoa, Italy

Filippo Orsini Polytechnic University of Milan, Milan, Italy

Giuseppe Orsini Sapienza University of Rome, Rome, Italy

Maria Giovanna Pacifico University of Naples Federico II, Naples, Italy

Giancarlo Paganin Polytechnic University of Milan, Milan, Italy

Massimo Palme Universidad Técnica Federico Santa María, Valparaíso, Chile

Elisabetta Palumbo University of Bergamo, Bergamo, Italy

Giulio Paparella Sapienza University of Rome, Rome, Italy

Spartaco Paris Sapienza University of Rome, Rome, Italy

Francesco Pasquale UNIMORE, Modena, Italy

Lorenzo Mario Pastore Sapienza University of Rome, Rome, Italy

Jelena Pavlović University of Belgrade, Belgrade, Serbia

Maura Percoco Sapienza University of Rome, Rome, Italy

Giacomo Pierucci University of Florence, Florence, Italy

Claudio Piferi University of Florence, Florence, Italy

Maria Rita Pinto University of Naples Federico II, Naples, Italy

Anna Pirani Centre for Theoretical Physics, Trieste, Italy

Giuseppe Piras Sapienza University of Rome, Rome, Italy

Nicola Pisani Colouree S.r.l., Genoa, Italy

Matteo Poli Polytechnic University of Milan, Milan, Italy

Riccardo Pollo Polytechnic University of Turin, Turin, Italy

Alice Paola Pomè Polytechnic University of Milan, Milan, Italy

Gianluca Pozzi Polytechnic University of Milan, Milan, Italy

Giulia Procaccini Polytechnic University of Milan, Milan, Italy

Donatella Radogna University “G. D’Annunzio” of Chieti-Pescara, Pescara, Italy

Alberto Raimondi University of Roma Tre, Rome, Italy

Andrea Rebecchi Polytechnic University of Milan, Milan, Italy

Rosaria Revellini IUAV University of Venice, Venice, Italy

Diletta Ricci Sapienza University of Rome, Rome, Italy;
Delft University of Technology, Delft, Netherlands

Guglielmo Ricciardi Polytechnic University of Turin, Turin, Italy

Alessandro Rogora Polytechnic University of Milan, Milan, Italy

Manuela Romano Polytechnic University of Milan, Milan, Italy

Rosa Romano University of Florence, Florence, Italy

Sabri Ben Rommane Erasmus Student Network AISBL (ESN), Brussels, Belgium

Laura Rosini University of Roma Tre, Rome, Italy

Massimo Rossetti IUAV University of Venice, Venice, Italy

Federica Rosso Sapienza University of Rome, Rome, Italy

Irina Rotaru Saint Germain-en-Laye, France

Helena Coch Roura Universitat Politécnica de Catalunya, Barcelona, Spain

Ana Šabanović University of Belgrade, Belgrade, Serbia

Samaneh Safaei Graduate University of Advanced Technology, Kerman, Iran

Ferdinando Salata Sapienza University of Rome, Rome, Italy

Sara Sansotta Mediterranea University of Reggio Calabria, Reggio Calabria, Italy

Antonello Monsù Scolaro University of Sassari, Sassari, Italy

Paolo Simeone Polytechnic University of Turin, Turin, Italy

Francesco Sommese University of Naples Federico II, Naples, Italy

Tianzhi Sun Polytechnic University of Milan, Milan, Italy

Chiara Tagliaro Polytechnic University of Milan, Milan, Italy

Maurizio Talamo Tor Vergata University of Rome, Rome, Italy

Andrea Tartaglia Polytechnic University of Milan, Milan, Italy

Chiara Tonelli University of Roma Tre, Rome, Italy

Agata Tonetti IUAV University of Venice, Venice, Italy

Matteo Trane Polytechnic University of Turin, Turin, Italy

Chapter 11
An Innovative Multi-objective Optimization Digital Workflow for Social Housing Deep Energy Renovation Design Process

Adriana Ciardiello, Jacopo Dell'Olmo, Federica Rosso, Lorenzo Mario Pastore, Marco Ferrero, and Ferdinando Salata

