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Indoor Environmental Quality Optimisation Model for Institutional Care Rooms of Elderly People

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Abstract: It is known that the elderly usually spend the last years of their lives indoors, with little contact with others and the outside environment. Indoor environmental quality (IEQ) conditions related to lighting, air quality, thermal comfort, and acoustics directly affect their quality of life. In this study, the main focus is on the design of institutional care rooms for elderly people to create an indoor comfort. However, considering all four factors of IEQ in one model is a challenging task. A multi-objective problem is formulated based on a weighted sum of IEQ components in a parametric modelling environment using computational design methods. Several simulation tools are utilised, and a Self-Adaptive Ensemble Differential Evolution Algorithm is proposed to tackle this complex problem. The results show that optimal ranges for each IEQ component are achieved, with average values reaching 72% of the ideal benchmarks after the algorithm is converged. Results reveal strong correlations between IEQ components. This significant improvement in indoor environmental quality (IEQ) demonstrates the efficacy of the optimisation algorithm used. This study emphasises the flexibility and relevance of these findings for wider implementation in similar settings.

Keywords: elderly care rooms; indoor environmental quality; indoor comfort; computational optimisation

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1. Introduction

The world is experiencing a dramatic increase in the aging population. By 2020, the number of people who are 60 years and older will be higher than the number of children below 5. WHO's projections indicate that 22% of the population will be elderly by 2050 [1]. One of the important consequences of aging is providing care services to the elderly, which would financially stress healthcare systems [2]. Thus, countries develop strategies to get prepared for this change, and residential care facilities (RCFs) are one of the solutions to this. RCFs help the elderly with their social participation, independence, and wellbeing, while providing healthcare support and daily activities. As the number of RCFs increases globally, many aspects are tackled in their design, such as starting from the early phase of the design process, where both architectural and engineering objectives should be satisfied while meeting the varying requirements of the elderly. RCFs serve 7/24, and their design entails the satisfaction of many comfort parameters, especially indoors, since the elderly spend most of their time indoors (90%) [3,4].

Creating comfortable spaces for occupants necessitates careful consideration of features of the indoor environment such as indoor air quality, thermal comfort, daylighting, and acoustic comfort. Indoor environmental quality (IEQ) is a term used in the literature to describe all of the above-mentioned aspects collectively. IEQ has a direct influence on health, comfort, wellbeing, productivity, and quality of life for occupants [5,6]. Providing IEQ for elderly users becomes especially significant, since they spend the majority of their time indoors. Inadequate IEQ that does not satisfy the elderly's comfort requirements or consider their special attention needs can negatively influence the quality of life [6].

Several studies have recently focused on integrating IEQ and elderly people in order to develop elderly-friendly interiors, particularly for care facilities. The approach to this issue is related to elderly room interior design, which includes indoor air quality [6–8], visual comfort [9,10], acoustical comfort [11,12], and thermal comfort [13–15]. The literature highlights that, due to strong correlations between IEQ components, changing just one of them could have negative effects on the others. For instance, increasing the glazing ratio for higher daylight availability results in excessive heat gains and reduced thermal comfort. Similarly, modifying wall layers to improve acoustic insulation restricts air flow between adjacent environments, making temperature and humidity control more challenging. Thermal comfort and IAQ are also closely associated; for example, increasing ventilation rates to improve IAQ leads to a decrease in thermal comfort, since increased air movement results in lower air temperatures. Conversely, reducing ventilation rates to improve thermal comfort causes an overall decrease in IAQ due to the accumulation of air pollutants and contaminants. As a result, a more comprehensive approach that aims to achieve balance across all IEQ components is required. Such a comprehensive strategy necessitates a thorough examination of each factor. The majority of studies used statistical analysis to create questionnaires based on user satisfaction or expectation [16,17], while some used on-site observations and measurements [18–20]. To the best of our knowledge, computational design methods are not considered in elderly care room design on the basis of IEQ optimisation. However, few studies considered IEQ optimisation [21] but not in a CAD environment, and they did not use parameters specific to the elderly. In this study, computational design methods are utilised to obtain IEQ-based design proposals for elderly care facilities through performative simulations based on common IEQ metrics and optimisation techniques. General methodology is presented in Figure 1 and explained in Section 3 in detail.

2. Importance of IEQ Parameters to the Elderly

2.1. Visual Comfort

Because the elderly suffer from various physical declines as they age, the impact of spatial environments on them differs from that on healthy young people. Some of the physical impairments are related to the visual system. Visual field area declines, reduced colour discrimination, and adaptation to darkness are common among the elderly [22]. Aside from lens yellowing, corneal flattening and decreased corneal sensitivity result in specific lighting requirements [23]. To address the issues raised, the Adapted Standard (AS) is recommended, which suggests a 55% increase in illuminance levels over the European Standard. For instance, in entrance halls, instead of 210 lux, 310 lux, and, in rooms, instead of 500 lux, 775 lux is recommended [24]. However, evaluation of lighting should not be limited to quantity alone; quality is equally important [25]. Increasing the illuminance level alone is not sufficient to provide visual comfort in cases of glare or veiling reflections. Negative consequences such as falls [24,26,27], disrupted circadian rhythms [26], and sleep cycles [28] are common when visual comfort is not achieved. Efficient usage of both natural and artificial light sources should be applied to provide visual comfort, which is also associated with psychological disorders (especially depression) [29,30]. Orientation, window, glazing, shading, and artificial lighting fixture selections are significantly important in achieving visual comfort and obtaining control [31].

2.2. Acoustical Comfort

One of the senses that regresses with age is hearing. Hearing problems that increase with age can both damage social relationships and cause problems such as lack of self-confidence, stress, discomfort, and health problems [32–35]. Due to hearing loss, the elderly need a quieter environment and a shorter reverberation time to understand speech in the environment [36,37]. In addition to causing hearing problems, noise is also very critical in terms of reducing the quality of life at later ages, just as it is at early ages. Sleep, privacy, and concentration problems caused by noise reduce the indoor environmental comfort of the elderly [35,38]. The subjective definition of what is and is not noise differs, but it is disturbing to everyone. In Potter et al.'s (2017) study, some elderly people found music and TV sounds annoying, while others found them enjoyable [39]. Instead of hoping to reach a consensus on noise and sound comfort, it is necessary to solve the problem at its source by making good sound insulation on building components [40].

2.3. Thermal Comfort

Thermal comfort is the state of being satisfied with the thermal environment [41]. Thermal comfort is a parameter that affects individuals in terms of physical, mental, and health; thus, people who feel uncomfortable do not want to be in the place and, when they are, they are negatively affected physically and spiritually [42]. The ISO 7730 standard and ANSI/ASHRAE 55 specify thermal comfort conditions for all healthy adults, including the elderly; however, studies have shown that the elderly have different thermal preferences compared to young adults [42–44]. The elderly, for example, prefer 2 °C higher ambient temperatures and are more sensitive to thermal conditions than young adults [44–46]. Due to low activity and a decrease in metabolic rate, the control of body temperature decreases and the elderly generally need warmer environments [47,48]. In addition, thermal sensitivity decreases with advanced age, making them more vulnerable and more likely to experience various health problems (such as hypothermia, hyperthermia, and pneumonia) in extreme weather conditions, whether in the summer or the winter [48]. Though the Chartered Institution of Building Services Engineers (CIBSE) Guide A suggests a relative humidity (RH) of 40% as the minimum acceptable level, dermatologists recommend a minimum of 45% RH to prevent dry skin problems in the elderly [49]. As an alternative to using HVAC systems to provide thermal comfort, the elderly can adapt to changing conditions by changing clothing levels, window opening practices, and fan use, which are colloquially known as "adaptive thermal behaviors" (Cena et al., 1988 [50]). To achieve thermal comfort for the elderly under climatic conditions, building materials' heat loss/gain properties and adaptive thermal behaviors should be holistically considered.

