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RESEARCH ARTICLE

A review on simulation based multi-objective optimization of space layout design parameters on building energy performance

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Abstract
Improving the energy performance of buildings is crucial for environmental protection, energy savings, and a better living environment. The growing emphasis on sustainable building practices has led to an increased focus on optimizing space layout design parameters to enhance building energy performance. This review explores the application of simulation-based multi-objective optimization techniques in the context of studying the impact of space layout design on building energy efficiency. The integration of advanced simulation tools with optimization algorithms allows for a comprehensive analysis of multiple conflicting objectives like energy performance, user comfort as well as cost factor. The review begins by outlining the key parameters influencing building energy performance, including spatial configurations, orientation, and space perimeter variables. Subsequently, it delves into the various simulation tools employed to model the complex interactions between these parameters and their effects on energy performance. The integration of energy simulation software is highlighted as a crucial step towards achieving accurate and realistic assessments. In summary, this review delivers a comprehensive overview of the state-of-the-art methods in simulation-based multi-objective optimization for studying space layout design parameters and their impact on building energy performance, offering insights for researchers, practitioners, and policymakers in the field of sustainable architecture. There is a requirement for a comprehensive multi-objective framework for complex structures in the investigation of building energy performance giving more focus on reducing the cooling load and optimization of space layout along with envelope parameters.

Keywords Architectural Space layout · Energy Performance · Optimization algorithms · Cost factor

Abbreviations

ANN	Artificial Neural Network
AAPPD	Annual Average Predicted Percentage Dissatisfied
AC	Acoustics Comfort
ACL	Annual Cooling Load
AEC	Annual Energy Consumption
AED	Annual Energy Demand
AEOCO	Annual Energy Operating Costs
ALL	Annual Lighting Load
aNSGA-II	Active Archive Non-Dominated Sorting Genetic Algorithm II
ASED	Annual Specific Energy Demand
ATL	Annual Thermal Load
CD	Cooling Demand
CL	Cooling Load
CO_2	Carbon Dioxide
DA	Daylighting, Autonomy
DB	DesignBuilder
DGI	Discomfort Glare Index
DI	Daylight Illuminance
DL	Daylighting
EC	Energy Consumption
ECO	Energy Cost
ED	Energy Demand
EE	Energy Efficiency
EP	Energy Performance
ES	Energy Saving
EUI	Energy Use Intensity (EUI)
EWSOA	Enhanced Water Strider Optimization Algorithm
GA	Genetic Algorithm
GCO	Global Cost
GHG	Greenhouse Gas Emissions

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HD	Heating Demand
HL	Heating Load
HVAC	Heating, Ventilation and Air conditioning
ICO	Investment Cost
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LL	Lighting Load
MLRGA	Multi-Linear Regression Genetic Algorithm
MO	Multi-objective Optimization
MOABC	Multi-objective artificial bee colony
MODE	Multi-Objective Differential Evolution
MOGA	Multi-Objective Genetic Algorithm
MOPSO	Multi-Objective Particle Swarm Optimization
NSGA-II	Non-dominated Sorting Genetic Algorithm II
OT	Operative Temperature
PE	Polluting Emissions
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfaction
PSO	Particle Swarm Optimization
SC	Solar Surface Coefficient
SHGC	Solar Heat Gain Coefficient
SOGA	Self-Organizing Genetic Algorithm
SR	Solar Radiation
TCO	Total Cost
TEC	Total Energy Consumption
TED	Total Energy Demand
TC	Thermal Comfort
TL	Thermal Load
TPMVD	Total Percentage of Cumulative Time with Discomfort
UDI	Useful Daylight Illuminance
VC	VISUAL COMFORT
VP	Visual Performance
VT	Visible Transmittance
WWR	Window-To-Wall Ratio

1 Introduction

The energy usage of built structures accounts for a substantial share of worldwide energy demand. The built sector is responsible for 30% of final total global energy consumption (EC) and 26% of total energy sector emissions [1]. Although the overall final energy utilization of the global building sector remained steady in 2020 compared to prior years, CO_2 (Carbon Dioxide) emissions from building projects increased by nearly 28% of total global energy-related CO_2 emissions [2]. Building and infrastructure construction contribute significantly to global warming because of the high participation of equipment and material consumption [3]. Making thoughtful, executive-level decisions on energy efficiency is one of the most important strategies to reduce the amount of energy used in buildings. Furthermore, implementing building energy efficacy measures is a significant strategy for reducing greenhouse gas emissions, that contributes to climate change mitigation and worldwide public health improvement [4]. An energy performance (EP) upgradation should lower the annual energy usage expenses based on the building's primary energy sources and annual CO_2 emissions in the environment [5]. In this context, research aimed at enhancing building EP has stimulated the concern of several researchers from around the world [3]. The optimization approach appears to be crucial in the battle to overcome these challenges. In the area of optimization, which is related to applied mathematics and computer science, models and algorithms are employed to address challenging problems. Optimization is the process of selecting the ideal combination of different solutions when the specified constraints are met [6]. For optimization to take place, constraints, decision variables as well as objective functions are required [7]. Using optimization to reduce building resource and energy needs will have a significant influence on resource management and related energy expenses. Optimization can be defined in terms of a single objective function, whereas multi-objective optimization can also contain two or three objective functions. Optimization objectives can be expressed explicitly, such as by reducing the annual energy needed for comfort, heating, cooling, ventilation as well as daylighting in buildings, or they can be expressed implicitly, such as by reducing CO_2 emissions or the price of energy-generating equipment [8]. It is easy to compare the values of each solution's objective function in a single-objective optimization problem, but in a multi-objective optimization (MO) problem, a solution's utility is determined by how well it excels with alternative solutions [9]. A single objective function is insufficient to explain a situation where many goals must be achieved simultaneously, necessitating the use of multi-criteria approaches [4].

