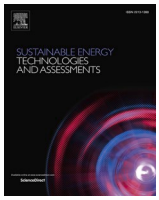
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Residential-IST: A web-based decision-support tool for bridging knowledge gaps in performance-driven residential building design and retrofitting in Istanbul, Türkiye

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ABSTRACT

This study proposes Residential-IST to bridge the gap between residential building design, retrofitting, and performance, facilitating effective communication between residential owners (demand) and architects (supply). This web-based decision support tool is designed to inform target decision-makers and enhance decision-making. Residential-IST advances access to multi-objective design solutions by integrating a feedback loop that aligns with early design exploration and iteration principles. The proposed tool employs a workflow that addresses the gap between the information required for transitioning from a conservative to a performance-driven approach and the accessibility of that information by incorporating: i) a computational performance-driven design support method that systematically explores and analyses the design space to identify optimal solutions, and ii) an interactive visualisation method that provides rapid, constructive feedback to decision-makers through an easy-to-use interface, covering a broad design space derived from this approach. The proposed workflow is contextualised for residential building design and retrofitting in Istanbul. This study discusses the potential of this first open-access, energy- and cost-based web tool to facilitate informed decision-making for novice architects and residential owners in Istanbul as well as throughout Türkiye.

Introduction

Motivation

Increasing urbanisation and climate change are transformative global trends that are crucial to the paradigm shift outlined in the New Development Agenda, which seeks economic growth, social inclusion, and environmental protection by 2030 [1,2]. The prediction that 68 % of the world's population will reside in urban areas by 2050 [3] raises concerns that urbanisation—known to alter local and regional climates—will exacerbate climate change effects [4,5]; this is particularly alarming for megacities in developing countries, which are highly vulnerable to climate change impacts [6,7]. As megacities expand to accommodate growing populations, the demand for energy-intensive services increases, leading to increased CO_2 emissions and accelerated climate change. This convergence of rapid urbanisation and climate change creates a dual-stress situation in megacities [6]. Furthermore, the reciprocal relationship between these phenomena indicates that megacities have significant potential to address climate change challenges [8]. Consequently, cities play a vital role in shaping the trajectory and effects of global climate change and are committing to ambitious targets to combat this issue worldwide [9].

Türkiye, a country highly vulnerable to climate change, ratified the Paris Agreement in October 2021 and set ambitious climate commitments, including a net-zero emissions target by 2053 [10]. In this context, Türkiye has revised its reduction target from a potential increase of 21 % to a decrease of 41 % by 2030, aiming to cut emissions by approximately 500 million tons by that year [11]. Realising these goals requires necessary actions at the national, regional, and local levels [12,13]. Istanbul, the centre of the Turkish economy and one of the world's leading megacities with a population of 16 million [3,14], faces the highest climate change risk in Europe [12,15]. With a population density of 3,062 people per square kilometre, it is Türkiye's most densely populated city [14] and among the highest in the European Union [16]. As the population and economy continue to grow, greenhouse gas emissions are expected to exceed 76 $MtCO_2e$ by 2030 and reach 115 $MtCO_2e$ by 2050 [17]. As of 2015, Istanbul accounted for approximately 10 % of Türkiye's greenhouse gas emissions (475.1 $MtCO_2e$) [18], making it the city with the highest emissions in the country. However, it also has the potential to achieve carbon neutrality by 2050 through significant emission reductions [12,13,19].

The residential sector, which contributes most significantly to this transformation, accounts for 63 % of Istanbul's greenhouse gas emissions [13,17]. By the end of 2020, Istanbul had approximately 6.4 million independent residential units, indicating significant urban

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Nomenclature

BEP	building energy performance
BPS	building performance simulation
Csa	hot-summer mediterranean climate
CSV	comma-separated values
CO_2	carbon dioxide
DM	decision-maker
DPP	discounted payback period (year)
DST	decision support tool
EU	European Union
GHG	greenhouse gas
IDF	intermediate data format
H/W	height-to-width ratio
KPI	key performance indicator
LCC	life cycle cost
MENA	Middle East and North Africa
MS SQL	Microsoft Structured Query Language
$MtCO_2e$	million tonnes of carbon dioxide equivalent
PCP	parallel coordinate plot
PE	primary energy
PEC	primary energy consumption
PV	photovoltaic
RB	residential building
SHGC	solar heat gain coefficient
SP	scatter plot
transparency ratio	total window area/total façade area
U value	overall heat transfer coefficient (W/m^2K)
UI	user interface
UX	user experience

growth [20]. The city must also address the risk of a major earthquake alongside climate change challenges. Following the 1999 Marmara earthquake, Istanbul has been deeply impacted by the urban transformation process aimed at renewing the residential building (RB) stock throughout Türkiye. The construction sector, a driving force in the Turkish economy, implemented a strategy focused on demolishing existing RB stock and rebuilding it to comply with earthquake regulations post-2000 [21,22]. However, sustainable, energy-efficient housing methods have often been overlooked in these urban transformation projects, which dominate the RB market [22,23]. As Istanbul and Türkiye strive to achieve carbon neutrality by 2050, the prevailing conservative production paradigm presents a significant obstacle to the rapid overhaul of a substantial portion of the existing RB stock [10,22,24].

Performance-driven RB production [25,26] is seen as the primary solution to overcome existing barriers. It requires radical changes in a sector currently reliant on conservative approaches that typically meet only minimum legislative standards, focusing on low initial costs and characterised by a weak innovation cycle. To facilitate this transformation, awareness-raising and information activities addressing the limited knowledge and lack of awareness among both the supply (architects, engineers, contractors, investors, and other stakeholders) and demand (residential owners and tenants) sides are essential. These gaps contribute to the efficiency deficit in the residential sector and are often highlighted in various policies [17,27–29]. To establish a balanced supply–demand relationship in the residential sector, concrete steps must bridge the gap between RB design/retrofit and performance, providing optimal guidance to decision-makers (DMs) during the early design process, which significantly influences RB performance. A review of case studies in Istanbul and Türkiye reveals that research on alternative design solutions to enhance RB performance offers substantial opportunities for informing the early design phase. These studies evaluate the effectiveness of various design parameters regarding energy [30–32], economic [33–35], and environmental [30–32] performance, identifying suitable solutions for specific needs [36–39]. Despite the substantial decision-support potential of these studies, their integration into RB production practices remains limited [40,41]. One primary reason for this is the complexity and scale of the design solutions, which makes them challenging for DMs to perceive and utilise effectively [42,43].

This study aims to reduce the mismatch between the information required and its accessibility during the transition from a conservative to a performance-driven approach in current RB design and retrofit processes. To this end, we developed a decision support tool (DST) called Residential-IST (Istanbul), which enables rapid, iterative feedback on early design decisions that significantly impact RB performance and compliance with normative frameworks and performance rating systems. By doing so, it aids in the transformation of the residential sector. The target DMs for this DST are architects and residential owners, representing the supply and demand sides of the sector. A methodological framework is proposed to help these DMs overcome existing limitations, making the complex RB design and retrofit process more efficient and effective. A user-friendly, free web-based tool has been created to facilitate informed decision-making through an intuitive interactive interface. The following sections discuss the importance of high-performance RBs, current challenges in producing such buildings, the need for appropriate tools to support DMs, and the urgency of these needs, particularly in Istanbul and Türkiye. Methodology Section outlines the proposed workflow designed to address these needs, forming the foundation of the DST, which is detailed in Residential-IST Section. The final section discusses the implications and limitations of the developed tool, summarising conclusions and outlining follow up research.