2.4. Indoor Air Quality (IAQ)

The World Health Organization (WHO) reports that, in developed countries, people spend 90% of their time indoors; thus, poor indoor air quality (IAQ) is as significant as outdoor air quality [8,51]. The Environmental Protection Agency (EPA) emphasises that interiors can have 100 times more contaminants than outdoors and lists poor air quality among the five biggest dangers to users' wellbeing [52]. A number of studies have focused on health issues related to building interiors. The term "Sick Building Syndrome" (SBS) is commonly used in the literature to describe the discomfort and acute health consequences caused by pollutants released by interiors [8,52–54]. In addition, the recent COVID-19 pandemic raised awareness of the airborne infections' impact on public health, especially for elderly users who are more vulnerable to indoor air pollutants (even at low concentrations) [8,54]. In fact, COVID-19 brought the importance of IAQ to the forefront and, in elderly care facilities, IAQ improvement measures are more likely to be considered by prospective residents and their families [55].

2.5. IEQ Optimisation through Weighted Schemes

Focusing on all the above-mentioned aspects associated with IEQ in one design problem can be a challenging task. The satisfaction of IEQ constraints can be handled with some computational intelligence techniques. Therefore, computational design methods are utilised, which facilitates the testing of the performance simulations through a generative model and running the optimisation algorithms in a parametric modelling environment. To consider all four components of IEQ in one model, weighted schemes are utilised. According to the literature [56], the components of IEQ have combined effects and, to evaluate their interrelated contributions, weighted schemes are defined for assessment. However, these weighted schemes show great variety and, to date, there are no standardised methodologies and defining each weight is a challenging task. A number of studies proposed weighted schemes through analytic hierarchy process (AHP) [57], multiple linear regression (MLR), or multivariate linear regression (MvLR) [58,59], assuming each component as an independent variable to influence the IEQ and neglecting inter-category relationships. The current literature on weighting schemes mainly relies on survey studies and examines user profiles such as university students and professionals (such as architects and engineers) [60,61]. To the best of our knowledge, this is the first study that considers IEQ optimisation with equal weights of each component (0.25) specifically for elderly people in computational design practice.

In this manner, institutional care room design tasks can be defined as real-parameter optimisation problems, since nonlinear objectives (e.g., the radiance method in daylighting) should be satisfied starting from the conceptual phase of the design process. In addition, it is clear that designing a healthcare facility building is controlled by a huge number of decision variables. In this respect, heuristics can play a vital role in order in dealing with complex design problems as an optimisation method. The aim of this study is to consider computational intelligence (heuristic optimisation) as a method for dealing with the complex design problem of institutional care facilities in the context of elderly people's rooms.

3. Methodology

Each of the IEQ parameters outlined above introduces additional design complexity that leads to challenges throughout the design decision-making process in general, while, in the case of elderly room designs, additional design aspects such as material selection and reflectance values intervene and increase complexity. With the aim of addressing these issues, in this study, a method for dealing with complex design problems with application to elderly room design is proposed. The general framework introduced in [62] consisting of "form generation", "performance evaluation", and "optimization" was considered. The proposed method comprises innovative techniques pertaining to form generation and performance evaluation and couples those with advanced multi-objective computational optimisation algorithms, namely the Self-Adaptive Differential Evolution algorithm. The proposed method is applied and validated on an institutional care's elderly room design case study based on an urban (inner city) scenario, which causes shading due to the context buildings and also the noise coming from the main road. It is noted that the methodology outlined in this paper has been developed with application in a computational optimisation context in mind, forming a generative model for satisfying the indoor comfort conditions of an elderly room that can be easily adapted to different scenarios. Within this context, the general outline of the proposed method comprises three elements: parametric form generation, performance evaluation for four IEQ parameters, and, finally, heuristics optimisation based on a weighted sum approach, as shown in Figure 1.

In the subsections hereafter, each of these components is outlined in detail. First of all, the form-generation part is presented. Then, the performance evaluation part is explained to present how IEQ parameters are formulated in the parametric CAD environment in the form of an objective function to be optimised. After that, optimisation algorithm details are explained.

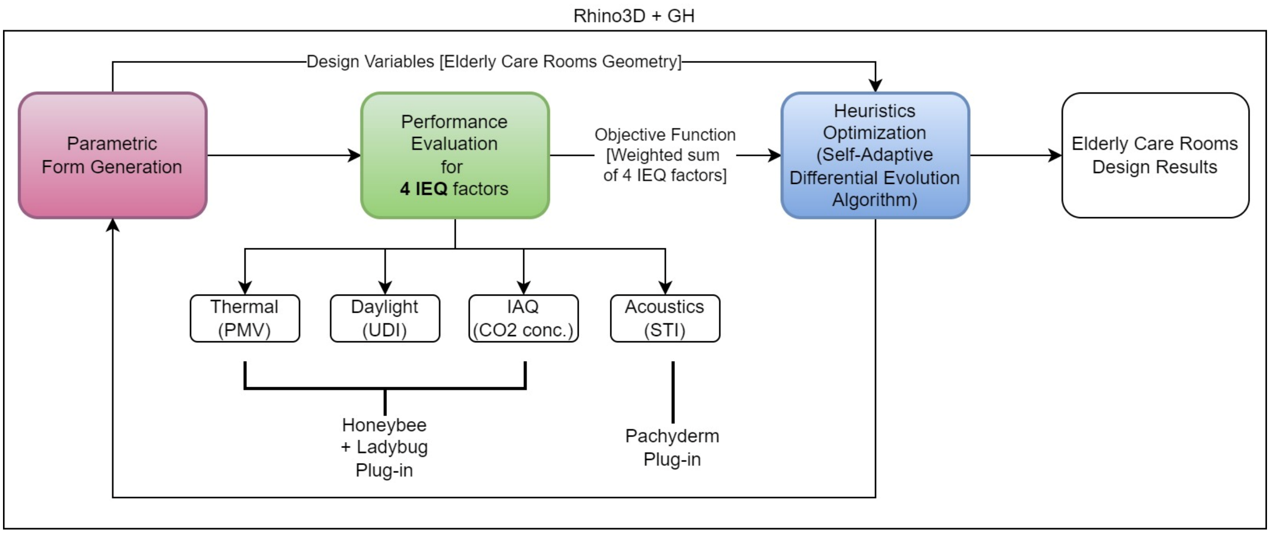


Figure 1. Methodology.

3.1. Parametric Form Generation

The parametric model for generating and evaluating the elderly care rooms has been implemented in the Grasshopper (GH), which is a plug-in of Rhinoceros CAD software version 7, defining geometric entities and performing simulations and calculations on them with great ease through visual programming. For the room model, a simplified geometric representation is generated as a first stage. A rectangular plan, whose dimensions are defined as constants, is considered. Furniture is created in Rhino 3D by setting its geometries in GH. Their geometries and placements are predefined based on the ideal layout planning of the elderly care rooms suggested by [63]. Regarding the layout planning of the room, there are some assumptions accepted in the model, as follows:

- Area of the room is taken as 24 m^2 (with 6 m × 4 m grid system).
- The studied room is placed at 10 m height of the building at the 3rd level.
- The scenario is created based on an urban (inner city) location, which means having surrounding buildings and a main street in front of the room.
- The location is selected as Ankara in Turkey.
- All performance indicators are calculated based on annual climatic conditions.
- The considered room is placed in the middle part, i.e., there are other neighbouring rooms next to the studied room in this paper. Therefore, the room has 3 interior walls and 1 exterior wall.
- The exterior wall has a window whose dimensions are changing, since the window-to-wall (WWR) ratio is one of the decision variables.
- The exterior wall is oriented in a south direction, which also has the main street in front.
- The door is at the side of the corridors and the bathroom is placed next to the door that corresponds to the entrance to the room from the corridors of the main building (Figure 2).