MO can be used to balance many building design requirements, including optimum comfort, least amount of energy used, and least number of resources used. Considering that complicated optimization problems involving integrated building design include multiple independent variables and goals. Building performance optimization is always best understood as a MO problem, for which the exchange of the many objectives is the appropriate course of action.[10].The optimization algorithm chosen is determined by the problem that needs to be solved [11]. It takes time to investigate all of the possibilities to create an effective design [12]. Given that complex optimization issues with integrated building design involve several independent variables and objectives, non-gradient-based techniques are employed to resolve complex discontinuous objective functions. The main objectives of building energy design, as stated by the objective functions, are to reduce energy consumption, costs, and discomfort. Numerous ideal solutions are put up to satisfy the demands of different public and private stakeholders [13]. In real-world building design concerns, including low EC and optimum thermal comfort or minimal EC and construction cost, building designers commonly have to reconcile conflicting design aims. MO is therefore frequently more appropriate than the single-objective approach. Building engineers use their knowledge, experience, and inventiveness to solve problems in the field; these qualities are hard, if not impossible, to translate into automated optimization systems [14]. Building design innovation aimed at improving energy efficiency, cutting CO2 emissions, and lowering life cycle cost (LCC)s has received a lot of attention in many countries in the name of sustainable development. Energy efficiency is crucial for energy-intensive constructions. While identifying the best options without considering all feasible combinations of retrofit interventions, the employment of a multi-objective optimization algorithm in combination with a building simulation can enable the exploration of all practical alternatives [9].

Building systems, building design, building management, and building geometry/orientation are the key areas of optimization for prior building energy performance optimization research. There are many reviews focused on the algorithms, softwares in multi objective optimization for total building energy performance, whereas focused building design and geometry/orientation influences on energy performance analysis through multi objective optimization research are negligible. This review paper focused on the building design especially, space layout related variables along with geometry and orientation and their influence on energy performance, cost, comfort and environmental impact through multi objective optimization strategy. Determining the arrangement of spaces is among the most crucial elements of architectural design. According to Tiantian Du, space layout design variables include function distribution, space volume/shape, interior division, and interior openness [15]. A building space layout refers to the arrangement and positioning of various elements within a structure, such as walls, rooms, corridors, doors, windows, and other architectural features. It's a critical aspect of architectural and interior design that involves planning how the space within a building will be organized to fulfil functional, aesthetic, and practical requirements. The previous study has shown that room layouts, as well as thermal, visual, and acoustical comfort, have a significant influence on energy use for cooling, heating, lighting, as well as ventilation. Changing space layout variables like an envelope, window details, zoning of spaces, etc. proved reductions in the annual final EC in various studies [15]. Optimization of numerous design management approaches such as building space load, occupancy, lighting, and Heating, ventilation, and air conditioning (HVAC) becomes unavoidable for a successful spatial layout on EP [16]. In order to save a substantial amount of time and money when evaluating architectural space layout elements like building orientation, overhang details, shading, window size, glazing, and wall material attributes on building EC, Delgarm, Navid, et al. evaluated the effects of specific architectural features of a standard room on electrical EC in four different climates of Iran [4]. Zhang et al. suggested a modelling-simulation optimization method for constructing free-form buildings using space efficiency and shape coefficient as geometric constraints to maximize solar radiation gain [17]. The process of selecting the best design from a wide range of space layout design options while verifying the energy performance requirements is known as building energy optimization [18]. Building energy performance optimization is a common example of a multi-objective issue. Designers usually address conflicting spatial design considerations simultaneously, such as consumption of energy, thermal comfort, building expense, and so forth [11]. When dealing with MO problems that have multiple contradictory objectives, the common approach is to combine the objectives into a scalar function and solve the resulting single-objective optimization problem [19]. In MO issues, there are two or more competing optimization goals, which means that achieving one goal would compromise the achievement of another [20].

MO can consider multiple factors of performance and has a wide range of applications in the field of building design. Because all variables are considered, 2–3 objectives are typically chosen to optimize the building design. The four main types of objective functions that are typically used in building performance research are energy use, cost, environmental impact and comfort. The efficacy and efficiency of different optimization methods depend on how well they function [21]. Because there are numerous potential solutions for any optimization problem, both the selection of the algorithm and the adjusting of the algorithm parameters may require repeated tries and errors [10]. The algorithms utilized in the multi-objective optimization frameworks includes Non-dominated Sorting Genetic Algorithm II (NSGA-II), Multi-Objective Particle Swarm Optimization (MOPSO), Multi-Objective Genetic Algorithm (MOGA), and Multi-Objective Differential Evolution (MODE). From this review we are able to identify the effective multi objective optimization algorithms in the study of space layout variables on energy performance. This article comparing various frameworks on MO connected to space layout variables on building energy performance. Investigating and contrasting various simulation-based optimization variables and methodologies in the field of building energy performance in relation to space layout parameters, as well as comprehending and analyzing the behaviors of various optimization algorithms in order to solve building performance design issues, are the primary goals of the review [11]. This research paper also aims to identify the interaction between space layout design variables and related functional objectives in the process of the MO method as well as the developments regard to this topic through the review of previous works of literature.

2 Methodology

Depending on the objective and level of execution, many review approaches, such as systematic, semi-systematic, integrative, etc., may be used. A semi-systematic literature review could be an effective strategy when it is impossible to read every article that might be pertinent to the subject at hand [22]. This type of study can be useful for determining the shared issues within a specific research area or methodology [23]. Among the potential contributions are the capacity to map a field of study, summarize the body of knowledge, and provide an agenda for upcoming research on a particular topic [22]. This review study has been conducted on simulation-based MO, building EP, and the cost-effectiveness of space layout and related variables. The search criteria are based on aforesaid topic-related keywords in the Scopus database. The main searched keywords are "multi-objective optimization", "Simulation-based optimization", "Energy performance of the building" and "Architectural space layout". Research published from 2016 to 2023 is considered for the review to investigate the recent trends in the field of MO framework in the study of space layout on building EP. Only journal publications focusing on simulation-based multi-objective optimization framework to examine the effects of space layout-related variables on EP were analysed where conference proceedings, review papers and book chapters were excluded. In this review, as a large volume of candidate papers came out of the initial survey, subsequently, papers got filtered in the areas of access (open), subject type (energy and engineering), year (2016–2023), research type (journals), publication status (final), language (English). Based on the titles and abstract reading some papers discarded by the author for the full paper reading criteria. The final phase was applied to screen the selected works based on fulfilment of various criteria which included the proposed optimization approach on energy, comfort as well as cost performance and the variables should be directly related to space layout along with space boundary, space character. The references of the extra relevant documents are included if they match the selection criteria or to elaborate some information. There is total 46 papers were selected after the full paper review. Ultimately, the following data was taken out of each of the chosen works: the publishing date, the kind of building, the location of the building, the climate, the optimization goals, the parameters of the space layout, the simulation tools, and the optimization tools, as indicated in Table 1 [24]. This study has highlighted new findings in the body of literature and offered possible directions for further investigation.