State of the art

In this century, often referred to the century of cities [44,45], urban areas account for two-thirds of global energy consumption [46]. These cities feature complex and dynamic energy and resource flow systems [47,48]. However, increasing population growth, rapid urbanisation, and expanding economic development intensify pressure on limited urban energy systems, resulting in unsustainable energy production and inefficient consumption. Consequently, cities are both significant contributors to climate change and sites where its effects are acutely felt, making them key players in addressing this challenge [49]. Achieving sustainable development in urban areas hinges on prioritizing sustainable energy use within the built environment. This is particularly crucial in light of Sustainable Development Goals such as Goal 13 (climate action), Goal 11 (sustainable cities and communities), and Goal 7 (affordable and clean energy) [50,51]. Prioritising sustainable energy in the building sector—central to the urban energy system—represents one of the fastest and most cost-effective solutions; this includes reducing energy consumption, enhancing energy efficiency, and minimising greenhouse gas emissions [47,52]. Despite the building sector's activity area more than doubling owing to increased floor space, expanded energy access, and higher living standards, it still has the potential to reduce direct CO_2 emissions by 97 % by 2050 [53,54]. Within this context, the residential sector, which has the highest energy demand, is critical for achieving rapid emissions reductions [55–57].

Countries are expanding energy efficiency and clean building policies while strengthening legal regulations to capitalise on the significant potential within the residential sector. However, investment opportunities in the residential sector remain largely underutilised, falling short of the levels needed to meet emission reduction targets

[54,58]. The slow adoption of energy efficiency practices, even when cost-effective, varies by country and city. Primary barriers include a lack of knowledge about energy consumption, the benefits of energy efficiency improvements, and the implementation of these measures [47,59–61]. Awareness-raising initiatives are crucial for reducing this knowledge gap and establishing a qualified supply–demand balance in the residential sector. The objective is to shift from conservative approaches to performance-driven RB production, which frequently only meets the minimum legislative requirements. This approach prioritizes low initial costs and a sluggish innovation cycle [25,26,62]. However, producing high-performance RBs—determining optimal solutions within a broad design space based on available resources and conflicting objectives of DMs—is complex. This complexity arises from the intricacy of buildings and integrated systems, as well as the involvement of various DMs with differing, often conflicting objectives in the design and retrofit process [63–65]. In this challenging context, making informed decisions during the early design phase is vital for achieving high-performance RBs at the lowest cost [66,67]. Consequently, there is a growing need for effective design decision-support methods and tools that assist architects (supply) and residential owners (demand), who play active roles in early-stage decision-making where uncertainty is high and design changes are likely [26,61,68–72].

In this context, Building Performance Simulation (BPS) tools, which provide feedback on proposed design performance and help understand complex systems, are integral to high-performance RB production [73,74]. Despite the development of numerous BPS tools [75], their integration into the decision-making process is low and insufficient to support the iterative nature of early design in the residential sector [76,77]. Consequently, parametric analysis and multiple-criteria decision analysis methods are increasingly used to incorporate BPS into early design processes and inform design decisions, marking a shift from single simulations to more effective DST applications [71,78,79]. Parametric simulation and simulation-based optimization tools have the potential to enhance decision-making during the early design phase. However, their integration into RB production practices remains limited, as they are primarily research-oriented [42,65]. Key barriers to this integration include [42,78,80,81]: i) the knowledge and experience needed for accurate problem formulation and tool selection; ii) the complexity of simulation and optimisation tools; iii) detailed data inputs that exceed the expertise of decision-makers (e.g., architects and residential owners); iv) lengthy calculation times; v) lack of integration into the design workflow; and vi) absence of a user-friendly interface for analysing extensive data. Addressing these barriers could bridge the knowledge gap and empower architects and residential owners in the design and retrofit processes. This continuous need necessitates the development of publicly accessible DSTs that can swiftly evaluate design and retrofit alternatives in a comparative format, with minimal input, while determining associated energy, CO_2 emissions, and cost savings and providing applicable energy-saving measures [82].

Web-based RB design and retrofit tools are vital for accelerating the adoption of high-performance RB production by estimating energy and cost savings in the fragmented residential sector [82,83]. Currently, energy performance in the existing sector is often evaluated only for compliance with legislation during the final phase of design and retrofit projects. Thus, the contributions of these tools to architects and residential owners—particularly those with limited knowledge—are significant for informing and guiding early design phases. Systematic reviews of web-based building energy analysis tools have been conducted, with an additional focus on tool retrofitting [82,84]. When examining web-based DSTs that integrate high-performance RB design and retrofit into broader urban development and climate strategies, the performance analysis includes characterising the RB stock, conducting energy calculations, and identifying key performance indicators (KPIs). For instance, the Building Energy Performance (BEP) tool, designed for the Middle East and North Africa region, assesses existing energy and economic performance for projects in Egypt, Jordan, and Lebanon, categorising RBs as single or multi-family units. The BEP tool targets architects, project developers, financial institutions, researchers, and policymakers [85,86]. Another example is Eco-Niwas, a free web-based tool for three RB typologies (detached, semi-detached, and row) across five climatic zones in India. This tool enables residential owners, contractors, and architects to quickly evaluate an RB's energy efficiency, carbon footprint, and cost savings during the preliminary design phase [87,88]. Building PathFinder is a free web-based tool that performs parametric analysis of various RB typologies (row, medium single-family, and high-rise multi-unit) according to the KPIs in British Columbia (B.C.) Energy Step Code and the City of Vancouver's Zero Emission Building Plan. It serves solely as an educational resource to raise awareness among decision-makers—such as architects, developers, and planners—about the impact of building design on energy use, greenhouse gas emissions, and other performance indicators [89]. Comparing the energy calculation methods of these three web-based tools reveals that the BEP tool and Eco-Niwas employ a simple calculation methodology. Conversely, Building PathFinder categorises buildings as simple or complex based on the B.C. Building Code. It uses the EnergyPlus v8.6 simulation programme for high-rise multi-unit RBs and the Natural Resources Canada HOT2000 programme version 11.3 for medium single-family and row RBs. Building PathFinder, unlike the BEP tool, employs pre-defined templates for the three RB types; the BEP tool uses simplified numerical inputs for geometry definition. In Eco-Niwas, users select templates but must input the area per floor and building orientation [86,88,90]. The BEP tool offers two data-entry interfaces: base mode, aimed at non-technical users, simplifies the entry process by focusing on key parameters, while advanced mode allows for detailed customisation of inputs related to the building envelope, energy systems, renewable energy systems, and operational parameters. The tool calculates KPIs such as primary energy use (kWh/m^2a), global cost ($€/m^2$), and CO_2 emissions ($kgCO_2/m^2a$). Its web interface comprises three stages—general information, input, and results—displaying data in tables and column charts, with visual comparisons to the baseline [85,86]. The Basic Tool Eco Niwas allows users to evaluate RB performance by combining seven parameters related to the building envelope (walls, roof, and windows), air conditioning, and ventilation. Users can drag and drop selected parameters onto the RB template to visualise their effects on three KPIs: energy savings (kWh), CO_2 savings ($kgCO_2$), and monetary savings (INR). The change in the energy performance index relative to the baseline—based on chosen energy-efficient retrofit measures—is expressed as a percentage using a slider. This tool employs a simple calculation methodology to assist users in identifying the best combinations [87,88]. Building PathFinder offers nine inputs for high-rise multi-unit RBs: shape, window fraction, wall R-value, roof R-value, window U-value, window solar heat gain coefficient (SHGC), heat recovery efficiency, infiltration rate, and heating fuel source. It utilises three KPIs: Thermal Energy Demand Intensity, Total Energy Use Intensity, and GHG Intensity. For medium single-family and row RBs, the tool considers nine inputs (airtightness, wall R-value, underslab R-value, roof R-value, window U-value, domestic hot water system, drainwater heat recovery, space heating, and ventilation heat recovery) and five KPIs (Mechanical Energy Use Intensity, Thermal Energy Demand Intensity, Peak Thermal Loads, GHG Intensity, and cost difference [%]) [89–91]. All calculated data are simultaneously visualised for each RB template through a parallel coordinate plot and a table, with filtering tools available for data analysis [89].