In addition to those, some of the design variables affect more than one performance indicator, e.g., window size and material effect not only affect visual but also thermal comfort calculations. Another example can be given for dry bulb temperature, where it affects both thermal comfort and indoor air quality through relative humidity.

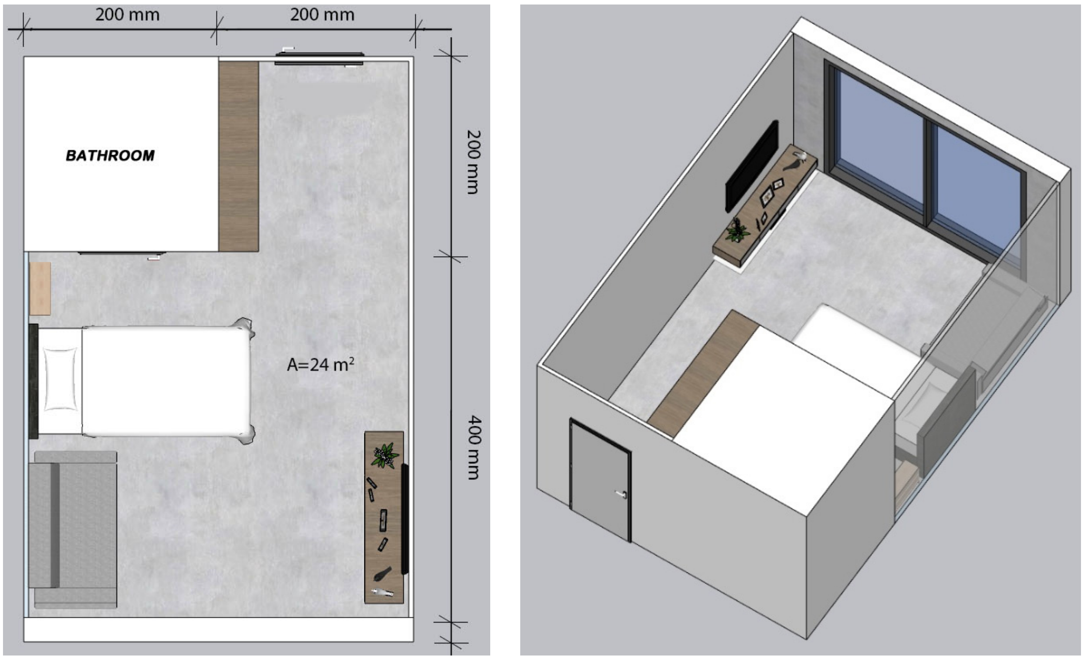


Figure 2. Typical layout of the elderly room considered in this paper.

In the next stage, the main characteristics of the walls are defined for both exterior and interior ones. Exterior walls have 19 different types of layer combinations. All of the alternatives have four layers consisting of cement, bricks, and thermal conductivity materials, but each of them offers different amounts of thickness, thermal conductivity value (U-value), unit volume mass, and water vapour diffusion coefficient. For the interior walls, five different types of layer combinations have been defined, consisting of drywall partition wall and double gypsum board partition wall with increased fire resistance with various amounts of thickness, acoustic value, thermal conductivity value, unit volume mass, and water vapour diffusion coefficient. In addition, since the colour of the coverings and materials of the interior elements (and also their reflectance levels) has an impact on the visual comfort, the colour selection is also adapted to the radiance model for the interior walls. For this aim, basic scripting has been performed in the C# component of the GH by defining such rules as in the example:

- $if\ x = 0\ then\ reflectance\ value = 20\%\ (very\ dark\ color\ for\ interior\ wall)$
- $if\ x = 1\ then\ reflectance\ value = 30\%\ (dark\ color\ for\ interior\ wall)$
- $if\ x = 2\ then\ reflectance\ value = 50\%\ (middle\ color\ for\ interior\ wall)$
- $if\ x = 3\ then\ reflectance\ value = 60\%\ (bright\ color\ for\ interior\ wall)$

For the creation of windows, the glass and its details are defined as design variables. Various types of glass–frame combinations are defined in the model. The joinery type, thickness, glass type, U value, and acoustic value (noise insulation value) of each alternative window can be changed. These combinations can be listed as follows:

- Double glazing–12 mm air gap–wood joinery;
- Double glazing–16 mm air gap–wood joinery;
- Double glazing–12 mm air gap–PVC joinery;
- Double glazing–16 mm air gap–PVC joinery;
- Low-e double glazing with 12 mm air gap–PVC joinery;
- Low-e double glazing–16 mm air gap–PVC joinery.

For preventing glare and controlling sunlight exposure, shading devices are designed and integrated into the exterior side of the windows as static components. In the generative model, those shading devices are defined by using two opposite points located on the frame of the window. Between those two points, a line is created and multiplied either in vertical or horizontal directions. Those lines are then converted to rectangular surfaces with some specific thickness values and an angle. The number of rectangular panels, their direction (horizontal or vertical), and their angle are defined as design variables (Figure 3).

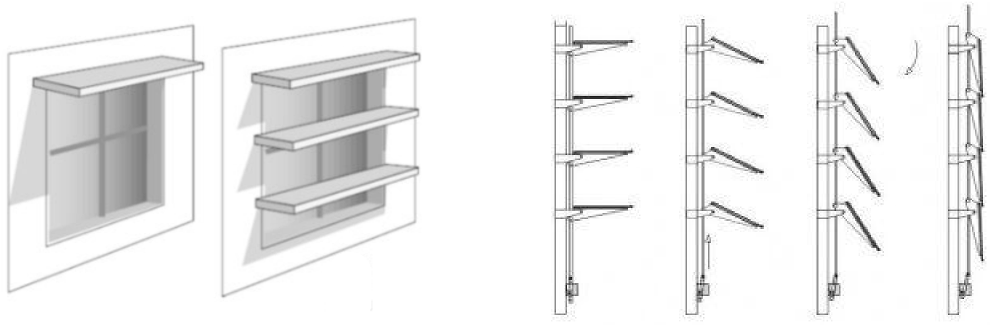


Figure 3. Left: perspective view of the shading devices with 1 horizontal and 3 horizontal louvers example; **right**: left view of the shading devices with 4 horizontal louvers in different angles.

Then, the suspended ceiling, which is an essential element for acoustics, is defined in the generative room model. For defining its geometry in GH, the centre point of the room ceiling is taken as the base point for the suspended ceiling. A rectangular box is defined by using this base point, and three combinations with the existing ceiling are determined to be selected in the optimisation model as follows:

- Ceiling 1: 15 cm ceiling + half 10 mm suspended ceiling;
- Ceiling 2: 15 cm ceiling + full 15 mm additional suspended ceiling;
- Ceiling 3: 15 cm ceiling + no suspended ceiling + 10 mm painted plywood.

Furthermore, the colour of the ceiling is defined as one of the decision variables, considering the following reflectance values as follows:

- $if\ x = 0\ then\ reflectance\ value = 30\%\ (very\ dark\ color\ for\ ceiling)$
- $if\ x = 1\ then\ reflectance\ value = 50\%\ (dark\ color\ for\ ceiling)$
- $if\ x = 2\ then\ reflectance\ value = 70\%\ (middle\ color\ for\ ceiling)$
- $if\ x = 3\ then\ reflectance\ value = 85\%\ (bright\ color\ for\ ceiling)$
- $if\ x = 4\ then\ reflectance\ value = 90\%\ (very\ bright\ color\ for\ ceiling)$

Concerning the room flooring, a surface of linoleum with a 5 mm thickness is defined. The colour of the floor surface is also generated as a design variable due to its essential effect on both visual and acoustical comforts. The colour of the floor is defined as one of the decision variables, considering the following reflectance values as follows:

- $if\ x = 0\ then\ reflectance\ value = 10\%\ (dark\ color\ for\ floor)$
- $if\ x = 1\ then\ reflectance\ value = 20\%\ (middle\ color\ for\ floor)$
- $if\ x = 2\ then\ reflectance\ value = 30\%\ (bright\ color\ for\ floor)$
- $if\ x = 3\ then\ reflectance\ value = 10\%\ (very\ bright\ color\ for\ floor)$

After the form generation stage is completed for the room model, numerical figures are derived from the geometrical model to formulate the objective functions with corresponding simulation models, which are explained in Section 3.2 in detail.