3 Analysis and discussion

3.1 General details

The optimization problem, the multi-objective optimization strategy, software and algorithms, variables and targeted objectives, the example used to evaluate a model, and the comparison with alternative approaches were all covered in 46 papers that were chosen between 2016 and 2023 [63]. The publication trend from the reviewed articles is shown in Fig. 1.

The majority of the reviewed research was concerned with building optimization, residential buildings accounted for 46% of the case studies examined, while offices made up 22% of the building typology. (Fig. 2). Building optimization frequently involves climate-based modelling, therefore determining the goals and required results of the optimization process can be greatly influenced by the building's location and its climate zone. Asia was the site of a sizable number of investigations, with China being the primary location. According to Fig. 3, the majority of the sites mentioned in the evaluated literature in this survey study, approximately 46% were in China, while Iran coming in second with 24%. It's important to note that research was done on multiple climate zones in the Asian continent.

In this review, researchers tried to optimize multiple functional objectives broadly categorised as energy performance, comfort/environmental and management factors through MO method which appears to be a robust and effective tool to obtain optimal solutions in lesser time with conflicting objective functions using efficient algorithms. The many EP objectives include minimizing EC, energy demand, total building energy load, heating and cooling loads, and maximizing savings. The building design variables segregated as space layout parameters, envelope (space boundary) parameters, functional (space character) parameters which includes services. Variables related to envelope are further divided to design aspects, material property and construction detailing.

3.2 Functional objectives and design variables in multi-objective optimization

The envelop parameters are much studied variable on energy, comfort and cost analysis factor. Tables 2 & 3. shows the studied functional objectives and types of space layout variables through MO framework in reviewed articles.

Table 1 The details of multi-objective optimization framework on energy performance of the building

Author	Year	Location	Case Study	Simulation Model	Climate	Optimization Algorithm	Simulation /optimization engine/tool, Softwares	Objective Function	Design Variables
[25]	2016	IRAN-Tehran, Kerman, Bandar	Office building	Test room	Temperate, warm-dry, warm-humid and cold	MOABC (Multi-objective artificial bee colony), MOPSO	EnergyPlus, jEPlus	EP, PPD (Predicted Percentage of Dissatisfaction), indoor TC	Rotation of the room, window dimensions, cooling/heating setpoint temperatures, wall and glazing material properties
[4]	2016	Iran	Office building	Case study model	Cold, mild, warm-dry, & warm humid	NSGA-II	MATLAB /EnergyPlus	ACL (Annual Cooling Load) ALL (Annual Lighting Load), ED (Energy Demand)	Building orientation, window size, overhang specifications
[26]	2016	Spain-Madrid	Residential building	Actual layout	Other	Harmony Search algorithm	EnergyPlus	ACL, ALL, ED	Shading devices
[27]	2016	Iran	Multi-story building	Single thermal zone test case model	Cold, mild, warm–dry, warm–humid	MOPSO	EnergyPlus	Comfort, ED, TDC, LDC, impact on summer comfort	Building orientation, shading/overhang specifications, window size, wall and glazing material properties
[28]	2016	Italy- Naples	Hospital	Reference /Block model	Mediterranean	Bi/Tri-objective genetic algorithm	MATLAB/EnergyPlus/DB(DesignBuilder)	AEC (Annual Energy Consumption), HL (Heating Load), CL, LL (Lighting Load)	Geometry/shape, envelope details
[29]	2017	Italy-Naples	Residential building	Case/Reference building model	Mediterranean	Mono/Bi-objective genetic algorithm	MATLAB/EnergyPlus	TDC, Cost, operating cost for conditioning of space	Building envelope's thermal characteristics, HVAC
[30]	2017	Italy	Office building	Reference model	Mediterranean	MOGA	MATLAB/EnergyPlus/DB	Global cost savings, EC, discomfort hours, polluting emissions	Envelop parameters
[31]	2017	Argentine Littoral region	Residential building	Typical house	_____	NSGA-II	Energy Plus/Python	Heating/cooling degree-hours ED, HD (Heating Demand), CD (Cooling Demand)	Roof, external/internal wall types, solar orientation, solar absorptance, shading details
[32]	2017	Ankara, Turkey	Other-Library	Computer model	Other	SOGA (Self Organizing Genetic Algorithm), MOGA	EnergyPlus/Open Studio	Building space, layout, EC, DL (Daylighting)	Design constraints / weights, initial building form
[33]	2017	China-Harbin	Residential building	Reference Building	cold	Multi objective evolutionary algorithm	EnergyPlus/Grasshopper, Radiance, and Daysim	DA (Daylighting Autonomy), UDI (Useful Daylight Illuminance), EUI (Energy Use Intensity), TCO (Total Cost)	Building width, roof height, south/ north WWR (Window-To-Wall Ratio), window height, Building orientation
[11]	2017	China, Nanjing	Residential building	Base case model	Hot summers & cold winters	NSGA-II, MOPSO, MOGA, MODE	MATLAB/EnergyPlus	Total Percentage of Cumulative Time with Discomfort (TPMVD), LCC, CO_2,	Conductivity, thermal absorbance, visible absorbance, WWR, azimuth

Table 1 (continued)