Abstract Nowadays, the energy retrofit of the building sector is identified as a major instrument toward a climate-neutral Europe by 2050. In accordance with the European Renovation Wave program, deep energy renovations are needed, starting from public and less efficient buildings. Furthermore, the renovation of the social housing building stock is also an important response to energy poverty, as it could contribute safeguarding health and well-being of vulnerable citizens. In particular, buildings from the 1960–1980, which constitute a large portion of cities, often have high energy demand and low indoor comfort because most of them have been built before energy-efficiency regulations. In this context, the paper aims to propose a multi-objective approach toward energy renovation of the social housing building stock, by means of an innovative digital workflow. The objective functions are minimizing energy consumption, CO_2 emissions, investment, and operational costs. Toward these contrasting objectives, numerous passive strategies are taken into account, which are compatible with the considered architecture. The optimal solutions are found by means of a genetic algorithm coupled with energy performance simulation software. The methodology is applied and verified on a significant and relevant case study, pertaining to the social housing building stock of Rome, Italy (Mediterranean climate). The outputs of the workflow are a set of optimal solutions among

A. Ciardiello (✉) · J. Dell'Olmo · F. Rosso · L. M. Pastore · M. Ferrero · F. Salata
Sapienza University of Rome, Rome, Italy
e-mail: adriana.ciardiello@uniroma1.it

J. Dell'Olmo
e-mail: jacopo.dellolmo@uniroma1.it

F. Rosso
e-mail: federica.rosso@uniroma1.it

L. M. Pastore
e-mail: lorenzomario.pastore@uniroma1.it

M. Ferrero
e-mail: marco.ferrero@uniroma1.it

F. Salata
e-mail: ferdinando.salata@uniroma1.it

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which to choose the fittest one depending on the need of the different stakeholders. The proposed multi-objective approach allows reducing the energy consumption for heating by 31% and for cooling by 17% and the CO_2 emissions up to 27.4%. The proposed methodology supports designers and policymakers toward an effective building stock renovation, which can answer the urgent energy and environmental targets for the coming decades.

Keywords Multi-objective optimization · Social housing · Existing buildings · Retrofit · Building energy simulation

11.1 Introduction

In the last decades, the European Union has encouraged Member States to develop strategies toward a deep renovation of the building stock since the 75% of the buildings is currently energy inefficient and the building sector is responsible for 40% of energy consumption and 36% of CO_2 emissions (European Parliament 2012). Indeed, the European Green Deal asks Member States to improve long-term strategies toward a more sustainable building stock, starting from the renovation of the public buildings (European Commission 2020). Furthermore, these strategies aim to fight energy poverty, allowing for clean and safe energy for everyone.

In a changing climate, operation costs will increase with the global warming level and energy poverty will worsen as a consequence (Santamouris 2016). Moreover, in recent years, the energy produced from non-renewable sources is becoming more and more expensive, making the transition to renewable sources and the energy-efficiency strategies for our buildings increasingly urgent. The EU Commission's proposal for the recast of the Energy Performance of Building Directive (EPBD) introduces better measures and tools to increase the rate and depth of building renovations and presents a pathway for buildings to become "Zero Emission" by 2050 (European Parliament 2021).

For all these reasons, the energy retrofit of the building stock is an urgent task. Retrofit strategies should highly reduce both energy consumption and CO_2 emissions, but at the same time, they should be cost-effective. Therefore, a highly complex problem is outlined, considering multiple objectives and multiple variables—where each can have a wide range of possible values (Jafari and Valentin 2018).

To deal with such a complex problem and to explore this wide space of solutions, optimization algorithms can be used, coupled with energy simulation software (Machairas et al. 2014).

These advanced digital tools can support the designer during his decision-making phase and can address the design problem toward more sustainable and comfortable solutions. Indeed, the space of solutions would be too wide to manually explore it and so "intelligent" algorithms can be used to automatically converge toward optimal solutions. In the scientific literature, the most common optimization algorithm used in building design optimization problems is the genetic algorithm (Costa-Carrapiço et al. 2020).

Multi-objective optimization in building design is an active research field (Kheiri 2018). Dealing with conflicting objectives, the optimization process does not provide only one solution—the absolute optimum—but a set of optimal solutions called Pareto solutions. This allows the designer to choose one of the selected solutions based on his preferences and requests. Moreover, it can be useful to explore different combinations and to allow architectural variability. The building energy optimization for existing buildings is a topic of increasing interest, and different methods were employed in the scientific literature with respect to the theoretical framework, objective functions, and genes and software (Hashempour et al. 2020; Ruggeri et al. 2020). Research is still needed to find an approach that can be worldwide shared and used in different design problems.