3.2. Performance Evaluation for IEQ Parameters

In this paper, designing an elderly care room is considered in order to maximise indoor environmental control parameters in a multi-objective manner, subject to some geometrical and architectural constraints. Certain design variables that contribute to IEQ are determined after careful consideration. For instance, for visual comfort, shading device angle and blind position, as well as glazing type and ratio, directly identify the amount of daylight penetration. In addition to them, artificial lighting density and surface (walls, floors, and ceiling) colours have an impact on light reflections, which ultimately affects the amount of illumination in the room as a whole. Similarly, dry bulb temperatures and relative humidity values determine thermal comfort and indoor air quality. The elements of interior and exterior walls, as well as the types of ceilings, have a direct impact on how sound behaves in the room. To formulate the problem, the following notations are needed for defining the decision or design variables in Table 1.

Table 1. Design variables.

Design Variable	Notation	Unit	Variable Type	Range
Shading Device Angle	SA	degree	continuous	[0, 90]
Glazing Ratio	GR	percentage	continuous	[0, 100]
Blind Position	SD	position	discrete	$0 : horizontal;\ 1 : vertical$
Suspended Ceiling Type	SCT	number	discrete	$0 : half - covered$ $1 : full - covered$ $2 : none$
Dry Bulb Temperature Summer	DBT_s	degree	continuous	[23–27]
Dry Bulb Temperature Winter	DBT_w	degree	continuous	[20–22.5]
Relative Humidity Summer	RH_s	percentage	continuous	[30–60]
Relative Humidity winter	RH_w	percentage	continuous	[30–60]
Interior Wall Type	IWT	number	discrete	$\{0, 1, 2, 3, 4\}$
Glazing Type	GT	number	discrete	$\{0, 1, 2, 3, 4, 5\}$
Exterior Wall Type	EWT	number	discrete	$\{0, 1, \ldots, 17, 18\}$
Interior Wall Colour	IWC	number	discrete	$\{0, 1, 2, 3\}$
Floor Colour	FC	number	discrete	$\{0, 1, 2, 3\}$
Ceiling Colour	CC	number	discrete	$\{0, 1, 2, 3, 4\}$
Lighting Density	LD	kWh/m^2	continuous	[3–30]

As can be seen in the above table, design variables can affect the design decisions related to thermal comfort, air quality, acoustics, and daylight aspects of the IEQ parameters. Therefore, the objective functions are defined, considering those aspects as explained in Section 3.2.1 in detail as follows.

3.2.1. Objective Functions

In the conceptual design phase of the elderly care rooms, four main objectives (thermal comfort, acoustics, indoor air quality, and daylight) as part of IEQ parameters subject to black-box constraints are formulated in the mathematical model. In this study, a simulation-based mathematical model is created so that all the calculations related to IEQ parameters are performed by using several plug-ins in the parametric modelling environment, which is also a plug-in of Rhinoceros CAD software called Grasshopper (GH).

Thermal Comfort: Predicted Mean Vote (PMV)

In this study, the predicted mean vote (PMV) parameter is used for thermal comfort analysis. American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 55-2004 offers a list of guidelines for supporting performative designs concerning thermal comfort codes and standards. For calculating the PMV parameter, ASHRAE elaborates using Fanger's heat balance equation [64] to control the scale of thermal comfort by four measurable parameters:

- Air speed (the velocity of air circulating through the building zone);
- Internal air temperature (can be measured by dry bulb temperature);
- Mean radiant temperature (the average amount of heat that is radiated into the building from surfaces);

- Relative humidity (how much moisture vapour is in the air as a percentage).
- In addition, it uses two expected parameters:
- Activity rate (can be expected by using the metabolism rate and external work of the user);
- Clothing level (the amount and type of clothing and the ratio of exposed/unexposed skin, e.g., 0.25 clo can be T-shirt and shorts).

The resulting PMV index value can be evaluated based on a thermal sensation scale as suggested by ASHRAE on a 7-point scale on the basis of Fanger's method, as shown in Figure 4 [65].

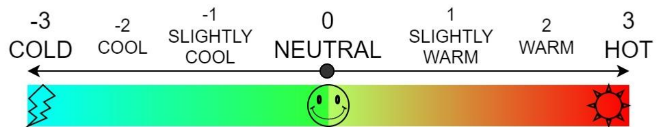


Figure 4. Fanger's method scale.

In our model, the PMV index value is calculated separately for winter and summer, and the appropriate value range for each season is limited to the range of −2 and +2, determined according to ASHRAE 55 and ISO 7730 standards [65,66]. However, it is aimed at reaching the neutral value for each season, e.g., being cold during the summer is also a discomfort situation. Therefore, the best value is defined as 0; the worst value is defined as either 2 or −2. Finally, the thermal comfort ($IEQ_{thermalcomfort}$) objective is formulated as follows:

The summer period TC_{summer} refers to those constraints:

$$-2 < PMV_{summer} < 0 \tag{1}$$

$$0 < PMV_{summer} < 2 \tag{2}$$

$$IEQ_{thermal\ comfort} = \left[max\left(0, min\left(1, \frac{TC_{summer} - 2}{0 - 2}\right)\right), max\left(0, min\left(1, \frac{TC_{summer} + 2}{0 + 2}\right)\right)\right] \tag{3}$$

For the winter period, TC_{winter} refers to those constraints:

$$-2 < PMV_{winter} < 0 \tag{4}$$

$$0 < PMV_{winter} < 2 \tag{5}$$

$$IEQ_{thermal\ comfort} = \left[max\left(0, min\left(1, \frac{TC_{winter} - 2}{0 - 2}\right)\right), max\left(0, min\left(1, \frac{TC_{winter} + 2}{0 + 2}\right)\right)\right] \tag{6}$$

For deriving PMV calculations in a CAD environment, the Honeybee/Ladybug simulation program is used as a plug-in for the GH environment in Rhinoceros CAD software. In this simulation program, parameters such as relative humidity, dressing level, and dry bulb temperature are entered as input values, which are also defined as decision variables in our model. The dressing level for the summer period is taken as 0.5, which is a t-shirt and shorts, but, for the winter time, it is defined as 1 clo level, which is roughly the insulation provided by three pieces of suit. The metabolic rate (which corresponds to activity level) is taken as 1, which can be described as a seated human without any other activity. The value range of the relative humidity and dry bulb temperatures is kept within the applicable ranges on the basis of the psychrometric chart suggested by ASHRAE 55 [64]. Relative humidity is taken in between 30 and 60%, while dry bulb temperature for summer is considered in the range of 23–26 °C and, for winter, 20–22.5 °C. Other input values are taken in the default setting as constants. In the generative model, inputs from the PMV, such as dry bulb temperature and relative humidity, are defined as one of the design variables in the optimisation model. Their effect on the PMV output can be simultaneously observed using the simulation component in GH.

Daylight Comfort: Useful Daylight Illuminance (UDI)

In the developed model, the Useful Daylight Illuminance (UDI) parameter is considered a daylight comfort factor. Various daylight metrics have been developed over the past decade, which can be categorised into two groups: static and dynamic metrics. Static metrics serve point-in-time illuminance-based results and have been commonly replaced by advanced dynamic metrics over the last few years. Useful Daylight Illuminance (UDI) is a dynamic metric that evaluates how often daylight illuminances within a range are achieved (in a year) and defines those ranges as UDI supplementary (100–300 lux), UDI autonomous (300–3000 lux), and UDI exceeded (over 3000 lux) [67–69]. The UDI metric is simple, informative, and sufficiently evaluates glare probability; thus, within this study, daylight evaluations are conducted by using UDI. The EN17037 standard requires that at least 50% of an area be illuminated by daylight for at least 50% of the time so the goal is to simultaneously maximise the time and the area [70].