These three web-based DSTs, despite their varying performance calculation methods, required inputs, outputs (KPIs), capabilities, and visualization techniques, all share a common focus on national scope, particularly targeting local governments. Megacities face critical challenges in managing inefficient RB stocks with low adaptability due to their long lifespan and high energy consumption resulting from rapid urbanisation and climate change. Such inefficiencies could incur significant costs in the future. To address this, megacities have established ambitious goals to ensure compliance with legal regulations and develop

sustainable settlements to mitigate the negative impacts of energy inefficiencies on national and local energy bills. Thus, interactive, comprehensible, user-friendly, open-access web-based DSTs are essential for designing new RBs and retrofitting existing stock. These tools enable novice DMs, such as architects and residential owners, to quickly evaluate design alternatives during the early design phase and facilitate comparisons within the multi-criteria decision-making process.

Problem statement and research objective

Türkiye views the Paris Agreement as a unique opportunity for a green and fair transition, actively supporting the implementation of its mitigation and adaptation policies. As a candidate for the European Union (EU), Türkiye closely monitors EU policies and develops climate change and environmental legislation to align with the relevant acquis [92]. Türkiye's total greenhouse gas emissions have risen, despite recent improvements in carbon intensity and energy efficiency, making it the 15th highest annual emitter globally. This rise is significant, as Türkiye's ranking has increased from 18th in 2019 [93]. RBs, identified as a key sector for reversing this trend [94], are central to Türkiye's action plans, which emphasise efficient energy use and on-site renewable energy production as pathways to low-carbon development [95–97]. Extending energy-efficient practices in RBs by 2030—improving existing building performance, designing new energy-efficient RBs, increasing renewable energy self-consumption, and implementing building performance codes—is vital for Türkiye [93,95].

Türkiye has made progress in establishing fundamental policy instruments for residential energy efficiency, including regulations, audits, and certification systems. However, several critical gaps remain that hinder sector development. These include inadequate coverage of current legislation, insufficient compliance, the complexity of producing energy-efficient buildings, and a lack of knowledge about alternative solutions [10,22–24,98]. Numerous guides, such as energy-efficient building design strategies and the Guidebook for Nearly Zero-Energy Buildings, have been published to address these gaps [99–103]; however, a qualified supply–demand balance has yet to be established in the residential sector [41,104]. Therefore, the primary objective of the new Action Plan for disseminating energy efficiency applications in residential buildings between 2024 and 2030 involves conducting awareness-raising and capacity-building activities focused on energy efficiency for both the general public and specific competency groups within a framework of social mobilisation [96].

This study aims to provide essential information to both the demand side (residential owners) and the supply side (architects), who play active roles in the early design phase but have limited awareness and knowledge. The objective is to eliminate inconsistencies in the information needed to transition from a conservative to a performance-driven approach in existing RB design and retrofit processes while enhancing access to this information. Focusing on this aim, the megacity of Istanbul—recognised as Türkiye's centre for growth and agglomeration economies [93]—is critical for reducing greenhouse gas emissions. The city's population is projected to exceed 20 million by the 2030 s. Therefore, Residential-IST has been developed to prevent ongoing urban transformation in Istanbul, which is in a seismic risk zone and serves as the country's primary economic hub, from resulting in high-emission urban growth through inefficient buildings. This web-based interactive DST incorporates an iterative feedback loop to produce energy- and cost-effective RBs, advancing access to multiple criteria design solutions. To the best of our knowledge, this is the first interactive platform that generates data, allowing target DMs (architects and residential owners) to make informed choices regarding new RB designs or retrofits in Istanbul and Türkiye. Furthermore, it presents data in a way that facilitates decision-making. The first prototype of this tool is available online at http://185.8.129.154/ [105].

Residential-IST addresses the key question: "How can architects and residential owners consider the energy, economic, and environmental performance of RBs when making informed design decisions about sustainable, energy-efficient new designs and retrofits?" It achieves this by visualising and facilitating the exploration of a broad design space through a systematic search for optimal, technically feasible design options, particularly in Istanbul. The main contributions of this study are as follows: i) integrating parametric and optimisation analyses of early-stage design decisions focused on energy and cost performance evaluation on a single platform, ii) considering shading effects from neighbouring buildings based on various urban configurations to establish a consistent analysis framework within a performance-driven design support approach, iii) optimising residential subsystems (building envelope, energy systems, and renewable energy systems) simultaneously in a multiple-criteria performance evaluation, holistically addressing the entire building system, iv) effectively exploring the high-dimensional design space by visualising substantial data, thereby meeting minimum requirements for Istanbul and facilitating the rapid production of high-performance RBs in an accessible, comparative format, and v) designing a web-based interactive DST that serves two distinct purposes: new RB design and RB retrofitting, offering high informative capacity and acting as an effective pathfinder for DMs in practice.

Methodology

This study focuses on developing a web-based DST for novice architects and residential owners, aiming to create a positive feedback loop that addresses low awareness in the residential sector and promotes the adoption of energy-efficient, high-performance buildings. The workflow comprises three main steps: i) performance-driven design, ii) system architecture, and iii) user experience (UX) and user interface (UI) design.

The first step emphasises a contextualised, performance-driven design approach that reduces barriers between RB design/retrofitting and performance. This method bridges the gap between theory and practice, thereby facilitating a transition to energy-efficient RB production in the built environment. The tool provides DMs with extensive information, enabling design queries to be transformed into actionable designs compliant with national legislation and nearly zero-energy building standards while considering local materials and construction techniques. To this end, an exhaustive design space search was conducted, integrating parametric building energy simulations with multiple criteria decision analyses. Building modelling was performed using DesignBuilder [106], a comprehensive interface of the EnergyPlus programme [107]. Extensive searches were conducted through parametric analysis, leveraging the coupling between EnergyPlus and MATLAB® [108]. EnergyPlus operates with text-based inputs (.idf) and outputs (.csv), facilitating interactions with mathematical tools. MATLAB® automates EnergyPlus simulations, modifies input files, and processes output files. In the multiple-criteria decision analysis, MATLAB® was used to obtain Pareto-optimal results by evaluating objective functions based on EnergyPlus outputs. Both programs are recognised for their reliability within their respective application areas [109].

In the second step, the DST client–server architecture was developed based on the multitiered cloud-based visual environment proposed by Önder and Balci [110]. The development employed.NET Core tools and Vue.js technologies to create a five-tier architecture. A model-view-controller framework was integrated, with the view as the client tier, the controller as the web tier, and the model encompassing the business, data mapping, and data source tiers.

The final step involved creating a web interface to facilitate the exploration of the large data volumes generated during the design space search. This interface visualises the design space according to two distinct objectives: "New Design" and "Retrofit." The visualisation aims to minimise the time required for novice architects and residential owners to interpret complex simulation results and translate them into actionable design strategies, thus enhancing the decision-making process. To ensure effective data analysis, users will be able to select

separate interfaces to visualise the results from the parametric analysis and multiple-criteria decision analysis. The multiple-criteria decision analysis results will include visualisations of Pareto-optimal solutions, allowing users to examine relationships between design alternatives and objectives. Conversely, the parametric analysis results will enable exploration of the entire design space. Consequently, a simple, user-friendly interface was designed to summarise relevant performance indicators, providing an overview of RB performance with detailed information available upon request.

Residential-IST

Residential-IST is an energy- and cost-oriented DST designed to inform target DMs and facilitate decision-making. It is freely accessible at https://residential-ist.com/#/. The workflow framework for developing this web-based tool, detailed in the previous section, is specifically tailored for Residential-IST.