11.2 Aim and Contribution of the Work

Based on the above-discussed context, the work aims to expand the discussion on multi-objective optimization of retrofit actions toward more sustainable and comfortable buildings. Indeed, the paper proposes a multi-objective approach toward energy renovation of the social housing building stock, by means of an innovative digital workflow. This kind of approach aims to consider simultaneously different aspects of the design (architectural, environmental, energy, social) to address the designer toward more sustainable retrofit strategies. Moreover, the paper aims to investigate the influence of the passive strategies only on the energy efficiency and the environmental impact of the building. The digital workflow is set to be easily applied to different design problems. Indeed, each building would require a specific and tailored optimization to better address a deep and effective energy renovation.

11.3 Method

In order to find suitable retrofit strategies that are tailored for each specific building, the proposed digital workflow is built on a significant and relevant case study. The digital model of the case study is first prepared, and then, architecturally compatible retrofit strategies are taken into account. On these base considerations, the optimization problem is outlined and genes and constraints are set. After running the simulations, the optimal combination of strategies for the retrofit intervention is chosen from the Pareto curve of optimal solutions.

11.3.1 The Case Study and the Energy Model

The digital workflow proposed is applied and verified on a significant and relevant case study, pertaining to the social housing building stock of Rome, Italy.

The selected case study is a building designed by Lucio Passarelli in the late 70s in the northeast area of the city, for the social housing complex "Vigne Nuove" (Lenci 2006).

In particular, the selected building is building C, chosen among the four residential buildings in that area. It is a linear block building, with the distinctive characteristic of external cylindric staircase volumes. The case study consists of seven floors of apartments, the ground floor is open, and the roof consists of common spaces employed as terraces and small closed volumes for private storage. The building consists of 108 apartments and the total area of the conditioned zone is 13,000 m^2.

Table 11.1 describes the envelope elements of the building with the description of layers and their thermophysical features.

The building is modeled by means of Rhinoceros and Grasshopper plugins and simulated by means of EnergyPlus. With respect to the thermal zones, the residential floors are considered as one thermal zone. The thermal zone is a conditioned area, with an occupancy schedule from the late afternoon until the early morning (recalling

Table 11.1 Description of layers and thermophysical features of the envelope

Layers	Thickness (m)	Conductivity (W/mK)	Density (kg/m^3)	Specific heat (J/kgK)	Transmittance (W/(m^{2}K))
Outdoor wall					
Gypsum block	0.10	0.27	950	840	1.16
Air gap	0.20	–	–	–	
Gritted concrete	0.10	0.52	1550	1000	
Loggia wall					
Inner plaster	0.015	0.32	950	1000	1.06
Gypsum block	0.10	0.25	750	840	
Expanded clay block	0.15	0.42	1100	1000	
Roof					
Inner plaster	0.015	0.32	950	1000	0.66
Predalles slab	0.24	0.58	1670	1000	
Polyurethane	0.03	0.04	32	1400	
Lightweight concrete	0.04	1.00	1100	1000	
Tiles	0.02	1.30	2300	840	
Window					
Single glass	0.004	1.00	0.82	0.88	5.8