Author	Year	Location	Case Study	Simulation Model	Climate	Optimization Algorithm	Simulation /optimization engine/tool, Softwares	Objective Function	Design Variables
[34]	2018	China -Wuhan	Other -two-star green building	Base case model	Hot summer-Cold winter	ANNGA, MLRGA (Multi-Linear Regression Genetic Algorithm)	EnergyPlus/DB	Annual thermal load (ATL), total number of discomfort degree hours	Different concrete /insulation thickness, absorbance of solar radiation for each exterior wall/ roof, WWR for each façade
[35])	2018	25 different places	Residential building	Base case model	25- different climates	NSGA-II	TRNSYS	CD, HD, LCC	External walls, thermal transmittance of roof, ground & glazing, WWR, glazing type
[13]	2019	Italy-Milan	Office building	Case study model	Mediterranean, with mild winters, hot, dry summers	GA	MATLAB/EnergyPlus	EC, GCO (Global Cost), CO_2	Building Geometry, Envelope
[36]	2019	Italy	Residential building	Base model	Mediterranean climate	GA	MATLAB/EnergyPlus	EP, economic benefits, Thermal Comfort (TC)	Window type, building orientation, Set point temperatures, radiative properties of plasters, thermo-physical properties of envelope elements
[37])	2019	Iran-Tehran	Office building	Typical space layout	Hot, arid,	MO	EnergyPlus/ GRASS HOPER, Ladybug Archsim	CD, HD, thermal discomfort time, Operative Temperature (OT)	Shading, building orientation, insulation, internal thermal mass & glass type
[38]	2019	China-Nanjing	Other	Hypothetical room model	Hot summers and cold winters	NSGA-II	MATLAB/EnergyPlus	TEC (Total Energy Consumption), indoor thermal environment, VP (Visual Performance)	WWR, Building orientation, outer glass, filling gas, inner glass of a double-paned window
[39]	2019	China	Other -Tourist centre	Case study	Hot summers & cold winters	NSGA-II	EnergyPlus/Open Studio	Annual Energy Demand (AED), Annual Average Predicted Percentage Dissatisfied (AAPPD)	Window types, shape of the eaves, thermal properties of opaque walls and roofs, thermostat set points
[40]	2019	Canada-Montreal	Institutional building	Case study	———	NSGA-II	EnergyPlus/DB	EC, LCC, LCA (Life Cycle Assessment)	Roof, fenestration, external walls, shading
[41]	2020	USA -Houston, Texas	Residential building	Reference model	Hot humid climate	Ray-tracing algorithm	EnergyPlus/ RADIANCE, Rhino Grasshopper	CL, DL performance during summer season	Geometric configurations of envelopes
[42]	2020	North Argentina	Residential building	Case study	Other	NSGA-II	Python (DEAP)/EnergyPlus	EE (Energy Efficiency), TC	Roof / external & internal wall types, solar orientation, solar absorptance, size/ type of windows, dimension of external window shadings

Table 1 (continued)

Author	Year	Location	Case Study	Simulation Model	Climate	Optimization Algorithm	Simulation /optimization engine/tool, Softwares	Objective Function	Design Variables
[5]	2020	European Countries	Residential building	Case study model	Arid, warm temperate, snow, polar	MOGA, aNSGA-II	Python/EnergyPlus/Open Studio	AED, Construction & Investment Cost (ICO), Annual Energy Operating Costs (AEOCO), Greenhouse Gas Emissions (GHG)	Climate, costs of primary energy sources & carbon intensity
[6]	2020	other	Other	Case study model	Mediterranean climate	aNSGA-II	Python/EnergyPlus/Open Studio	TED (Total Energy Demand), HD, CD	Geometry, passive & active Strategies
[43]	2020	ROME	Residential building	Case study model	Mediterranean climate	aNSGA-II, NSGA-II	Python/EnergyPlus	ICO, ECO (Energy Cost), ED, CO_2 emissions	Insulation thickness, windows type
[44]	2020	Iran	Office building	Case study	Cold semi-arid, Mediterranean, Cold desert, Hot semi-arid, Humid continental Hot desert	NSGA-II	Python/EnergyPlus	AEC, PPD, DGI (Discomfort Glare Index)	Window orientation, shading control strategy & set points, shading location, dimensions, angle, material
[45]	2020	China	Office building	Base case model	Severe cold, cold, hot summer, cold winter, hot summer & warm winter climate	NSGA-II	DB with jEplus + EA	HL, CL, LL, discomfort hours,	Building orientation, window configuration, shading system, window materials, installation angle and depth of overhangs
[46]	2020	Iran	Reference office room			Hypervolume-based evolutionary algorithm (HypE)	Octopus (A Grasshopper plugin)	LL, DL, view to the outside	Window width and height, window sill and head height
[47]	2021	Iran	Residential building	Base case model	Hot and dry	Enhanced Water Strider Optimization Algorithm (EWSOA)	EnergyPlus,	TC, GHG	Insulations for outer wall, roof, floor, airtightness
[48]	2021	Serbia	Residential building	Physical model	Cold	NSGA-II	EnergyPlus/DB	HD, CD, minimum number of discomfort hours	WWR, glazing type, facade wall details, window/facade shading arrangement
[49]	2021	India -Delhi	Other	Case study	Composite climate	NSGA-II	MATLAB	TC, VC (Visual Comfort), AC (Acoustics Comfort)	Total floor area, storey height, the total number of stories, envelope parameters
[50]	2021	China -Nanjing	School	Case study	Subtropical monsoon climate	ANN (Artificial Neural Network), NSGA-II, MOPSO	Python/EnergyPlus	DL, TC, ES (Energy Saving), economy	Thermal conductivity/solar absorptivity/thickness/ material density/specific heat of the wall, WWR, U-Value, Solar Heat Gain Coefficient (SHGC), Visible Transmittance (VT) of an external window

Table 1 (continued)

Author	Year	Location	Case Study	Simulation Model	Climate	Optimization Algorithm	Simulation /optimization engine/tool, Softwares	Objective Function	Design Variables
[51]	2021	Turkey-Osmaniye & Erzurum	Residential building	Reference model	Mediterranean climate	NSGA-II	MATLAB/EnergyPlus/ Open Studio	LCC, low-capacity thermal equipment	Building orientation, external wall material, thermal mass, insulation thickness, glazing types, WWR
[52]	2021	China	School -Primary & Secondary	Simulation model	Sub-Tropical climate	NSGA-II ANN	Python/EnergyPlus	TC, DL, EC	Thermal conductivity/ solar absorptivity / thickness/material density/specific heat of wall, WWR, U-Value, SHGC, VT, height, overhanging depth of exterior window, orientation, cooling setpoint, heating setpoint, air tightness grade
[53]	2021	Jordan	Residential building	Computer model	Cold climate	GA	EnergyPlus/DB	TEC, CD, HD	Site orientation, WWR, types of shading, glazing, window blind infiltration rate, type, flat roof construction, external wall construction, natural ventilation rate, type, window shading control schedule, partition construction
[17]	2021	China, Shenyang,	Other-Exhibition Hall	Reference model	Cold climate	MOGA	Octopus/Grasshopper plug-in,	SR (Solar Radiation), SC (Solar Surface Coefficient0, Space Efficiency	Core space, envelope
[54]	2021	China-Hanzhong	Residential Building	Baseline model	Hot summer & cold winter zone	NSGA-II	EnergyPlus/IDA-IEC, TRNSYS	TEC, IICO	Building orientation, dimensions of south & north windows, wall & roof thickness, insulation material type, window type (U-values & SHGC) & Shading Parameters