Performance-driven design

The computational performance-driven design support approach in this study is contextualised for both RB design and retrofitting (Fig. 1). To provide effective information support, the developed tool must represent the majority of RBs in Istanbul.

Model setting

In Residential-IST, the focus is on multifamily RBs, specifically apartments, which account for 80 % of the total residential area [111]. The study also examined applications by the Housing Development Administration, a key player in apartment block production and urban transformation. Various design parameters were considered to define the geometry of the RBs at both building and settlement scales. At the building scale, parameters included plan type, building height, roof type, and transparency ratio (total window area/total façade area). At the settlement scale, parameters comprised settlement form, the height-to-width ratio (H/W), and orientation. Housing units with a base area of 100 m^2 were used to define the building form, establishing two plan types: a square floor plan formed by combining four units (form factor 1.00) and a rectangular floor plan formed by two units (form factor 2.00) (Fig. A.1). Three building heights were considered: three, five, and ten storeys (9 m, 15 m, and 30 m, respectively), with a floor-to-floor height of 3.00 m. Roof types included pitched and terrace options. The transparency ratio was set at three values (30 %, 40 %, and 50 %), applied uniformly across all façades of the RBs. Two settlement forms, detached and row, were defined to explore the relationship between RB thermal behaviour and solar gain. Based on this data, a detached settlement form with a square floor plan and both detached and row forms with a rectangular floor plan were developed (see Fig. A.2). A uniform configuration of nine identical RBs was created in a hypothetical area using a 3 × 3 matrix, with the central RB as the focus of the analyses. The H/W ratio and orientation were derived from a comprehensive parametric analysis by Mangan et al. [112]. The H/W value was standardised at 1.00 (uniform canyon) for all forms, with the optimal orientation at 0° for rectangular and 90° for square floor plans. Street widths for the archetypal building typologies of three, five, and ten storeys were set at 9 m, 15 m, and 30 m, respectively. From the settlement and building-scale design parameters, 54 distinct RB geometries were developed, detailed in Table A.1.

The layering details of the opaque and transparent components, regarding the optical and thermophysical properties of the building envelope, were determined based on the limit U (W/m^2K) values specified for Istanbul in the Thermal Insulation Requirements for Buildings – TS 825 [113] (see Table A.2). The building envelope's air tightness was considered "high," with a natural ventilation air change rate (n) set at 0.5 (1/h) [114]. Heating energy demand is met by a central hot water boiler with a radiator system, using natural gas as the energy source, while split air conditioners provide cooling. Individual electric water heaters are assumed for hot water systems. The illumination level for each housing unit was set at 150 lx. An occupancy schedule was developed based on the Turkish family structure, with user density at 0.04 m^2/person [115,116] and an activity level of 110 W/person [117]. Energy systems maintain an indoor air temperature of 20 °C from 07:00 to 23:00 and 13 °C at other times when heating is required. For cooling, indoor temperatures are set at 26 °C between 07:00 and 23:00 and 32 °C at other times, with natural ventilation active during cooling. Istanbul represents Türkiye's temperate-humid climate zone [118], classified as Csa according to the Köppen classification [119] and the second climate zone according to the TS 825 standard [113].

To define appropriate RB configurations for retrofitting, the revision dates of the TS 825 standard and building permit statistics were considered. Configurations prior to 2000 were excluded because of the ongoing urban transformation, resulting in three identified construction periods: 2000–2008, 2008–2013, and post-2013. Each period involved creating three different base RBs with varying limit U values (W/m^2K) and energy system efficiency values, detailed in Table A.3 [113,120–126].

Performance indicators

In this study, the performance indicators are vital for the success of new designs and retrofitting processes. This study aims to define indicators that i) facilitate communication between architects and residential owners, the primary target DMs of the developed DST; ii) enable these DMs to focus on significant design parameters, allowing for comparisons of different design alternatives; and iii) enhance awareness of the data presented in the energy identity document required by Türkiye's Energy Efficiency Law No. 5627 [127] and the Regulation on Energy Performance for Buildings [123]. The KPIs selected include primary energy consumption (PEC) and life cycle cost (LCC) for new designs, as well as primary energy (PE) savings and LCC savings for retrofits. Furthermore, to provide comprehensive support to target DMs through this tool, the following indicators are presented for new designs: i) annual PEC, including heating, cooling, lighting, hot water, renewable energy share, and annual final energy consumption; ii) initial investment cost and annual operational cost (energy cost plus maintenance and repair), along with LCC; and iii) annual CO_2-equivalent emissions for environmental performance. Additionally, for retrofitting, CO_2-equivalent emission savings and the discounted payback period (DPP) are determined for each alternative, in addition to PE and LCC savings.

Design Space Input Parameters

Defining the design space to comply with current and future building codes, as well as the needs of DMs, is crucial for the effectiveness of the developed DST [128]. The design space input parameters are classified into four groups: geometry (at both settlement and building scales), building envelope, energy systems, and renewable energy systems. To develop a reliable tool, national and international standards, along with existing analyses of the residential sector [111,113,122–127,129], were used to determine the ranges and distributions of variable parameters, excluding those with negligible impact on energy performance. The design space input parameters encompass various geometry considerations at both settlement and building scales, allowing representation of most RBs in Istanbul through the developed residential settlement models. The definition of archetypal building typologies—detached and row—was based on the optimal height-to-width (H/W) ratio and orientation angles (0° for rectangular plans and 90° for square plans), alongside variability in floor numbers (3, 5, and 10) for both plan types, providing extensive information to DMs. Roof types (terrace and pitched) and transparency ratios (30 %, 40 %, and 50 %) further enhance this breadth of information. For the settlement form alternatives based on the seven defined geometric parameters, 13 additional parameters were considered regarding the building envelope, energy systems, and renewable energy systems (see Table A.4). This approach diversified the design space, developing alternatives related to the building envelope, energy, and renewable energy systems that range