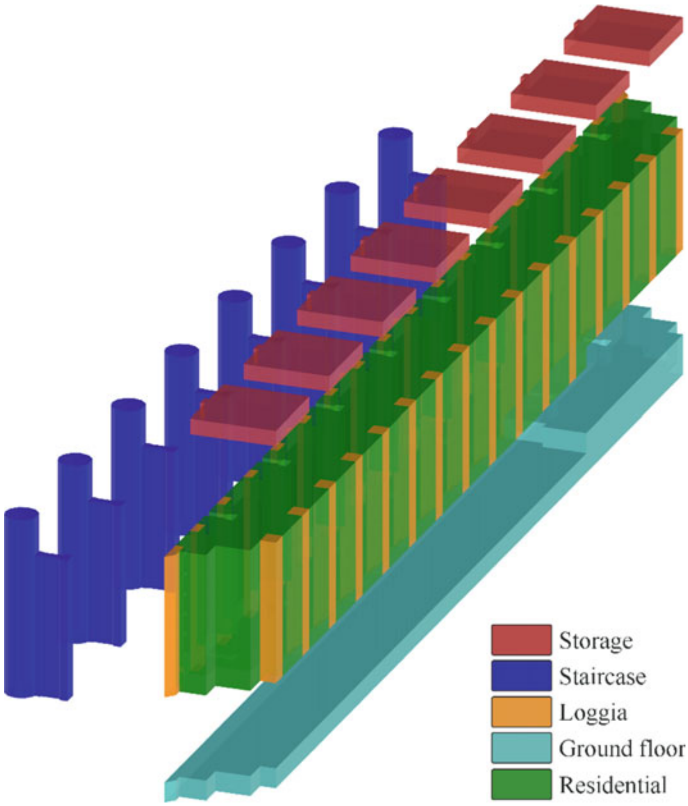


Fig. 11.1 Exploded view of the energy model

a typical working day). The setpoint temperatures are set to 20 °C for heating and 26 °C for cooling. The energy system, which is not the focus of this preliminary work, is set as an ideal system, working with natural gas for heating and electricity for cooling. The natural ventilation is set to 0.3 vol/h. In addition, there are non-conditioned zones for the staircases, the storage volumes on the roof, the loggias, and the open ground floor. Figure 11.1 shows the model and its thermal zones.

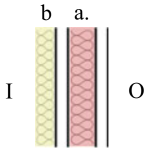
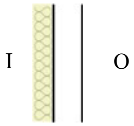
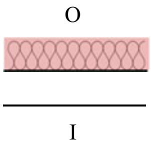
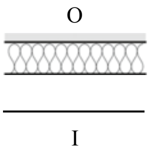
The model prepared with Rhino and Grasshopper is then exported to be used in the optimization process, conducted by means of an in-house implemented genetic algorithm written in Python and connected to EnergyPlus with the Eppy library.

11.3.2 *Retrofit Strategies*

Based on the analysis of the current status of the building, different architecturally compatible strategies are considered toward an energy renovation of the building.

These retrofit strategies—which constitute the "genes" of the building for the genetic optimization—are the following: (i) adding mid and internal thermal insulation to the external cavity walls, (ii) adding internal thermal insulation to the loggia walls, (iii) adding external thermal insulation to the roof, (iv) changing solar reflectance of the finishing layer of the roof, (v) changing windows, (vi) closing the loggias with operable glazing, (vii) adding solar shading in the loggias, (viii) closing the open ground floor with operable glazing. For each gene, a range of possible solutions is considered and the costs are evaluated based on the regional price list for Lazio, where the case study is located (Table 11.2).

Table 11.2 Investigated genes for the energy retrofit, range of variability, and costs

	Gene	Range of variability	Costs
	Thermal insulation outdoor wall a. Air gap b. Internal layer	a.1 Expanded clay a.2 Expanded granular cork a.3 Polyurethane foam b. Polyurethane board 0–6 cm (steps of 2 cm)	a.1 45.20 €/m^2 a.2 60.76 €/m^2 a.3 70.50 €/m^2 b. 44 €/m^2
	Internal thermal insulation loggia wall	Polyurethane board 0–6 cm (steps of 2 cm)	44 €/m^2
	External thermal insulation roof	Polyurethane board 0–7–8–9 cm	450 €/m^3
	Solar reflectance of the finishing layer of the roof	Solar reflectance 10–90% (steps of 10%)	40 €/m^2
	Windows	W0. $U = 1.80$ W/m^2K W1. $U = 1.60$ W/m^2K W2. $U = 1.40$ W/m^2K W3. $U = 1.10$ W/m^2K W4. $U = 0.90$ W/m^2K W5. $U = 0.70$ W/m^2K	270.20 €/m^2 326.00 €/m^2 366.00 €/m^2 390.00 €/m^2 422.00 €/m^2 478.00 €/m^2

(continued)

Table 11.2 (continued)

	Gene	Range of variability	Costs
	Closing loggia	Yes/No	210 €/m^2
	Solar shading	Yes/No	75 €/m^2
	Closing ground floor	Yes/No	210 €/m^2