Table 1 (continued)

Author	Year	Location	Case Study	Simulation Model	Climate	Optimization Algorithm	Simulation /optimization engine/tool, Softwares	Objective Function	Design Variables
[52]	2021	Southern China	Primary and secondary school classrooms		Subtropical monsoon climate	ANN, NSGA-II	EnergyPlus software	TC, EC, DL	Thermal conductivity/ solar absorptivity/ thickness/ material density/ specific heat of the wall, WWR, U-value /SHGC/VT of the external window, the height and depth of the overhanging, orientation, cooling/ heating setpoint, air tightness grade
[55]	2021	Morocco	Typical house	Simulation model	tropical climate	NSGA-II, MOPSO and MOGA	TRNSYS	ATED, HD, CD, discomfort degree-hours,	Thermal transmission coefficient of external walls/ roof/windows, thermal resistance of floor, solar factor of the glazing
[56]	2021	China-Guangzhou	School	Simulation model	Hot & humid climate	ANN, NSGA-II	Python/EnergyPlus/Rhino Grasshopper, Radiance	TC, VC, TEC	Building orientation, geometry, envelop parameters -windows, shading devices, wall
[57]	2022	Indonesia -Jakarta	Residential Building	Base case model	Continental Temperate, dry-cold, dry-hot, tropical	NSGA-II	Python/TRNSYS	TL (Thermal load), ICO	Building orientation. insulation level of envelope, window detailing for passive cooling, WWR, shading fraction, radiation-based shading control,
[58]	2022	China-Sanya	Office building	Simulation model	Tropical	MOGA	OpenStudio	CL, UDI, PMV (Predicted Mean Vote)	WWR, window height, and louvers
[59]	2022	China	Residential building	Prototypical models	Cold	SPEA-2 algorithm	Rhino-Grasshopper	DL, HL, CL, TC	Northward, westward and southward WWR are 0.10, 0.11, 0.12, transmittance
[60]	2022	Birmingham, UK, Jakarta, Indonesia, Sydney, Australia	Office	Hypothetical room model	Different climates	(HypE)- Hypervolume-based evolutionary algorithm	Octopus (a Grasshopper plugin)	UDI, EC	Orientation/rotation of louvers
[7]	2022	China-Harbin, Beijing, Shanghai, Shenzhen and Kunming	Residential building	Typical layout	Severe Cold, Cold, Hot Summer & Cold Winter, Hot Summer & Warm Winter, Temperate	NSGA-II, ANN	Grasshopper /Honeybee and Ladybug	TED, HD, CD, DI (Daylight Illuminance)	Floor height, total building width, WWR
[61]	2023	Iran -Tehran	Office building	Middle-floor office room	Hot and dry	NSGA-II	Grasshopper plugin Walacei 2.6	TEC, TC, VC	WWR, multi-slat shading depth, angle/distance to the wall, orientation
[62]	2023	Passo Fundo, southern Brazil	Multifamily social housing buildings	Warm temperate climate	Cold region	NSGA-II	python/EnergyPlus	CD, HD	Building orientation/ shape

Many researchers optimized two to five or more five independent variables in more than 70% of studies. There are more than 60 different functional objectives are accounted for in the MO method from the reviewed articles. Several functional objectives are of maximum 7 numbers and a minimum 2 numbers are considered in the reviewed articles. Annual cooling load, heating demand,and annual energy load were studied in more than 10 articles each whereas EC, DL, thermal comfortglobal cost, and investment costs are cited in more than 5 articles each.

Building envelope characteristics as a space perimeter are one of the factors that significantly affect a building's performance, along with space layout variables including how much energy is used for heating, cooling, lighting, and ventilation as well as for environmental factors like thermal comfort, visual and acoustical comfort along with cost factor [64].

The building geometry and orientation along with physical aspects of the building envelope and window details were optimized simultaneously to achieve the optimization of functional objectives (Fig. 4). Building space layout variables like orientation, geometries, number of stories, room configurations, along with space perimeter variables like wall. roof, window and shading configurations, material characteristics as well as functional requirements of the space have been optimised to enhance energy performance parameters like heating, cooling, lighting EC, and comfort parameters and also to discover the mutually beneficial relationship between them via optimization procedures using selected algorithms [13, 51, 54]. Along with energy performance and comfort parameter the cost management which includes LCC, material cost, global cost, and investment cost are also the main functional objectives in many MO research. Lin, Y et al. chose to optimize 19 continuous design variables, with the target functions being thermal load and annual discomfort degree hours. These variables included different concrete and insulation thicknesses, solar radiation absorbance for each exterior wall and roof, and window-to-wall ratios for each façade [34].