UDI is calculated using illuminance values obtained through the radiance method [71,72]. An interface for radiance has been used, namely Honeybee + Ladybug simulation software, which is a plugin developed for Grasshopper Algorithmic Modeling Environment, a part of the Rhinoceros CAD program. The UDI is calculated using the illuminance value L as follows:

$$UDI(PT_i) = \frac{1}{n}\sum_{j=1}^{n} H(L(Pt_i, j)) \times 100 \quad (7)$$

$L(Pt_i, j)$ is the result of simulation for sampling point PT_i and time (for a year) j. Illuminance values are gathered from a ray-tracing simulation. Function of H can have a binary value. If the illuminance value is in the specified range, then H outputs 1; else its output is 0. Since the average of UDI values is desired to become bigger than 50%, the daylight comfort objective is calculated as follows:

$$50 < Avg(UDI) < 100 \quad (8)$$

$$IEQ_{Daylight\ Comfort} = max(0, min(1, Avg(UDI) - 50/100 - 50)) \quad (9)$$

As can be seen here, in addition to colour, materials, and shading device selections, the lighting density per area is defined as a decision variable in the optimisation model.

Acoustics Comfort: Speech Transmission Index (STI)

Acoustic comfort is another indoor environmental quality aspect addressed in this study. The elderly rooms can suffer from background noise, echoes, and noise coming from adjacent rooms (such as medical equipment). To evaluate the acoustic comfort, the Speech Transmission Index (STI), which is a metric used to evaluate the level of speech intelligibility in a specific acoustic environment, is used. STI measures the degree to which speech can be heard and comprehended in a certain location while considering things like background noise, reverberation, and the room's general acoustics. Measuring the STI in a single elderly room in a residential care facility can reveal important information on how effectively people can communicate with one another and caregivers. Another common acoustic metric, reverberation time (RT), is determined by the building volume, materials inside the room, and overall area; however, it is not considered because the overall space is small and the absorber surface area used in the volume (such as curtains, beds, clothes, and carpets) is so large. Rather, the STI is used for acoustic analysis because it is more closely related to the building elements and background noise is an important parameter in STI calculation.

According to van Schoonhoven, Rhebergen, and Dreschler (2017), the acceptable ranges for STI levels for an elderly person are 0.60 and 0.75. STI readings can vary from 0 to 1 and, while the range of 0.60–0.75 is considered good, the range of 0.75–1 is considered exceptional [73]. For deriving STI calculations in a CAD environment, the Pachyderm simulation program is used as a plug-in for the GH environment in Rhinoceros CAD software. In this program, the materials and acoustical properties of each building element are defined as inputs and *STI* values are gathered as an output of the plug-in. The acoustic objective is formulated as follows:

$$0.6 < STI < 1 \tag{10}$$

$$IEQ_{Acoustics\ Comfort} = max\left(0, \left(1, \frac{STI - 0.6}{1 - 0.6}\right)\right) \tag{11}$$

As shown here, the sound source is defined as the TV unit (50 dB), the background sound (50 dB) is defined as the sounds coming from outside (for urban scenarios), and the human source is defined as a point above the bed. The raytracing component of the Pachyderm simulation program is shown in Figure 5.

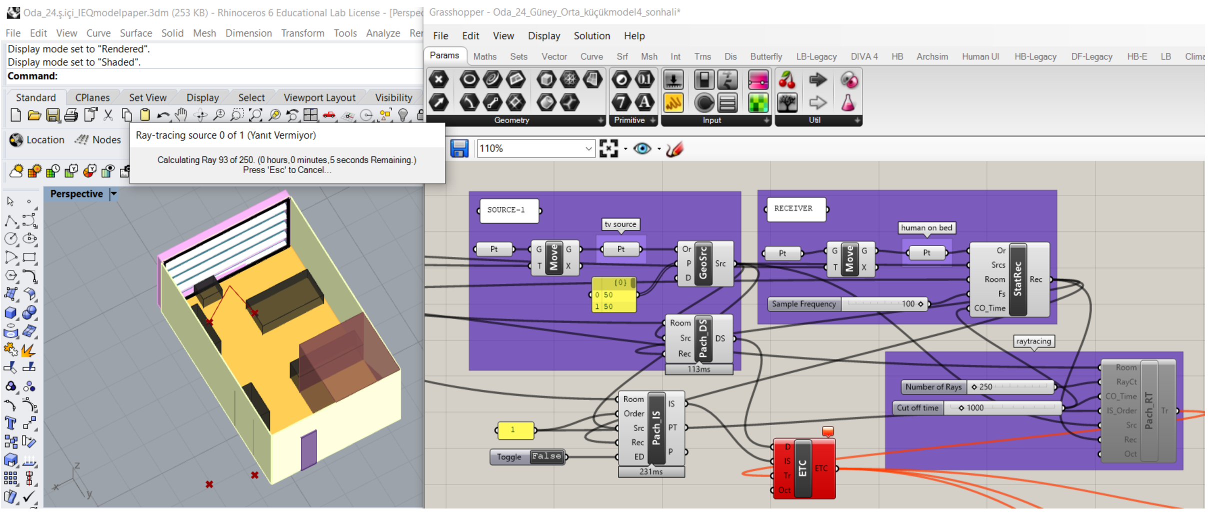


Figure 5. Part of the acoustics analysis (**left** side: Rhino CAD; **right** side: GH plug-in including pachyderm simulation model).

Indoor Air Quality: CO_2 Concentration

There are numerous air pollutants that can degrade the quality of indoor air. CO_2, one of numerous identified indoor pollutants, has long been the focus of ventilation and IAQ [74]. The CO_2 concentration is used in this study, since it is simple to measure and can be produced by a variety of sources (users and equipment). CO_2 is heavily influenced by occupancy density and outside air ventilation rates, unlike many other indoor contaminant sources [75]. The concentration of CO_2 in a room can be an indicator of hazardous air pollutants, and measuring CO_2 levels can help to acquire a daily pattern of CO_2 concentration, which can assist in intervention planning [54]. Especially during COVID-19, CO_2 levels are used as an indicator of airborne infection transmission risk. Though the former ASHRAE standard recommended 1000 ppmv for CO_2 levels, several sources, including ASHRAE, currently highlight that a single CO_2 concentration cannot be applied to all sorts of spaces. For elderly occupants, CO_2 concentrations lower than 700 ppm are recommended [21,54,75,76].

For CO_2 calculations, the Grasshopper EnergyPlus plug-in Honeybee + Ladybug is used. EnergyPlus can model the CO_2 concentration at each timestep but, for using this feature in the GH, additional strings are inserted to the .idf in the energy model and the simulations for gathering the CO_2 concentration values are made. In the elderly room, the HVAC system of Ideal Air Loads is used during the simulation. According to [77], CO_2

concentration can be calculated using mass balance theory, which calculates the carbon dioxide changes within a space over time as follows:

$$\frac{dC_i}{dt} = \frac{S_{CO_2}}{V} + PC_0Q - C_iQ - kC_i \tag{12}$$

where C_i is the indoor CO_2 concentration, mg/m^3; C_0 is the outdoor CO_2 concentration, mg/m^3; S_{CO_2} is the CO_2 generation rate, mg/hr; V is the space volume, m^3; P is fraction of outdoor air; Q is outdoor ventilation rate, m^3/hr; and k is any CO_2 removing process within the zone. Typical desired conditions for carbon dioxide range below 700 ppm above outdoor air concentration, given that the outdoor air is at acceptable levels of about 420 ppm [75].