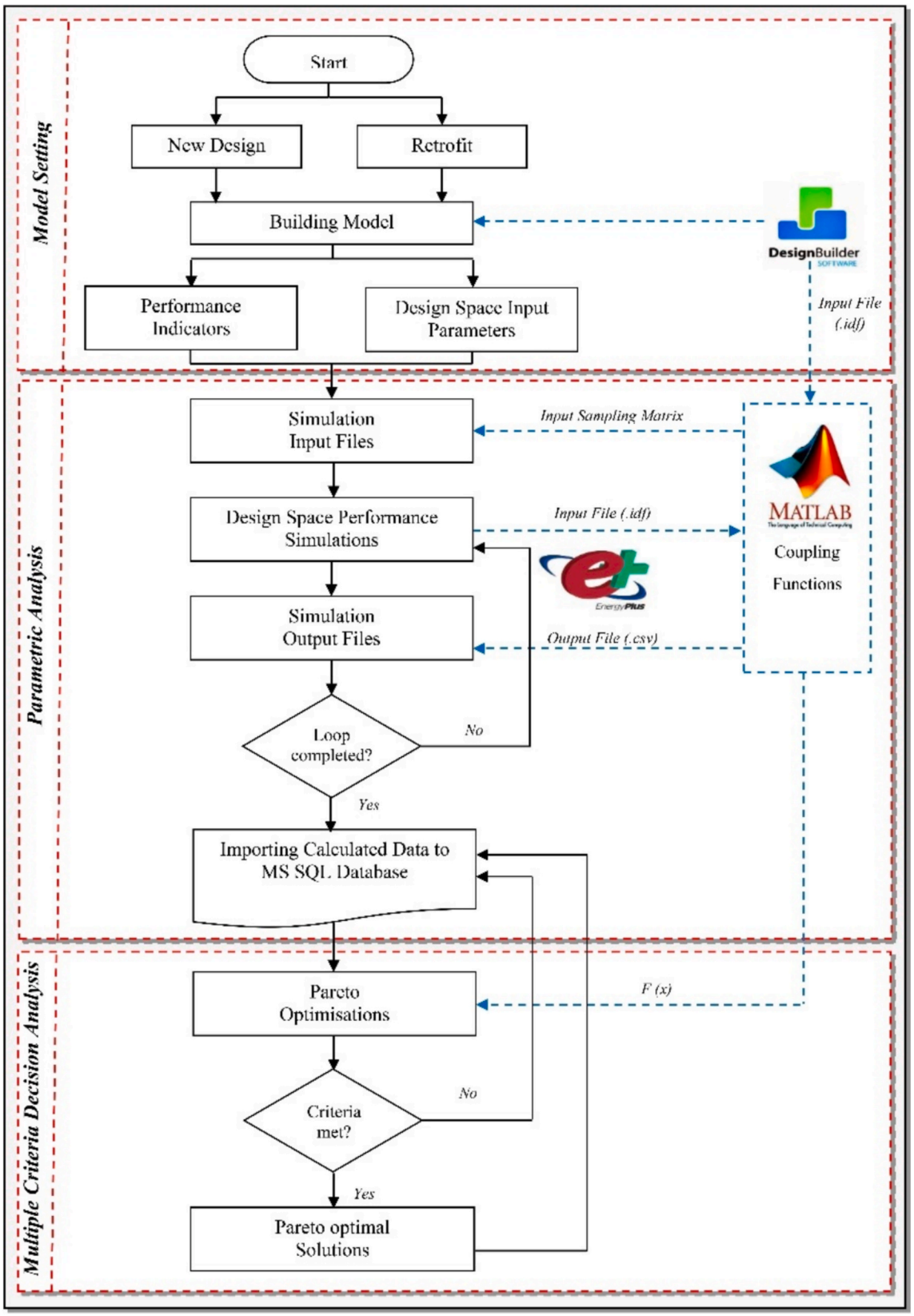


Fig. 1. Overview of the computational performance-driven design approach.

from compliance with the national building standard TS 825 for 54 different RB geometries to combinations that facilitate nearly zero-energy buildings (e.g., passive house U-values and photovoltaic systems).

Parametric analysis

Parametric analysis enables the simultaneous examination and comparison of numerous design alternatives, facilitating iterative improvement of building performance during the early design phase. This approach establishes a broad design space, promoting a conscious and informed design process [130–132]. By leveraging the collaboration between EnergyPlus and MATLAB®, a parametric simulation method was adopted to help DMs quantify the impact of various design parameters on building performance. The workflow for the analysis conducted in MATLAB is detailed in the following subsections.

Simulation input files (pre-processing)

In the pre-processing step of the parametric simulation, input files for the EnergyPlus simulation program, known as IDF files, must be created. These files define the RB and settlement forms for both new designs and retrofits. As mentioned in Model Setting Section, they were generated using DesignBuilder—the comprehensive interface of EnergyPlus. During this stage, 162 IDF files were created, varying in settlement and building geometry, as well as solar control elements. The files were organised according to the variable ranges specified in Tables A.4 and A.5, resulting in new IDF files for each design alternative. An exhaustive sampling method was employed, with the procedure iteratively repeated according to a specific parameter tree. The coupling function enabling communication between EnergyPlus and MATLAB® was crucial for executing this iterative process and creating the IDF files for each EnergyPlus RB alternative.

Design space performance simulations

In the second step, the design space parameterised in text-based IDF files was modified using the MATLAB® coupling function, thereby initiating relevant EnergyPlus simulations with Istanbul climate data [133]. The x vector, encoding each design alternative, was generated through MATLAB® code, automatically executing dynamic energy simulations based on EnergyPlus calculations for each alternative.

Simulation output files (post-processing)

In the post-processing step, the EnergyPlus output files (.csv) from the parametric energy simulations were processed in MATLAB®, calculating the performance indicators outlined in Model Setting Section for each design alternative. The KPIs included PEC [134] and LCC [135] for new designs, as well as primary energy savings and LCC savings for retrofits. Calculations were based on the equations provided in Appendix A.

Two key elements in LCC calculations are the calculation period and costs. This study sets the calculation period at 30 years. Costs for components not impacting energy performance and those consistent across alternatives were excluded [136]. Initial investment costs for the design space alternatives were based on current market unit costs from supplier price offers, presented in Turkish Lira (TL) and Euro (€) in Table A.4. These costs only reflect material prices. The timing and frequency of replacements for building systems depend on the calculation period and the estimated lifespan of each system. The calculation period encompasses the lifespan of the building envelope variables [137], with no replacements anticipated. Lifespan data for energy system components were derived from Annex A of the EN15459 standard [138], and annual maintenance and repair costs were calculated accordingly. Replacement and maintenance costs for photovoltaic (PV) system components (modules plus balance of system) were also included [139,140]. Energy costs were based on local energy prices [141,142], energy consumption by fuel type, and energy production from PV systems. Residual values were calculated for components with lifespans exceeding the calculation period. All costs, except initial investment costs, were discounted at a rate of 3 % [136], using 2019 as the starting year, to determine their net present values. Additionally, DPPs were calculated using the same data and assumptions [135].

Investments aimed at enhancing energy efficiency in RBs are long-term, which leads to uncertainties in the data required for assessing economic performance. To address this, sensitivity analyses were conducted to gauge the uncertainty associated with economic data, which significantly affects LCC calculations. These analyses enhance the reliability of these calculations in decision-making. The sensitivity analysis centres on discount rates and energy prices, both of which substantially influence economic performance evaluations. The assumptions for the sensitivity analysis, alongside those for the base-case LCC calculations, are as follows:

i. Base case: Discount rate set at 3 %, neglecting energy price development.
ii. Sensitivity analysis I: Discount rate increased to 6 %, with energy prices neglected.
iii. Sensitivity analysis II: Discount rate at 3 %, with an annual energy price increase of 15 %
iv. Sensitivity analysis III: The discount rate remains at 3 %, with an annual energy price increase set at 30 %.

For the environmental performance of design alternatives, CO_2-eq emissions and savings were calculated using the equations [143] provided in Appendix A.

Importing calculated data into an MS SQL database

The parametric analysis yielded a design space of approximately 8 million alternatives from 331,746 automated dynamic energy simulations across 20 different design parameters for new designs and retrofits. To reduce the lengthy simulation and post-processing times, simultaneous parallel calculations were performed in MATLAB® using an Intel® Core™ i7 9750H CPU at 2.60 GHz. Subsequently, the calculated data were imported into the MS SQL database for use in the subsequent multiple-criteria decision analysis.

Multiple-Criteria decision analysis

Identifying design alternatives that optimise performance within the high-dimensional design space is challenging because of the conflicting nature of the KPIs. Thus, multiple-criteria decision analysis was employed to evaluate alternatives that best address these conflicting objectives, effectively solving the multi-objective optimisation problem. The workflow for the analysis conducted in MATLAB is detailed in the following subsections.

Pareto optimisations

Pareto optimisation involves an exhaustive search of the design space to identify trade-off solutions that align with the DMs' preferences. Architects favour design alternatives with high energy performance, while residential owners prioritise low LCC. Thus, the objective functions for Pareto optimisation aim to minimise PEC and LCC for new designs and maximise PE and LCC savings for retrofitting, defined as follows:

Min $\{f_1(\bar{x}),f_2(\bar{x})\}\ \bar{x} = [x_1, x_2,....x_m]$ *(new design)*

Max $\{f_3(\bar{x}),f_4(\bar{x})\}\ \bar{x} = [x_1, x_2,....x_m]$ *(retrofit)*

where f_1 is the PEC (kWh/m^{2}a), f_2 is the LCC (TL/m^2), f_3 is the PE savings (%), f_4 is the LCC savings (%), $\bar{x}$ represents combinations of design parameters and, m is the number of design parameters.