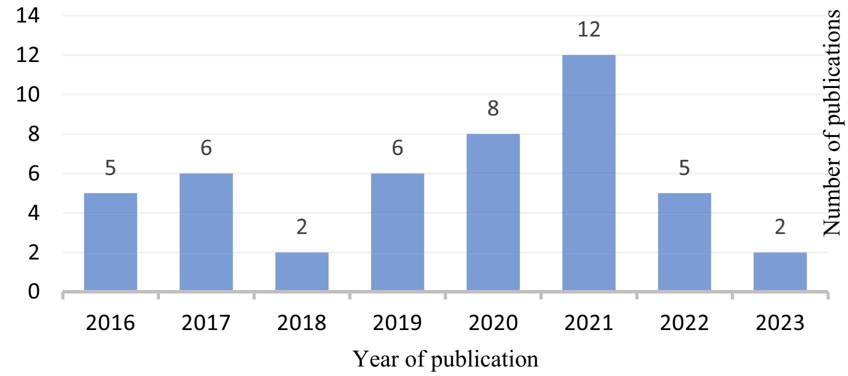
Ascione et al. considered 16 design variables relating to set point temperatures, plaster radiative characteristics, thermo-physical properties of envelope materials, window type, and building orientation of a residential building located in four different climate zones in Italy for a MO to minimize primary EC, energy-related global cost, and discomfort hours [13]. It has been observed that a major portion of an office building's net EC is related to window heat loss and cooling requirements caused by solar radiation, while also reducing lighting EC. Because solar radiation via windows has different impacts on building EC and comfort in the winter and summer, window design is a complex multi-objective challenge[45]. Building position, window, and shading configuration settings, including window materials, installation angle, and depth of overhangs, have all been considered to minimize heating, cooling, lighting EC, and discomfort hours, as well as to discover the mutually beneficial relationship between them via ha optimization procedures using selected algorithms[13, 45, 51, 54]. The annual EC expenses are based on the building's primary energy sources and annual carbon dioxide emissions in the atmosphere [5]. In this context, research aimed at enhancing building EP has stimulated the interest of several researchers from around the world [3]. In general, along with space layout variables the perimeter parameters like window and shading design along with wall construction detailing affect the building energy performance and indoor environmental quality (IEQ) for occupant comfort as well as cost factor [61]. The window, wall and shading material properties which includes U-value, transmittance values, insulation along with their design, orientation, placement with different incremental values are highly optimised to achieve desired energy performance, comfort level and cost management, which also have an impact in reducing environmental emissions.

3.3 Multi-objective optimization algorithms and simulation tools

Optimization approaches for building design are developing as a captivating tool for constructing energy-efficient buildings that meet a variety of goals [26]. Because there are various optimization alternatives accessible for each of the architectural design layout characteristics of the building, and there are many viable design solutions. The search for the ideal design combination is a demanding endeavour that becomes significantly more difficult when many performance criteria must be met. A building simulation optimization strategy is used to find the optimal combination of energy-efficient design elements. It does this by combining building energy simulation models with optimization algorithms to find the ideal parameters for structures that meet a specific set of desired goals. An optimization procedure for a building simulation consists mostly of two elements: building energy models and optimization algorithms. The optimization algorithm looks throughout the architectural space for a design solution that, when combined with the selected set of envelope parameters, will best meet the specified objectives. In contrast, building energy models assess the design solutions' fitness by analysing how the building will behave during its operational phase [49].

The energy simulation model EnergyPlus, DOE-2, TRNSYS, IDA-ICE, and Radiance software are widely applied simulation engines and software packages for optimizing building EP in the review articles. DB, Rhino Grasshopper, and open studio are just a few of the software packages available for building modelling and simulation and also acted as

Fig. 1 Year wise publication trends from reviewed articles



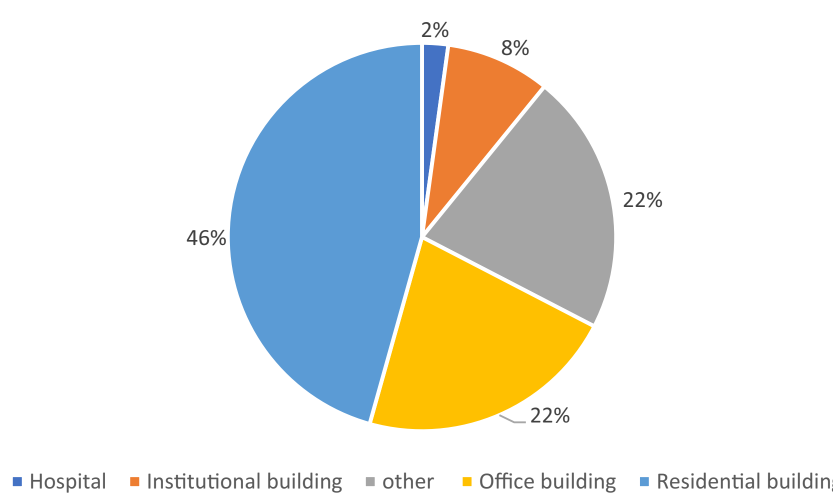
a graphical interface to the EnergyPlus simulation engine. These building simulation softwares helps to generate the energy simulation model based on the optimization targets and variables that have been defined in the studies. The review shows that MATLAB was explored to perform optimization analyses together with TRNSYS, and EnergyPlus software, in 30 studies. MATLAB is the most widely used platform for optimization. It is followed by mathematical optimization, GenOpt, JEPlus, BeOpt, mode FRONTIER, ENEROPT, etc. From the review, more than 10 researchers investigated to conclude that the EnergyPlus SE coupled with the optimization tool MATLAB implied in most algorithms like GA, NSGA-II [4, 11, 38, 42, 51], MOGA [11, 17, 30] MOPSO [11], MODE [11] to optimize the energy and cost-efficient related objective to get the effective results from MO technique. Python and MATLAB were the most used programming languages for developing optimization methods**.**

About 8 researchers used the EnergyPlus simulation engine in conjunction with DB as a visualization tool in this investigation. DB performs far better than other software when it comes to defining building geometry, segmenting thermal zones, and defining pertinent thermophysical property parameters for the building envelope, internal gains, shading overhangs system, lighting management, and HVAC system [45]. Open studio in another software prominently coupled with EnergyPlus which is an open software and comparatively found to be less reliable than DB. Since there is a limitation in the model development of a building in DB software, the rhino Grass hopper gained more popularity among the reviewed articles from past 5 years because of its parametric approach and design flexibility. The highest studies with 8 numbers utilized Rhino Grasshopper and related plugins as optimization software to analyse the energy performance, comfort and cost factors.

The top 4 MO algorithms from the literatures are analysed further to identify their efficiency on functional objectives of energy performance, environmental performance and cost analysis factor. In most of the articles energy performance objectives are studied using NSGA-II and aNSGA-II algorithms where as MOPSO and MOGA used to analyse the environmental performance factors like comfort, emissions etc. (Fig. 5).