3.2.2. Weighted Summation of IEQ

To formulise the resulting objective function, all comfort parameters should be in the specified range and the value of being in the specified range for each comfort index should be maximised as follows:

$$IEQ_{Visual\ Comfort} = max\left(0, \left(1, \frac{current\ value - worst}{best - worst}\right)\right) \tag{13}$$

$$IEQ_{Thermal\ Comfort} = max\left(0, \left(1, \frac{current\ value - worst}{best - worst}\right)\right) \tag{14}$$

$$IEQ_{Acoustics\ Comfort} = max\left(0, \left(1, \frac{current\ value - worst}{best - worst}\right)\right) \tag{15}$$

$$IEQ_{Indoor\ Air\ Quality} = max\left(0, \left(1, \frac{current\ value - worst}{best - worst}\right)\right) \tag{16}$$

Here, a weighted sum method is referred to for handling the problem in a multi-objective manner. The weighted sum method combines all the multi-objective functions into one scalar, composite objective function using the weighted sum as:

$$F(x) = w_1 \times f_1(x) + w_2 \times f_2(x) + \cdots ....w_m \times f_m(x)\ where\ m = 4 \tag{17}$$

As already stated above, the weights are taken as equal for each IEQ component:

$$Maximize\ Obj = \frac{1 \times 0.25}{IEQ_{Visual\ Comfort}}, \frac{1 \times 0.25}{IEQ_{Thermal\ Comfort}}, \frac{1 \times 0.25}{IEQ_{Acoustics\ Comfort}}, \frac{1 \times 0.25}{IEQ_{Indoor\ Air\ Quality}} \tag{18}$$

After the performance evaluation stage is completed for the room model, design variables and objective functions are connected to the optimisation algorithm, which is explained in Section 3.3 in detail.

3.3. Optimisation Algorithm

In this paper, metaheuristics are selected as an optimisation method, since they are capable of solving complex design problems in a reasonable time and widely used in the field of architecture to cope with nonlinear architectural objectives by presenting near-optimal design solutions. Referring to a comprehensive review paper [62], "Self-Adaptive Differential Evolution with Ensemble of Mutation Strategies" algorithm used in this paper is one of most effective and efficient algorithms utilised in architectural design optimisation, especially when having an objective that requires real-parameter simulations. It is powerful and converges very fast in solving complex real-parameter problems. In this paper, the algorithm is run on a computer with an Intel I7 4 core processor at 2.7 GHz, 16 GB DDR3 memory, and a 256 GB solid-state drive. The population size is taken as 30 and it is recorded that computation time for 5 generations with 30 population sizes is taken as approximately 8 h.

Differential evolution (DE) was developed by [78]. The basic DE has four main stages: initialisation, mutation, crossover, and selection. In the initialisation part, the initial target population (x^0_{ij}) is created based on Equation (19):

$$x^0_{ij} = x^{min}_{ij} + \left(x^{max}_{ij} - x^{min}_{ij}\right) \times r \tag{19}$$

where x^0_{ij} is i-th target population in generation $g = 0$ and r is a uniform random real number producing a range of [0, 1]. The target population has population size (PS) individuals with D-dimensional vectors. Population size is user-defined and D-dimension is based on the number of decision variables in the problem. In the mutation part, a mutant population (v^g_{ij}) is created based on Equation (20):

$$v^g_{ij} = x^{g-1}_{aj} + MR \times \left(x^{g-1}_{bj} - x^{g-1}_{cj}\right) \tag{20}$$

where a, b, c are three randomly selected individuals from the target population when $a \neq b \neq c \neq i \; \epsilon \; (1, .., PS) \; and \; j = 1, .., D$. In addition, MR is a mutant factor bigger than zero. Afterwards, a trial population (u^g_{ij}) is generated as in Equation (21):

$$u^g_{ij} = \begin{cases} v^g_{ij}, \; if \; r^g_{ij} \leq CR \; or \; j = D_j \\ x^{g-1}_{ij}, \; otherwise \end{cases} \tag{21}$$

where D_j is a randomly selected dimension from $j = 1, .., D$. This condition guarantees that at least one parameter of the trial population is going to be different from the target population. CR is a crossover factor defined as a constant in the range of [0, 1]. r^g_{ij} is a uniform random real number producing a range of $[0, 1]$ at generation g. For the next generation, a selection process is realised in between the trial and target population based on a survival of the fittest method. The population that has the lower fitness value (objectives are in the form of minimisation) is selected according to one-to-one comparison and the selected population is used in the next generation to be mutated and cross-overed. This recursive process continues until g reaches the defined number of generations (*max_gen*). The general loop pf DE process is shown in Figure 6. In a self-adaptive approach, so-called MR and CR values are not taken as constant but, rather, are produced based on some adaptations in each generation. In this way, the DE algorithm performance is getting higher and the convergence process is much faster than the basic DE [79]. In the ensemble approach [80], the mutant population is generated based on some conditions and different types of mutation strategies are performed. The details can be found in [81].

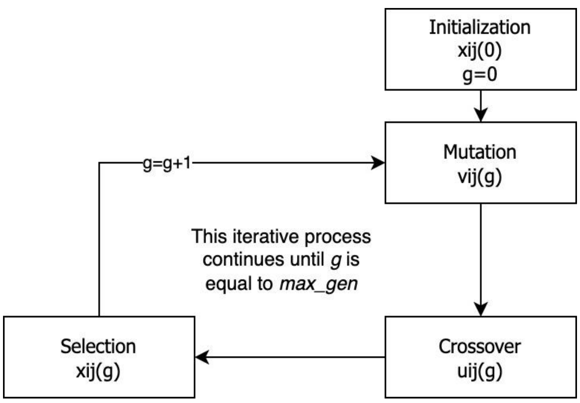


Figure 6. A flowchart showing the DE algorithm process.

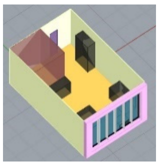
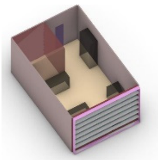
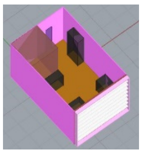
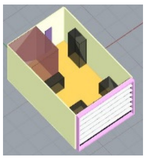
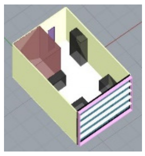
4. Results

Based on the proposed objective function in the form of a weighted sum, the computational results and discussion of the architectural results are explained in the following sub-sections.

4.1. Computational Results

During the optimisation process, five replications were taken with five different seed numbers. The minimum, maximum, average, and standard deviation of the resulting objective functions for each seed are recorded in Table 2. Since the algorithm works for minimisation, the resulting objective is taken as $1/Obj$, where Obj was formulated in Equation (18) for maximizing the percentage of satisfied IEQ components.

Table 2. Optimisation results for each replication.

	Rep.1	Rep.2	Rep.3	Rep.4	Rep.5	Min	Max	Avg	Std.Dev
$1/Obj$	0.7213	0.7077	0.7274	0.7236	0.7134				
Elderly Room Result						0.7077	0.7274	0.7187	0.007993

According to the optimisation results, the minimum resulting objective is obtained as 0.7077 in replication 2 with a seed number of 20,000, which means that IEQ results are closer to the desired values in the defined intervals. In this case, each IEQ component result is shown in Figure 7 in a 4D graph for all population sizes: 30. In this study, only the nondominated solutions that have 0 pareto rank are considered. Therefore, the minimum nondominated solution among five replications is discussed in this paper.