11.3.3 Optimization Problem and the Genetic Algorithm

The optimization problem is formulated based on the need to simultaneously consider energy, environmental and economic aspects of the retrofit interventions. Therefore, a multi-objective optimization is conducted, dealing with the minimization of (i) energy demand (ED), (ii) CO_2 emissions (CO_2), (iii) investment costs (IC), (iv) energy costs (EC). The problem can be summarized by the following equation:

$$\min\ F(x) = \min[\mathrm{ED}(x), \mathrm{CO}_2(x), \mathrm{IC}(x), \mathrm{EC}(x)] \quad (11.1)$$

The ED is evaluated by means of yearly dynamic simulations with EnergyPlus. Based on the energy consumption of the building and the source of energy used, the CO_2 emissions are automatically evaluated according to the European Environment Agency data (EEA, https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1). The IC is the sum of each retrofit action cost implemented on the building based on the regional price list (Regione Lazio 2020). The EC is the cost of the primary energy yearly consumed by the building based on the energy price in the Eurostat database (Eurostat, https://ec.europa.eu/eurostat/databrowser/view/NRG_PC_202_C__custom_1358122/default/table?lang=en).

Therefore, the space of solutions is a four-dimensional space with 82,944 possible alternatives, considering all the genes (the retrofit strategies described in the previous section) and their range of variability.

A genetic algorithm is used to explore the space of solutions in a faster and more efficient way. Indeed, the algorithm is set to automatically converge toward optimal solutions with respect to the considered objective functions. From the 82,944 possible solutions, only 2000 are simulated, allowing a significant reduction of the computational time.

The optimization algorithm used is an in-house developed active archive Non-dominated Sorting Genetic Algorithm (aNSGA-II). This algorithm is still not widely employed in literature, but its high efficiency is demonstrated in different works (Rosso et al. 2020; Hamdy et al. 2012).

The outputs of the digital workflow are a set of optimal solutions along the Pareto curve, among which the designer can choose the fittest one depending on the need of the different stakeholders. In this case, as the building is public, we hypothesize that the best solution for all the stakeholders is the solution that simultaneously minimizes all the objectives.

11.4 Results

The results of the multi-objective optimization are shown in Fig. 11.2, where the dots represent the simulated buildings. To represent the fourth dimension (the CO_2 emissions), a color axis is used. Compared to the reference building, the optimal solution adds vertical insulation in the cavity of the external wall with expanded clay, replaces the Windows with W0 windows, and closes the loggias with operable glazing. With these genes implemented, the optimal solution allows reducing ED up to 28%. In greater detail, the reduction of the energy consumption for heating is 31% and for cooling 17%.

With respect to the CO_2 emissions, the passive strategies implemented in the optimal solution allow reducing the greenhouse gas emissions up to 27.4%. The EC is reduced by 23.2% and the IC is 70.11 €/m^2.

Figure 11.3 compares the results of the reference building and the optimal solution according to each objective function.

11.5 Conclusions

A deep renovation of our building stock is urgent to reduce energy consumption and the environmental impact of buildings. In particular, social housing plays an even more important role toward this goal, as low-income families that live in these buildings are vulnerable to energy poverty. For these reasons, the research aims to develop an innovative digital workflow that can take into consideration energy, environmental and economic aspects simultaneously for the optimization of building retrofit strategies.