According to Jing Zhao et al., the jEplus + EA linked NSGA-II algorithm is a powerful tool for architecture and engineering optimization. Unlike Matlab and Rhinoceros Grasshopper, jEplus + EA does not require designers to create sophisticated optimization engine programs, construct

Fig. 2 Building typology publication trends from reviewed articles



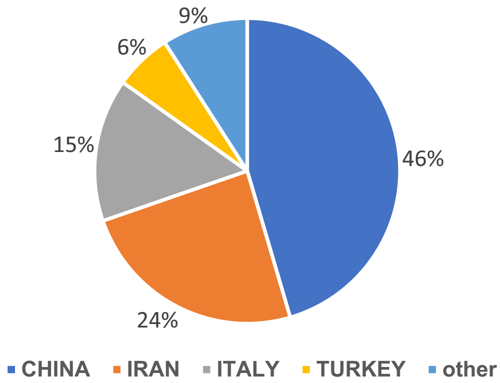


Fig. 3 Location wise publication trends from reviewed articles

complicated mathematical expressions of objectives, or make intricate connections, which is a significant advantage for non-programming designers. Binghui Si et al. used a surrogate model created by the ANN in conjunction with the multi-objective algorithm NSGA-II to increase energy efficiency and indoor thermal comfort in a newly constructed building. To choose the best algorithm for the optimization problem, the performances of four commonly used MO algorithms, namely, NSGA-II, MOPSO were compared using the research performance criteria. The results showed that the effectiveness of NSGA-II is best in all performance aspects, followed by MOPSO, whereas ES and MOGA are not competitive, with MOGA appearing to be sensitive to the parameters of the research [39].

Ascione, F. et al. proposed a multi-stage MO that combined MATLAB with EnergyPlus to consider the HVAC system and thermal characteristics the envelope parameter of a multi-zone residential building in a Mediterranean-climate of Italy. They used mono-objective GA and bi-objective GA to identify the cost-optimal building thermal design in the presence of an enhanced simulation-based model predictive control (MPC) strategy for space heating and cooling operations [29]. He also presented CASA, a multi-stage framework for cost-optimal analysis using MO and artificial neural networks, for the rigorous assessment of cost-optimal energy retrofit in another research [30]. Dino & Üçoluk offered a design to handle building performance challenges while also considering design decisions such as building shape, spatial layout, orientation, and envelope articulation. Genetic optimization is used in two stages by the optimization application Multi-objective Architectural Design Explorer (MADE). In order to maximize the energy and DL performance of the structures, MADE first uses a single objective GA to produce building layouts that meet formal, topological, and placement requirements. Next, it uses a MOGA to calculate the opening sizes of the generated layout or layouts [32]. Ascione, F et al. proposed Harlequin, a three-phase structure related to the implementation of a GA, smart exhaustive sampling, and finding the optimal design solutions to optimize design variables like building geometry, systems and envelope details while considering different energy, comfort, economic, and environmental performance indicators[29]. Delgarm et al. proposed a novel multi-criteria optimization using NSGA-II with the architectural design parameters and their corresponding objective functions, which demonstrated that even though the annual lighting energy demand of an office building increases by 1.0% to 4.8%, the annual cooling load decreases from 55.8% to 22.7%, and the total energy demand decreases 76.4% to 42.2% when compared to the baseline model in the cold climate [4]. Khoroshiltseva et al. used an m-EDO technique that combined Harmony search and Pareto-based procedures to design shading devices with an appropriate shape area of 7.84 m^2, reducing overheating of building space by roughly 20.19% and EC rate [26]. We can find that NSGA-II is the most used algorithm from the maximum

Table 2 Building performance factors and associated functional objectives in reviewed articles

Building performance factors	Functional objectives	Authors
Energy performance	AED, AEC, HL, LL, ATL, CD, CL, EC, ECO, ED, EE, EP, ES, EUI, HD, HL, LL, TEC, TED	[5–7, 13, 17, 25–62]
Comfort environmental performance	AC, AAPPD, CO_2, DI, DL, DA, GHG, ITC, ITE, OT, PMV, PPD, SR, SSC, TC, TDC, TL, UDI, VC, VP, Comfort, Cooling degree-hours, OT, Space efficiency performance during summer season, DGI, Discomfort hours, ED impact on summer comfort, Heating degree-hours, Impact on summer comfort, Lightning discomfort, Minimum number of discomfort hours, Polluting emissions, Thermal discomfort time, Total number of discomfort degree hours, TPMVD over a whole year	[5, 7, 11, 13, 25–27, 29–34, 36–39, 41–45, 47–50, 52–62]
Cost factor	GC, IIC, IC, LCA, LCC, TCO, ECO, AEOCO, Economy, GCO savings, Operating cost for conditioning of space, Construction & installation costs	[5, 6, 13, 29–31, 33, 34, 36, 43, 50–52, 57]

Table 3 Building design variables identified in reviewed articles

Building design variables		Authors
Space layout parameters	Climate, building orientation, building geometry, total floor area, building width, floor height, number of stories, core space, room rotation	[4–7, 13, 17, 25, 27, 28, 32, 33, 36–38, 45, 49, 51, 53, 54, 56, 57, 60–62]
Envelope (Space perimeter) parameters		
Design aspects	Geometric configurations of envelopes. Shading devices -installation angle, depth, dimensions, location, system, shape, control, louvers, Windows -types, WWR, size (height, width), orientation, roof types, external/internal wall types	[4–7, 11, 13, 17, 25–28, 30, 31, 33–45, 47–49, 51–54, 56–59]
Material property	Absorbance of solar radiation for each exterior roof/wall, external wall, shading material, Insulation of envelope, type of insulation, Insulations for floor/roof/outer wall, internal thermal mass, radiative properties of plasters, thermal mass, Thermal properties of roofs/opaque walls, thermal transmittance of roof, thermo-physical properties of envelope, SHGC, VT of exterior window, Wall Material Density, Wall Solar Absorptivity, Wall Specific Heat, Wall Thermal Conductivity, U-Value -wall, window transmittance, window glazing, window materials, window blind infiltration rate, external wall type, glazing material properties, glazing type, internal wall types, overhang specifications, wall/Roof thickness	[5, 7, 11, 13, 17, 25, 27, 29–31, 34–40, 42–45, 48–54, 57, 59]
Construction detailing	External wall types, flat roof construction, glazing material properties, glazing types, overhang specifications, partition construction, thickness of wall, roof, different concrete thicknesses	[4, 5, 7, 17, 27–31, 36, 37, 39, 40, 45, 48, 49, 51–54, 56, 57]
Functional (space character) parameters	Active Strategies, air tightness grade, Carbon intensity, cooling /heating setpoint, HVAC, natural ventilation rate, passive Strategies, thermostat set points	[5–7, 25, 29, 39, 43–45]

number of researchers implementing it along with EnergyPlus and TRYNIS in the framework of MO to investigate the energy, comfort and cost performance of the building towards efficiency leading to more sustainable design [35, 42, 57]. MOGA is the second-highest-used algorithm in the reviewed articles. Ascione et al., in much of their research on MO for EP and cost-optimal analysis coupled the optimization tool MATLAB with the EnergyPlus SE and in a couple of research used DB software as a visualization tool for the study building model [28–30]. There are 4 number of researches highlighted the intervention of Artificial neural network with optimization algorithm NSGA -II to reduce the consumption time of MO to optimize energy demand cost factor along with environmental factors like GHG emission, DL, and CO_2 emission by researchers. When faced with an energy-efficient design optimization problem, the algorithm

