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Optimal design of energy conversion units and envelopes for residential building retrofits using a comprehensive MILP model

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HIGHLIGHTS

- Development of a building energy model suitable for MILP.
- Verification according to ASHRAE standard and more detailed models.
- Application to retrofitting of a residential building.
- Energy system modifications appear more cost effective than envelope retrofits.

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ABSTRACT

The optimal design of buildings is a complex task involving energy systems as well as construction measures. Typically, in exact optimization models, only energy systems are considered, whereas envelope components are neglected. When considering both, heuristics are commonly used, which do not guarantee optimal or close to optimal results.

Thus, this paper presents the governing equations, validation and exemplary usage of a building model suitable for exact optimization problems. The developed model simultaneously considers energy systems and building envelopes. It is based on ISO 13790 and validated according to ASHRAE 140 and further compared to a more detailed model. The findings show that the developed model largely complies with the ASHRAE requirements and is able to assess buildings' dynamic behavior regarding indoor air temperatures as well as hourly, peak load, and annual heating loads.

The simultaneous optimization of energy system and envelope is further demonstrated analyzing retrofitting options of a residential building. We consider solely installing additional PV units, modernizing the building envelope according to German regulations and an optimization without constraints regarding building envelope and energy system. The results indicate that installing additional PV units can moderately reduce total costs and CO_2 emissions. The envelope modernization according to governmental regulations leads to largely increased costs at lower emissions, whereas the unconstrained optimization is able to simultaneously achieve significant cost and CO_2 emission advantages.

1. Introduction

The transition towards a more energy efficient and environmentally friendly economy is a recognized objective of the European Union [1]. In Germany, this concept is known as "Energiewende" and aims at reducing greenhouse gas emissions, increasing electricity generation from renewable energy sources (RES) and achieving higher energy efficiency in general [2]. In the context of buildings, which account for approximately 40% of total energy consumption in the European Union [1], emission reductions and energy savings can for example be achieved by increasing envelope insulation as well as by installing more efficient heating devices and by improving their control strategy.

The optimal design of buildings and building energy systems (BES) can therefore make a significant contribution towards meeting these goals. However, determining such an optimal design is a complex problem that involves buildings' electricity and heat consumption as well as generation and storage devices. According to Kaklauskas et al. [3], this problem is further complicated by the interrelationship between BES and heat consumption, which is among other factors influenced by passive construction measures.

So far, many studies have addressed specific parts of this problem with different approaches. The optimal design of building

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Nomenclature

Variables and parameters

Symbol	meaning [unit]
A	area [m^2]
C	capacitance [kW h/K]
E	energy content [kW h]
F	form and correction factor [–]
H	heat transfer coefficient [W/K]
I	solar irradiation [kW]
P	electrical power [kW]
R	heat resistance [(m^2 K)/W]
Rv	residual value [–]
U	thermal transmittance [W/(m^2 K)]
V	volume [m^3]
a	capital recovery factor [–]
b	adjustment factor [–]
c	costs [Euro]
e	emissions [kg]
f	fixed parameters [–]
g	solar energy transmittance [–]
h	area specific heat transfer coefficient [W/(m^2 K)]
inv	specific investment costs [Euro/m^2]
n	air exchange rate [h^{-1}]
p	linearized product [–]
q	airflow rate [m^3/h^{-1}]
Δt	time interval length [h]
w	weight for each typical period [–]
x	(binary) decision of purchase [–]
z	(binary) building class [–]

Greek letters

α	absorption coefficient [–]
θ	temperature [°C]
κ	heat capacity [J/(kg K)]
ρ	density [kg/m^3]
φ	storage's loss factor [–]
ϕ	heat flow rate [kW]

Subscripts and abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAT	battery
BES	building energy system
CHP	combined heat and power
COP	Coefficient of Performance
DHL	design heat load
EH	Electrical resistance Heater
EnEV	German Energy Saving Ordinance
HC	heating and cooling
HP	heat pump
ISO	International Organization for Standardization
MILP	mixed-integer linear program
PV	photovoltaic
RES	Renewable Energy System
STC	solar thermal collector
TES	thermal energy storage
VDI	Association of German Engineers
S	set of available types
cl	building class
e	environment
d	demand
f	floor
g	generator
int	internal
inv	investment
j	component
lb	lower bound
m	thermal mass
op	opaque
p	typical period (month)
s	surface
sol	solar
t	time step
tr	transmission
ub	upper bound
ve	ventilation
w	windows

envelopes for example is often investigated by coupling building simulation software with heuristic optimization methods. The TRNSYS[1] simulation software has for example been used by Chantrelle et al. [4] in combination with a Genetic Algorithm [5]. EnergyPlus[2] for instance has been used by Echenagucia et al. [6] together with a multi-objective Genetic Algorithm, named NSGA-II [7]. Lin et al. [8] coupled EnergyPlus with Tabu Search [9,10]. However, Negendahl and Nielsen [11] argue that for early stages of energy optimization, the aforementioned building simulation software might be too time consuming regarding the parameterization and calculation. Therefore, they propose a combination of the simplified, hourly building simulation method described in ISO 13790 and a Genetic Algorithm. All these studies conclude that optimal building envelope configurations significantly reduce the energy demand of heating, cooling and air-conditioning systems.

Most studies solely focusing on BES use exact optimization algorithms such as mixed-integer linear programming (MILP) [12]. MILP models have been developed for solving operation optimization of BES [13,14], the combined optimal design and operation of BES [15–18] and even city district applications [19–22]. In these works, buildings' thermal demands are considered as fixed time series that are computed before the optimization and only present parameters within the optimization.

Relatively few studies have attempted to treat both, BES and envelope. Ashouri et al. [23] include a low-order building model into the design and operation optimization of BES. This model is able to consider building's thermal mass as additional storage option for the BES components' operation, hereby enabling economic advantages by increasing building temperature during periods with low tariffs or high solar availability. However, since this low-order model uses constant parameters that are computed before the optimization is executed, building envelope optimizations cannot be conducted. Asadi et al. [24] implement a static model based on ISO 13790 to determine optimal building envelopes for retrofit purposes. They consider windows, external wall insulation, roofs and solar collectors but their calculations are based on annual demands, therefore neglecting the BES components' operation and buildings' heat capacity. Stadler et al. [25] develop a dynamic MILP approach to simultaneously determine

[1] http://www.trnsys.com/.
[2] https://energyplus.net/.