Pareto optimisations were conducted in the MATLAB® environment for both new designs and retrofits, with separate analyses for the three sensitivity scenarios in the LCC calculations.

Pareto optimal solutions

In multi-objective optimisation problems, it is impossible to optimise all objective functions simultaneously, resulting in multiple solutions rather than a single optimal one, as in single-objective optimisation. Pareto optimisation identifies the Pareto front, which comprises dominant solutions that aren't overshadowed by others in the design space. This approach yields various solutions, allowing DMs to select designs based on their preferences. Furthermore, sensitivity analyses reveal that

solutions excluded from the Pareto optimal set due to high initial investment costs can achieve optimal energy and economic performance under different energy price increase rates; this highlights to DMs how LCC calculations and optimal solutions may vary with different economic data.

System architecture

The Residential-IST client–server architecture comprises five tiers: client, web, business, data mapping, and data source (Fig. 2). The client tier offers the user interface for the DST via web browsers like Google Chrome, Safari, Firefox, or Microsoft Edge. The web tier manages interactions between the DM in the client tier and the model in the business tier, employing Vue.js technologies. The server-side components of the DST operate in the business tier, utilising.NET Core technologies for execution and interactive visualisation of the design space. The connection among the data mapping, business, and data source tiers is facilitated by.NET Core. In the business tier, data is displayed through interactive tables and graphs and processed using structured query language (SQL). The data source tier employs MS SQL to store design space data and respond to DM queries.

UX and UI design

A key challenge is ensuring that high-dimensional datasets generated by the computational performance-driven design support approach for new designs and retrofits are accurately explored and translated into informed decisions by target DMs. Effective visualisation methods in UX/UI design can significantly address this issue [144,145]. An interactive visualisation method was adopted to provide rapid feedback during the early design phase and help DMs quickly understand the complex datasets stored in the MS SQL database. This method employs an iterative query process that transforms datasets into simple, comprehensible information through visualisation and interaction cycles [146]. The UX and UI design workflow is illustrated in Fig. 3, and its detailed description is provided in Appendix A.

Home page

The homepage provides general information about the tool, including the design objective, scope, and target DMs, along with a tutorial video explaining its features. Additionally, the video plays automatically and can be viewed on YouTube (https://www.youtube.com/watch?v=YJzi5LxYzfo) by clicking the tutorial space. DMs can send feedback via the 'Contact' link at the bottom of the page. Language options allow switching between Turkish and English. Simply click the 'Launch' button in the top-right corner to start using the tool; no log-in or sign-up is required (Fig. 4).

Input selection page

The input selection page prioritises a simple user interface that is easy to navigate and independent of detailed design inputs expected from the DM. To address issues of complexity, data entry, and lengthy simulation runtimes [84] typically seen in freely accessible tools, the dynamic simulation tool EnergyPlus was utilised to derive performance results for 54 different RB geometries. These results were then transferred to the MS SQL database (see Performance-Driven Design Section) without compromising accuracy, ensuring minimal input and short runtimes. The DM progresses by defining the necessary information through check boxes and combo boxes across four successive screens, preventing novice architects and residential owners from skipping required data (Fig. 4).

Exploration page

The exploration page focuses on visualising complex, multi-dimensional design solutions generated from parametric analysis and multiple-criteria decision analyses, allowing DMs to perceive them quickly and easily. In this context, complex datasets comprising 8 million design alternatives were visualised using the three-step 'visual information seeking mantra [147]': i) overview first, ii) zoom and filter, and iii) details on demand. Two separate pages—Pareto optimal solutions and design space—were created with interactive data visualisation to facilitate effective exploration and interpretation of the data. Both pages provide a general view, enabling DMs to identify interesting subsets and offer access to detailed information for further exploration. This design structure helps DMs maintain an overview while navigating details, thereby preventing them from becoming overwhelmed by information and supporting efficient decision-making by reducing the time needed to analyse extensive data (Fig. 4). Readers are encouraged to visit https://residential-ist.com/#/ for more examples and to gain hands-on experience in design space exploration using interactive visualisations.

Discussion and concluding remarks

Residential-IST is a unique open-access web tool tailored specifically for Istanbul and Türkiye. Its user interface is interactive, simple, and user-friendly, requiring no local installation and offered free of charge. The tool supports both new RB designs and retrofitting, significantly contributing to energy efficiency in the residential sector through a social mobilisation approach. It aims to bridge critical gaps (*such as insufficient compliance with legislation, the complexity of creating sustainable buildings, and a lack of awareness about alternative solutions*) that hinder the sector's transition from a conservative to a performance-driven approach. The tool's high potential is detailed in Residential-IST Section, highlighting its validity, utility, quality, and efficacy. The study's key question, framed within the methodological framework, divides into two sub-questions: "What if" questions, such as "If I prefer low-e coated glass, to what extent will energy performance improve?"—common in architects' and residential owners' decision-making

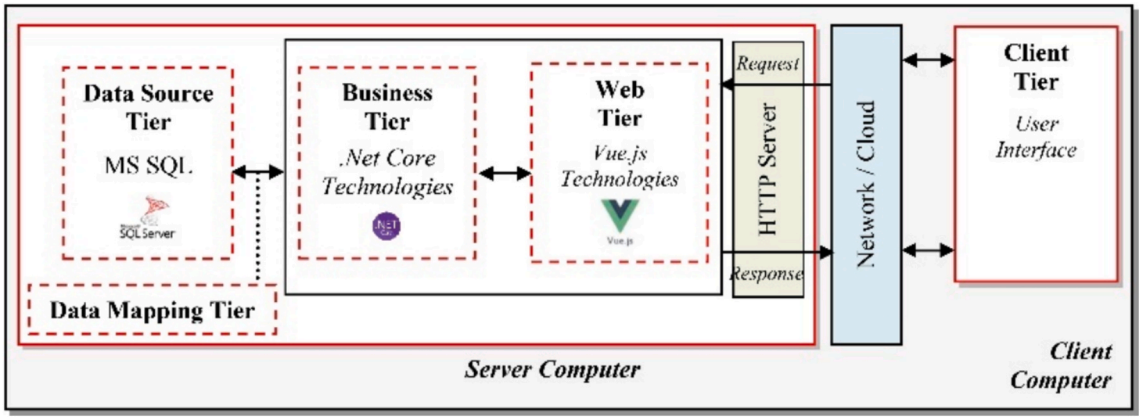


Fig. 2. Overview of the client–server architecture of Residential-IST.