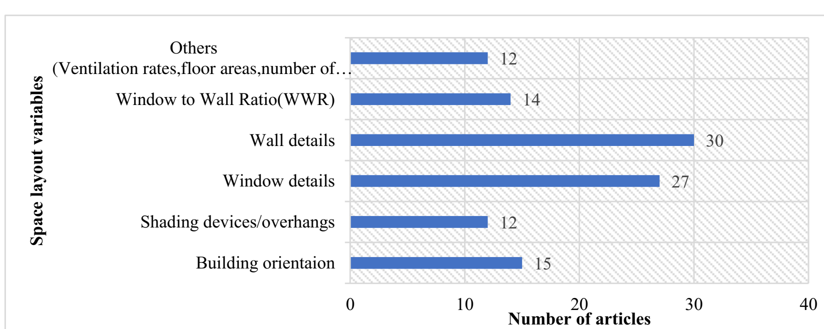


Fig. 4 Major space layout variables considered in the review articles

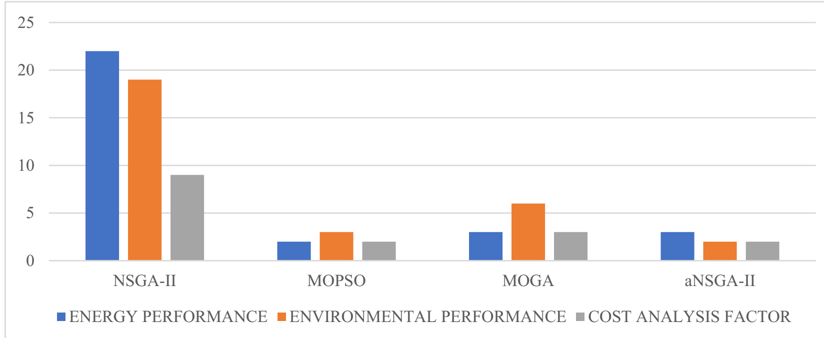


Fig. 5 Analysis of MO algorithms on functional objectives

should be carefully chosen depending on the nature of the problem and the most important performance indicators. The appropriate multi-objective algorithms can be chosen based on their performance characteristics, which include validity, speed, coverage, and locality. European countries in 2020 used the advanced algorithm aNSGA-II in MO along with NSGA-II and MOGA to mainly on energy performance and cost management along with environmental emissions[5, 6, 43]. By using aNSGA-II, it was possible to significantly reduce the computational time and identify the multi-objective optimal solution. This solution was able to maintain an almost 60% lower investment cost compared to other criterion-optimal solutions while reducing annual energy demand by 49.2%, annual energy costs by 48.8%, and annual CO_2 emissions by 45.2% [43].

4 Conclusions

The MO method has seen significant growth in the construction industry over the last 5–6 years. From the review we can observe that there is negligible multi objective optimization research done considering only the space layout design on energy performance study. Most of the studies focused on space perimeter variables in the study of optimization on performance of the buildings. along with space layout variables from the review, wall construction details with 65%, window details with 59%, shading details with 28% and window to all ratios with 22% are investigated. Window design and detailing appears to be complex and significant optimisation task in contribution to building energy performance, DL and occupant comfort especially in buildings like offices, institutions as well as residences. WWR optimization plays a major role in enhancing energy performance and user comfort in any buildings along with cost effective strategies as per the researchers. The building orientation also played another important variable in the building energy optimization process with 31% of reviewed studies. Based on a study of the optimization targets, 3 separate categories could be identified, with the majority of the examined research focusing on energy-related objectives as opposed to cost analysis factors and environmental performances. Material characteristics as well as properties to be optimised along with spatial configuration or design to get effective energy performance, occupant comfort in the building along with cost effectiveness. The cooling load was found to be a main functional objective in many reviewed articles which is addressed by considering perimeter parameters as effective variables in the MO framework. The thermal comfort were the next highest studied functional objectives through MO method. NSGA-II identified the most popular algorithms among 50% of researchers, of which 85% are used in conjunction with EnergyPlus in the MO framework to study the energy, environmental and cost performance due to its good quality solutions and diversity preserving mechanism, which give users more flexibility to estimate their preferences with diverse objectives and variables. To handle computational obstacles as well as raise energy-related issues to building design, an integrated strategy for optimizing both spatial layout and building performance is important. There has been a lot of work done on building algorithms and software to improve the art of establishing energy-efficient designs that contribute to sustainable architecture. The architects and designers can contribute significantly in optimization to minimize building EC and cost in their design in adaption to local restrictions, usage needs, investment scale, etc. Since most of the studies focused on residential, office and educational buildings, there should be greater research into complex structures like hospitals, which have a wide range of functional requirements as well as occupant comfort levels including specialized design aims. Very few studies have examined hospital design typologies in terms of simulation-based multi-objective optimization, considering comfort, cost, and spatial arrangement in relation to energy performance. For healthcare buildings, good energy planning and management based on the principles of energy efficiency and cost-effectiveness is required, without neglecting functional needs or architectural flexibility. There is a need for an effective multi-objective framework to improve the EP of healthcare facilities, which currently consume more energy than other building typologies.

Author contributions Harshalatha -Wrote main manuscript text, Conceptualization, Analysis and Writing—original draft preparation.

Shantharam Patil—Resources, overall supervision, Writing—Review and editing the manuscript.

Pradeep G Kini—Resources, Supervision- Review and editing the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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