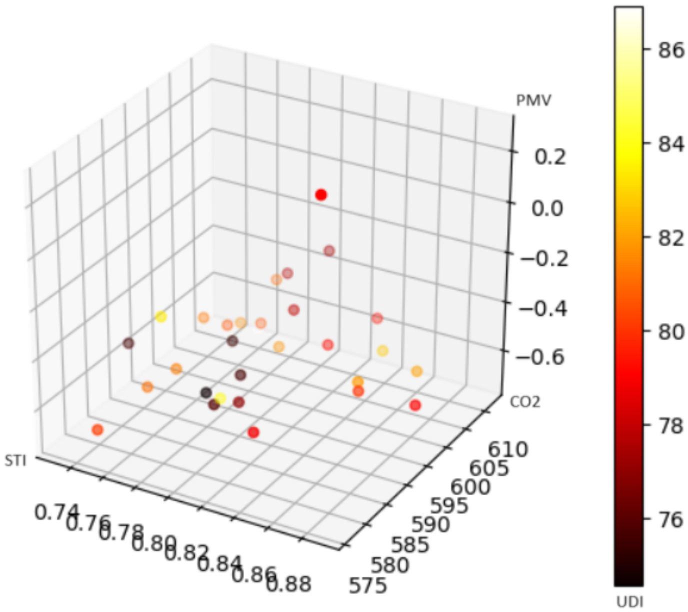


Figure 7. D graph of IEQ components for each population size in Rep.2 solution.

In the nondominated solution in Rep.2, the STI result is obtained as 0.75, which is in the "excellent" range according to IEC 60268-16 because STI value interval is defined as "good" levels if in between 0.60 and 0.75 and "excellent" levels if in between 0.75 and 1 in the model. The UDI value resulted as 83.3, in the range of 50–100, as expected. The PMV value resulted as −0.29 on average, which is close to the value of 0 that can be defined as perfectly close to the defined best value. The CO_2 concentration result is obtained as approximately 590.76, which is a value closer to the upper limit (700) than the lower limit (420). As can be seen in Figure 8, all objective functions are found in acceptable ranges, as the lines of each objective show a nearly linear pattern.

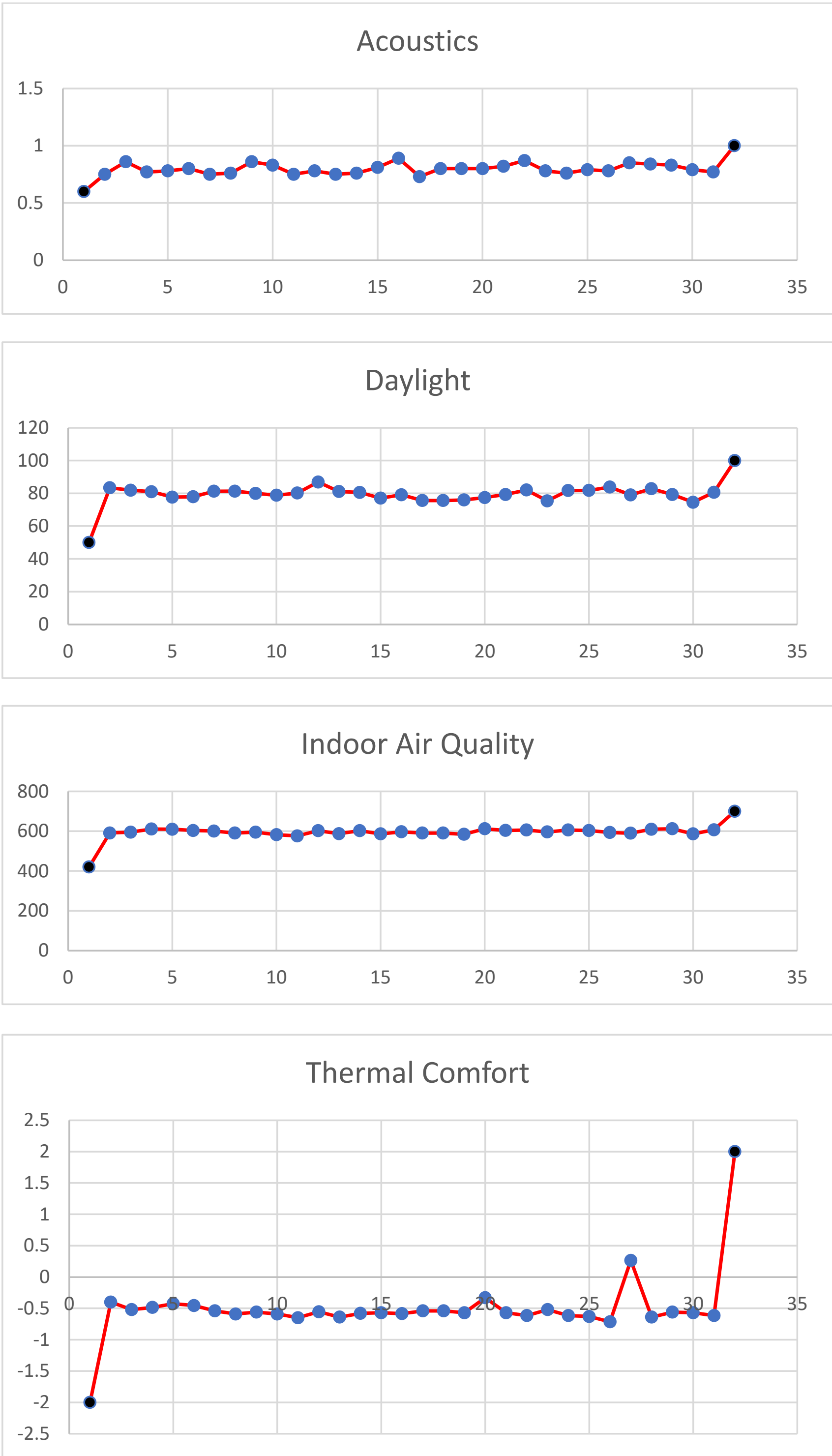


Figure 8. Graphs showing the objective values' closeness to the desired values (black points represent the min–max values; blue points are obtained points).

The design variables belonging to this resulting objective function are obtained as follows in Table 3.

Table 3. Design variable solution based on optimisation.

Design Variable	Result
Shading device angle	0
Glazing Ratio	0.74
Blind Position	0: horizontal
Suspended Ceiling Type	1: fully covered
Dry Bulb Temperature Summer	26
Dry Bulb Temperature Winter	22.5
Relative Humidity Summer	60
Relative Humidity winter	59.9
Interior Wall Type	2
Glazing Type	0
Exterior Wall Type	15
Interior Wall Colour	0: very dark_20% reflectance value
Floor Colour	2: bright_30% reflectance value
Ceiling Colour	4: very bright_90% reflectance value
Lighting Density	26.36

As can be seen in the above table, the shading device is designed to be horizontal at 0 degrees and the suspended ceiling is fully covered. The interior wall type is Partition Wall 2—double drywall partition wall (with 4 mm insulation panels), which has six layers, where four layers are composed of gypsum wallboards and blocks (including porous, perforated, filled, or aggregate ones), while mineral and vegetable fibre thermal insulation materials (glass wool, rock wool, etc.) and space are located in the middle. The colour of the interior wall index is 0, which means very dark colour with a 20% reflectance value. The glazing type is obtained as 0, which means the window has double glazing with a 12 mm air gap and wooden joinery. Regarding the colour of the floor, a bright colour with a 30% reflectance value is obtained, while the colour of the ceiling is obtained as a very bright colour with a 90% reflectance value. The exterior wall type is chosen as the 15th alternative (Wall Type 15) with four layers, where the details are shown in Table 4.

Table 4. Exterior wall type which was provided after optimisations (Wall 15-EPS).