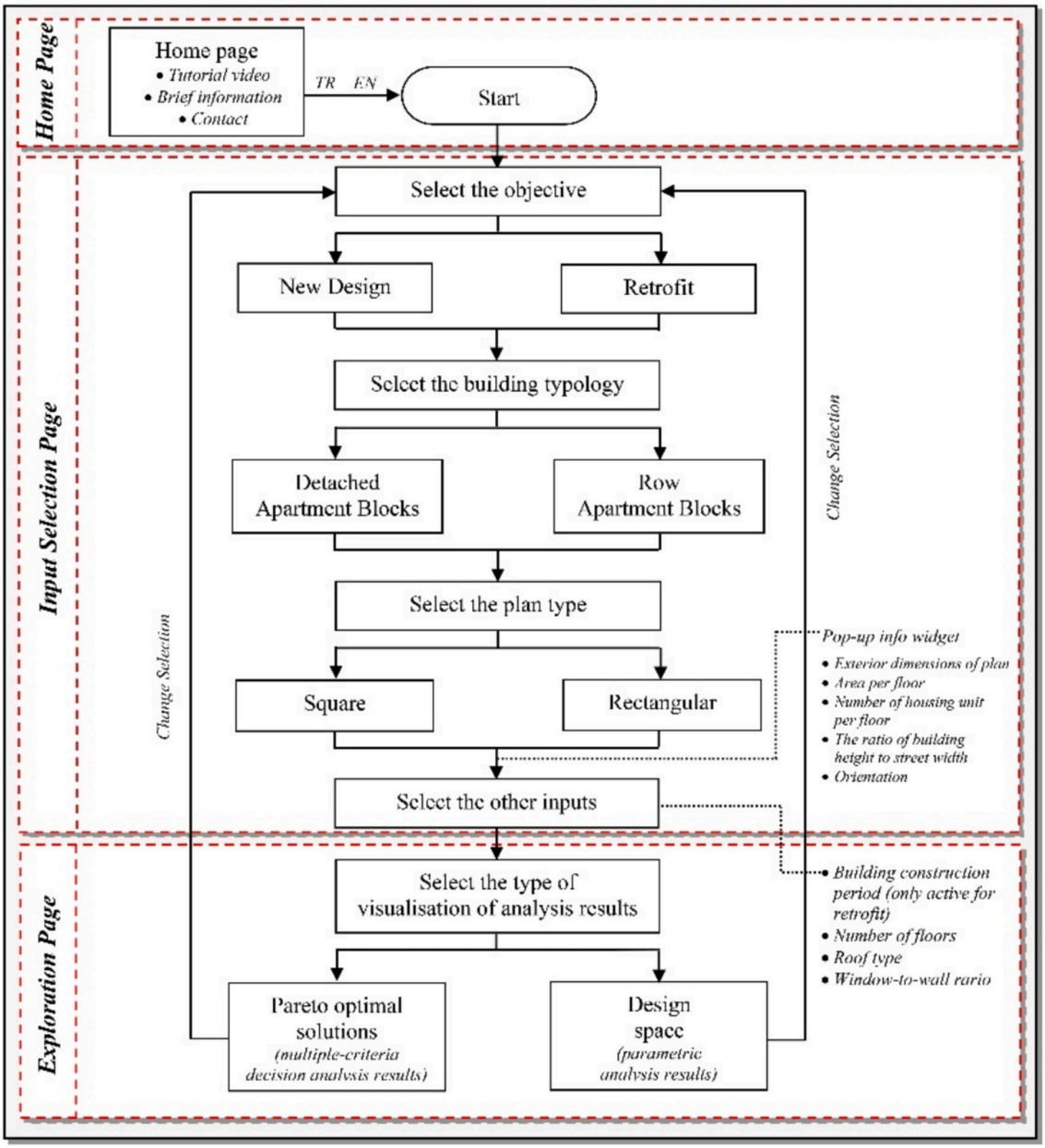


Fig. 3. Overview of the UX and UI design approach.

processes—and "What are the energy and cost-effective optimal design alternatives?" based on numerical comparisons of "optimal" solutions. Consequently, through effective multi-dimensional design exploration, the DM can achieve high-performance solutions.

Within the computational performance-driven design support approach, various RB geometries were developed based on seven key settlement and building-scale design parameters, considering the urban context as a source of solar shading. This approach aims to represent the majority of RBs in Istanbul, informed by urban densification strategies and transformation projects. A vast multi-dimensional design space was created by defining discrete values for 13 parameters related to the building envelope, energy systems, and renewable energy systems. This design space meets current and future building code criteria for 54 RB geometries, offering technically applicable solutions specific to Istanbul. Additionally, base RBs for three different construction periods have been established to support the ongoing urban transformation process in the city. A crucial aspect of this approach is the use of parametric and multiple-criteria decision analyses. Approximately 8 million alternatives were generated through detailed dynamic energy simulations based on exhaustive sampling within the parametric analysis. Optimal performance design alternatives were identified through multiple-criteria decision analyses. Separate Pareto optimisations for three sensitivity scenarios in LCC calculations informed target DMs how LCC calculations—and thus optimal solutions—may vary based on different economic data. Although this approach involves exhaustive sampling to generate all design alternatives, comprehensive energy performance analysis methods, sensitivity analyses in LCC calculations, and repeating Pareto optimisations for each LCC scenario, resulting in increased calculation intensity, it effectively guides and ensures the tool's high reliability in the multiple-criteria performance-driven RB design and retrofit process [132,135,136,148].

Another significant strength of the tool is its interactive visualisation of the extensive multi-dimensional design space, achieved through a computationally intensive performance-driven design support approach based on the visual information-seeking mantra. This is facilitated by a user-friendly web interface that empowers novice architects and

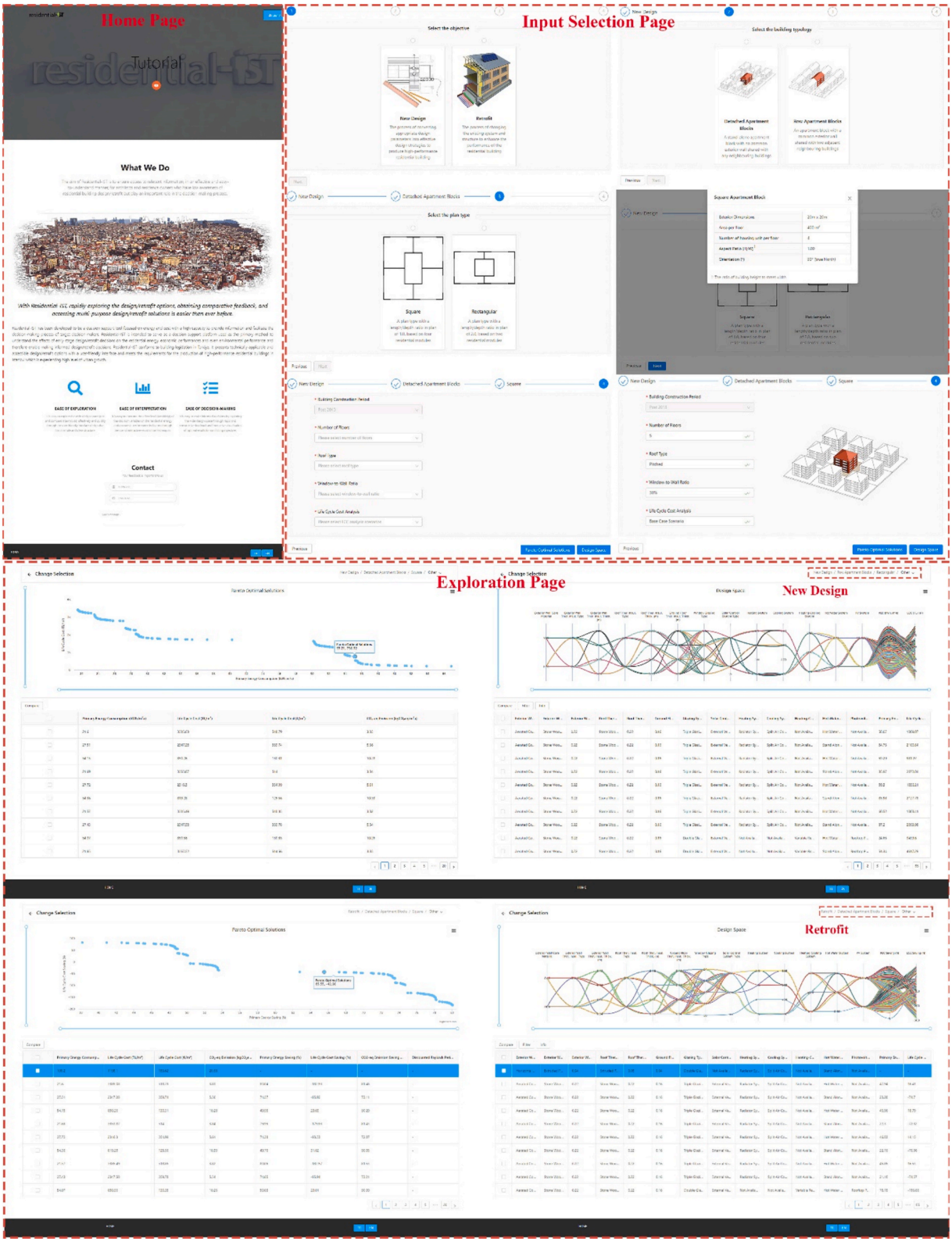


Fig. 4. Overview of the UX and UI design approach with exemplary screenshots of the home page, input selection page and exploration page. (Best viewed in colour, the reader is referred to the Web version of this paper.).