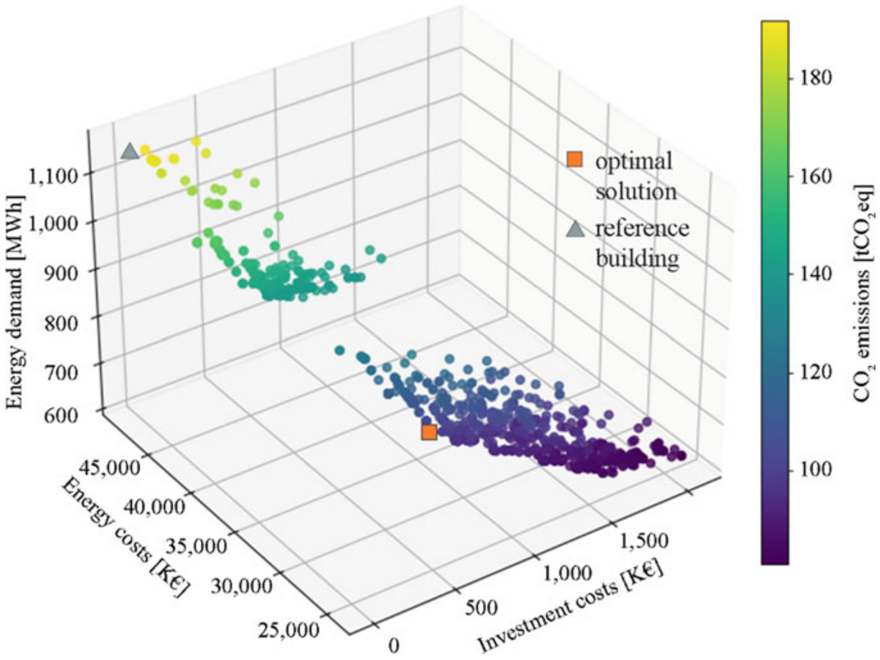


Fig. 11.2 Space of solutions with respect to annual energy demand, energy costs, investment costs, and CO_2 emissions

The workflow is applied and verified on an existing social housing located in Rome, which constitutes a relevant case study. Based on the analysis of the current status of the case study building, architecturally compatible strategies are taken into account as genes of the optimization process. The results of this multi-objective optimization are a set of optimal solutions, among which the designer can choose the fittest one for the specific design problem. Therefore, the proposed approach can highly support the decision-making process of retrofit design by exploring and simulating a wide space of solutions. This is possible by means of the genetic algorithm that reduced the energy simulations required from 82,944 to 2000.

In this work, the optimal solution is chosen among the Pareto frontier as the solution that minimizes simultaneously all the objective functions, i.e., energy demand, CO_2 emissions, energy costs, investment costs. The results demonstrate that high reductions (around 30%) can be achieved using this approach.

The proposed digital workflow is set to be easily repeated in different design problems and could support the activities of professionals and policymakers about retrofit actions to be undertaken on existing buildings.

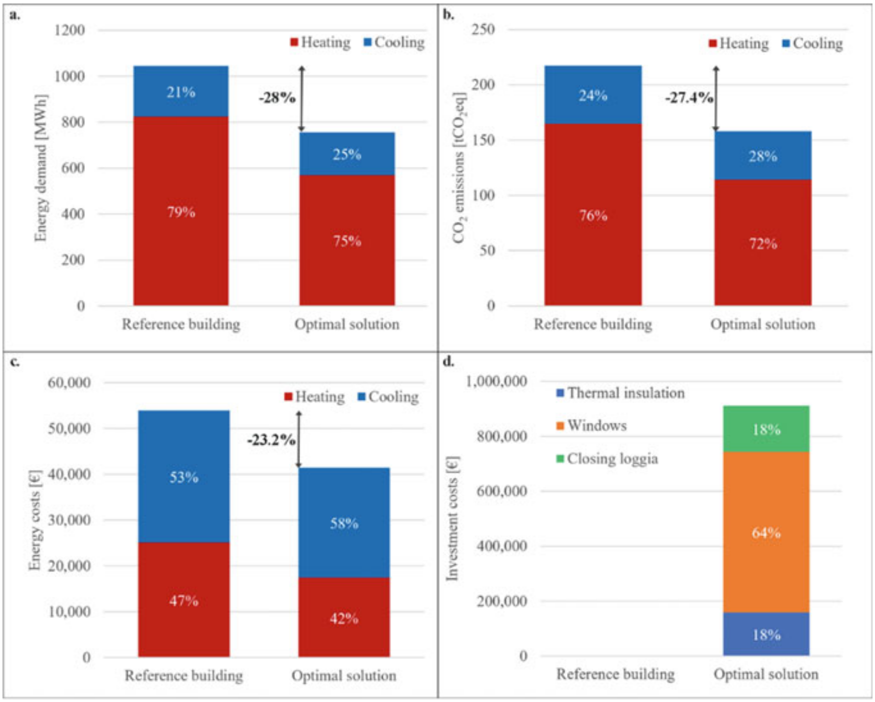


Fig. 11.3 Comparison of the reference building and the optimal solution with respect to **a** ED, **b** CO_2, **c** EC, **d** IC

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