	Wall 15-EPS (40 mm-u:0.035 W/mK-Brick Exterior Wall with Thermal Insulation Material
1. Layer	Lime mortar, lime-cement mortar
2. Layer	Walls made with AB grade bricks using regular mortar
3. Layer	Polystyrene-Particle Foam
4. Layer	Lime mortar, lime-cement mortar

4.2. Discussion on Architectural Results

According to the optimisation results, the glazing ratio of 74% is higher than the recommendations for the window-to-wall ratio (WWR), which ranges from 25% to 40%. While a high WWR (74%) can cause glare and overheating, horizontally positioned shading devices can decrease excessive heat and daylight access. Despite the shadings, the high UDI percentage (83.3%) shows that the room is primarily lit by daylight, that glare is minimised, and that artificial lighting usage is moderate at 26.36 W/m^2. The ceiling surface has the greatest impact on the uniform daylight distribution of any interior surface because it is the largest uninterrupted surface in a room and is located at the top of the room, where it can more effectively reflect and diffuse natural light throughout the space. Thus, the ceiling reflectance optimisation results are very bright, and they are paired with medium walls and darkly coloured floor materials to avoid glare and provide uniformity of light. This combination helps to improve visibility by establishing contrast between the surfaces and the objects around them. Brightly coloured walls can affect how people perceive depth and distance, make it challenging for the elderly to accurately judge the proximity of objects, and even cause accidents.

The implementation of double glazing, along with shading components and low-U-value wall types, has successfully controlled indoor temperatures. During the winter, the dry bulb temperatures averaged at a comfortable 22.5 °C, while, in the summer, they remained within the optimal range at 26 °C. These temperature levels are ideal for a variety of occupied spaces, including offices, schools, and residential buildings.

To prevent dry skin problems in the elderly, dermatologists recommend a minimum relative humidity of 45%. The relative humidity values have been optimised to closely match these recommendations throughout the year, with an average of 60% in the summer and 59.9% in the winter. Additionally, the optimisation efforts yielded a nearly optimal predicted mean vote (PMV) value. This result shows that, despite the elderly's greater sensitivity to temperature and relative humidity, thermal comfort is effectively achieved through optimisation measures.

The room in the given scenario is in an urban environment with heavy traffic and nearby buildings. Effective measures are put in place to address the issue of both exterior and interior noise. To effectively reduce noise transmission, high-mass walls with multiple layers are employed as well as double glazing with a 12 mm air gap. A fully covered suspended ceiling, which is renowned for its superior acoustic performance, was also chosen as a result of the optimisation results. Sound waves are absorbed and reflected less when acoustic tiles or panels cover the entire surface area of the ceiling. This comprehensive ceiling design establishes an uninterrupted barrier between spaces, ensuring superior sound insulation between adjacent areas.

Aside from noise issues, the urban environment presents issues with indoor air quality. A room's location can have a significant impact on its air quality, and urban areas tend to have higher levels of outdoor air pollution, which can infiltrate buildings and affect indoor air quality. Although CO_2 concentrations are found to be within an acceptable range at 590.76 ppm, further improvements can be made by increasing ventilation rates and the effectiveness of air filtration systems (Figure 9).

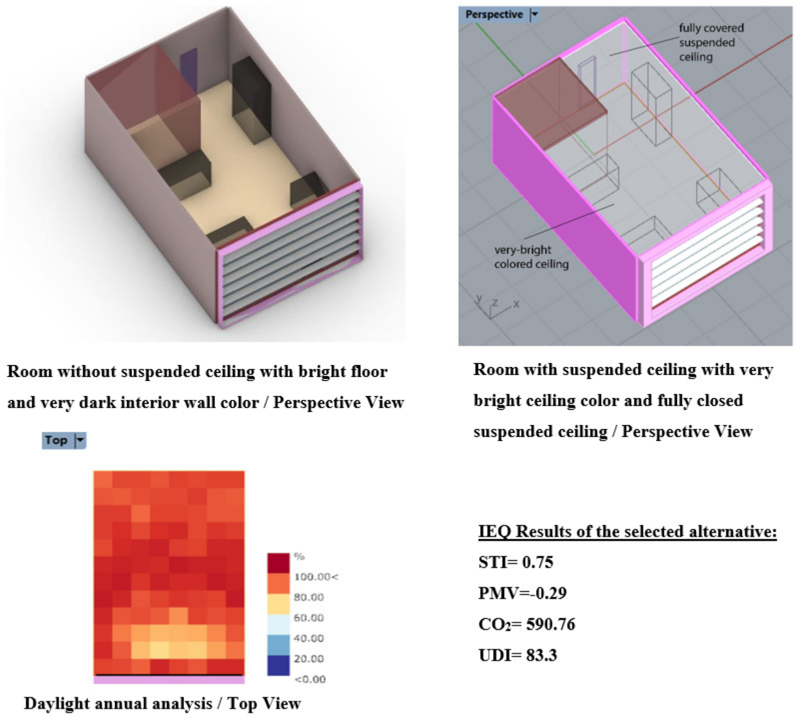


Figure 9. Optimisation result visuals for the Rep.2 solution exported from Rhino CAD.

5. Conclusions

This study introduces a new generative model for an elderly care room design optimisation based on IEQ components (lighting, acoustics, indoor air quality, and thermal comfort) in the form of a weighted sum and presents the test results on a case study of a single elderly room located in Ankara within the city centre, which oriented to the south direction. One of the novelties of the presented model is that it combines all four IEQ components in one objective function to optimise the elderly care room designs using a heuristics algorithm. Results show that weighted objective value is reasonably maximised to achieve the acceptable ranges for all IEQ components.

The linked impacts of IEQ components necessitate a more comprehensive strategy that considers all IEQ components collectively. For example, expanding window area or altering glazing type to improve daylight availability may have an impact on thermal comfort via heat gain or loss. Similar to this, opening windows to improve indoor air quality and air flow may contribute to thermal discomfort. Therefore, these kinds of effects are tested using the developed model for the purpose of validation. The findings of the optimisation choose a glazing ratio of 74% to increase daylight availability, which is balanced with the use of horizontal shadings and dark-coloured wall materials to prevent glare and increase contrast. Similarly, both internal and external wall types, as well as glazing, are highly insulated materials for noise and thermal comfort.

To achieve IEQ, architectural design and material decisions should consider all IEQ components in a holistic manner. The repercussions are especially crucial when the subject is elderly, who spend most of their time indoors and are quite vulnerable to discomforting environments. To handle all IEQ components in one model as a complex task, computational intelligence methods are proposed using parametric modelling in a CAD environment, and a heuristics optimisation algorithm is utilised. Through this method, plausible elderly room design results are gathered, and all IEQ component requirements are handled in the presented model.

Integrating IEQ optimisation into computational design workflows can provide an awareness of the performance of the rooms or buildings in terms of indoor comfort and, in that sense, it can even be used as an informative tool for the conceptual design of new elderly care rooms or buildings, as well as redesigning existing ones.

6. Limitations and Future Work

The model is restricted to the single elderly room instead of focusing on the whole facility on a building scale because, in addition to the rooms, the whole facility includes the common areas, which have many variations in terms of architectural design features and layouts. Despite the differences observed in institutional care facilities, elderly rooms show much less diversity, facilitating the generalisation of the design problem. The study concerns an assumed scenario for the design of a single elderly room in a typical institutional care building to offer well-performing design results in a design environment.

In future work, a larger scale can be considered for presenting a solution to the drawbacks of the variations that can be observed in common areas. Furthermore, the algorithm converged after 30 generations, but artificial intelligence techniques can be used to reduce the run-time of the model. More variations related to the room, such as location, orientation, materials, and adaptive systems, could be implemented to improve this model. Additionally, user profile features such as occupant clothing level, gender considerations for metabolic rate, and activity level can be considered as decision variables. Due to the model's generative and parametric design foundation, these types of variations can be adapted with manageable effort. The study does not concern any real measurements with IEQ equipment, such as a lux meter or air quality kit. Since a real building is not considered in this study, a comparison between simulation results and real measurements cannot be realised. This observation is not necessarily a shortcoming of the method in itself; however, it presents a promising opportunity for future research where performance aspects are incorporated in the design–decision-making process in a well-formulated and consistent manner.

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