residential owners to make informed decisions during the early design stage. The interface stands out for its free access, ease of use, and simplicity, enabling quick exploration of a multivariate design space. It provides rapid access to energy-efficient and cost-effective design alternatives, facilitates the filtering and comparison of these options from multiple perspectives, offers iterative feedback specific to early design phases, and accommodates geometric variations through adjustments to design parameters at both settlement and building scales. Furthermore, it is highly contextualised for local use, ensuring compliance with legal regulations, construction systems, materials, and other relevant factors.

The input selection page design allows the DM to create geometry variations quickly and intuitively visualise the selected RB geometry in 3D, making it easy to review or modify selections (e.g., to create alternative RB geometries). On the exploration page, results are presented through interactive plots and tables that are easy to interpret and supported by filtering and comparison options. This functionality enables multiple-criteria analyses concerning energy, economic, and environmental performance; tests compliance with local legislation; visualises the effects of various design parameters (related to settlement, building, building envelope, energy systems, and renewable energy systems) on RB performance; presents necessary information for design or retrofit decisions through simple, accessible solutions; and facilitates communication among target DMs (architects and residential owners). The developed tool significantly reduces the number of difficult, time-consuming, and costly design and retrofit iterations. It supports DMs in managing variability and uncertainty during the early design phase, allowing effective exploration of a broad design space concerning multiple conflicting objectives. The tool boasts several crucial functional features that enhance its ease of use. These include rapid input data entry and quick presentation of results through interactive graphical plots and well-designed tables. Additionally, the tool's predefined RB designs minimise modelling time, making it adaptable to DMs with varying levels of knowledge and skill. Consequently, Residential-IST, as the first web-based interactive tool of its kind, will significantly contribute to the transition from conservative approaches to performance-driven RB production. Traditional methods often rely on a single design alternative with low initial investment costs, typically involving a manual trial-and-error approach to meet minimum code compliance during the final design or retrofit phase. Conversely, the performance-driven approach addresses the growing complexity of considering factors beyond a single building, recognising that intuitive decisions or simple guidelines are no longer sufficient. This new method necessitates meeting a wide range of often conflicting requirements and goals, advancing multiple criteria performance evaluation, and encouraging the simultaneous creation and assessment of various design alternatives. Accordingly, Residential-IST presents significant advantages compared to web-based DSTs that integrate high-performance residential building design/retrofit with broader urban development/climate action strategies (Table 1).

While Residential-IST has been developed to inform and facilitate decision-making for target DMs in new RB designs and retrofitting, particularly in Istanbul and Türkiye, the primary limitation of this study is the lack of usability evaluations. A usability test on the tool's first prototype [105] revealed that it did not meet the effective usability level required by DMs, with the absence of instructional documentation identified as a major drawback. To address this, a tutorial video was added to the homepage, guiding DMs on using the tool and its features, alongside general information about its objectives, scope, and intended users. Recognising that novice architects and residential owners may be unfamiliar with some energy- and cost-related concepts, this study aims to enhance usability, comprehension, and user satisfaction by incorporating mouseover texts, pop-up pages, warning messages, static images, and clear definitions. Additionally, a technical document, accessible via the 'info' button on the design space page, provides essential information on the tool's calculation and visualisation methodology, supporting informed decision-making. Follow up research will prioritise usability tests with target DMs to evaluate the tool's effectiveness, efficiency, and user satisfaction, particularly regarding the visualisation of the high-dimensional design space, and to identify areas for further enhancement. Another limitation is that the analysis of energy and economic performance did not consider the impacts of deepening climate change, despite the exhaustive search method used to reduce epistemic uncertainty and the sensitivity analyses conducted to address data uncertainty in LCC calculations. It remains crucial to account for climate uncertainty, which could lead to additional performance gaps in the calculations. Determining the performance of RBs under various climate

Table 1
Features of residential-IST vs. other web-based DSTs.

DST	Application		Geometry Definition	Urban Configuration	Performance Analysis	Calculation Method		Types of Decision Support			Sensitivity Analyses	Visualisation	
	New Design	Retrofit				Simplified Methods	Detailed Comprehensive	Compared to Baseline	Parametric	Optimisation		Static	Interactive
BEP Tool	√	√	Numerical inputs	x	Energy & Economic	√	x	√	x	x	x	√	x
Eco-Niwas	x	√	Archetype with numerical inputs	x	Energy, Economic & Environmental	√	x	√	x	x	x	√	x
Building PathFinder	√	x	Archetype	x	Energy & Environmental	√ *(for two archetypes)*	√ *(for one archetype)*	x	√	x	x	x	√
Residential-IST	√	√	Archetype	√	Energy, Economic & Environmental	x	√	√	√	√	√	x	√

change scenarios is essential for enhancing the tool's ability to inform target DMs and facilitate decision-making. This focus will contribute to establishing a qualified supply–demand balance in the residential sector in follow up research. Additionally, minimising computational difficulties, often referred to as the 'curse of dimensionality," is crucial for ensuring the tool can effectively guide the adaptation of RBs to future climate conditions. In this study, the exhaustive search method was employed despite its high computational cost to provide the flexibility needed by DMs regarding design decisions that may vary in the early-stage design process. This approach allows us to accurately present as much information as possible. The exhaustive search method used conducts the process of determining optimal design alternatives within a very wide design space in a much more robust way compared to other conventional optimisation methods and provides a complete solution to the optimisation problem. However, the disadvantage of this time-consuming method was mitigated using parallel computing method in this study. Therefore, incorporating fast metamodels should also be considered for addressing these computational challenges during the development process of the tool. Thus, the robust, broad, and high-dimensional design space obtained provides a solid basis for the use of effective, accurate surrogate models to eliminate the accuracy problem experienced due to the high level of uncertainty in the design space created based solely on *meta*-models and, thus, to develop the scope of the tool for different issues.

Additionally, while the Residential-IST is specifically contextualized for local use (in terms of compliance with legal regulations, construction system, materials, etc.) in terms of general scope, it can be potentially used as a guide for decision makers in other cities with temperate-humid climate zones characteristics for sustainable, energy-efficient building construction. Although this study focused on temperate-humid climates, the scope of follow-up research could be expanded by incorporating various residential building templates and different climate zones. Another issue planned to be considered within the scope of follow-up research is the integration of the life cycle assessment method into the computational performance-driven design approach. This will make it possible to consider the principles of the circular economy in the transition from a conservative approach to a performance-driven approach in current RB design and retrofit processes in the building sector. Another follow-up research topic is the integration of different techniques such as gamification in data visualisation into the Residential-IST tool based on the findings obtained after performing the usability tests.

CRediT authorship contribution statement

Suzi Dilara Mangan: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization.

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Declaration of competing interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2025.104529.

Data availability

Data will be made available on request.

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