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Optimizing tradeoffs among housing sustainability objectives

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ABSTRACT

The sustainability of housing units can be improved by integrating green building equipment and systems such as energy-efficient HVAC systems, building envelopes, water heaters, appliances, and water-efficient fixtures. The use of these green building measures often improves the environmental and social performances of housing units; however they can increase their initial cost and life cycle cost. This paper presents a multi-objective optimization model that is capable of optimizing housing design and construction decisions in order to generate optimal/near-optimal tradeoffs among the three sustainability objectives of maximizing the operational environmental performance of housing units, maximizing the social quality of life for their residents, and minimizing their life cycle cost. The model is designed as a multi-objective genetic algorithm to provide the capability of optimizing multiple housing objectives and criteria that include minimizing carbon footprint and water usage during housing operational phase, maximizing thermal comfort, enhancing indoor air and lighting quality, improving neighborhood quality, and minimizing life cycle cost. An application example is analyzed to illustrate the use of the developed model and evaluate its performance. The results of this analysis illustrate the novel capabilities of the model in generating 210 near-optimal tradeoff solutions for the analyzed housing example, where each represents an optimal/near-optimal and unique tradeoff among the aforementioned three sustainability optimization objectives of maximizing the operational environmental performance of housing units, maximizing the social quality of life for their residents, and minimizing their life cycle cost. These novel capabilities of the developed model are expected to improve the design and construction of housing units and maximize their overall sustainability.

1. Introduction

The overall sustainability of housing units can be maximized by optimizing their environmental, social, and economic performances [66]. This can be achieved by integrating a number of green building equipment and systems in the design and construction of housing units such as geothermal heat pumps and water-efficient faucets. While the use of these green measures can improve the environmental and/or social performances of housing units, they often lead to an increase in the initial cost of housing units and their life cycle cost. Accordingly, decision makers in the housing industry need to optimize housing design and construction decisions in order to strike an optimal/near-optimal balance among the conflicting objectives of maximizing housing operational environmental performance, maximizing social quality of life for its residents, and minimizing its life cycle cost.

A number of research studies have been conducted to investigate and improve the environmental, social, and economic performances of residential buildings. Several research studies focused on maximizing the operational environmental performance of buildings by optimizing their (i) building envelope variables such as window glazing type, wall-to-window ratio, exterior wall type, roof type, and foundation systems [2,12,28,40,62,69,71]; (ii) HVAC systems [17,29,43]; (iii) building envelope and HVAC systems [7,9,27,31,44,74]; and (iv) building envelope, HVAC systems, lighting fixtures, and appliances [13,33].

Other studies studied focused on providing better social-quality of life for housing residents. These studies focused on improving the thermal comfort for the residents [45,51,60], daylighting quality in housing units [34,42,46], indoor air quality [10,41,57], and the level of services and amenities in housing neighborhoods [23,50,65]. Other related studies developed multi-objective optimization models for optimizing the design of the building envelope (e.g., window types and sizes) and HVAC systems (e.g., heating and cooling set points) in order to maximize housing indoor thermal comfort conditions and minimize its annual energy cost and energy usage [7,44,72].

Despite the significant contributions of the aforementioned studies, there is no study that (1) provides a comprehensive set of metrics for quantifying the collective impact of housing design and construction decisions on the overall sustainability of housing units that considers housing operational environmental performance, social quality-of-life for

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the residents, and life-cycle cost of the housing unit; and (2) optimizes housing design and construction decisions to generate optimal/near-optimal tradeoffs among the operational environmental performance, social quality of life, and life cycle cost of housing units. To address this critical research gap, this study focus on developing a sustainability model for single-family housing units that represent 66% of the residential housing inventory in the US [63].

2. Objective

The objective of this paper is to develop a novel multi-objective optimization model that is capable of simultaneously maximizing the operational environmental performance (ENV) of single-family housing units, maximizing the social quality of life (SQOL) for their residents, and minimizing their life cycle cost (LCC). The model is developed in the three stages: (1) model formulation stage that identifies all relevant criteria, metrics, decision variables, objective functions, and constraints; (2) model implementation stage that performs the optimization computations using multi-objective genetic algorithms, and (3) model evaluation stage that analyzes and refines the performance of the developed model using a single-family housing unit application example. The following sections of the paper provide a brief description of these three phases of the model development.

3. Model formulation

This stage of model development is formulated in four steps: (1) identifying all model criteria and their relevant metrics; (2) defining the model decision variables; (3) formulating the optimization of objective functions; and (4) identifying model constraints.

3.1. Model criteria and metrics

This section presents the development of a comprehensive and practical set of sustainability criteria and metrics in order to quantify and evaluate the impact of single-family housing design and construction decisions on the three objectives of the model. This was accomplished in two steps that focused on (1) identifying all related criteria and metrics that were reported in the latest research studies on housing operational environmental performance (ENV), social quality of life (SQOL), and life cycle cost (LCC); and (2) developing a comprehensive and practical set of criteria and metrics, as shown Table 1. This set is identified to ensure that each selected metric is simple, measurable using a quantitative value or a qualitative expression, independent of other metrics, and can be easily understood and evaluated by decision-makers [5,36,58,68].

3.2. Decision variables

The model incorporates a total of thirty-three decision variables, as shown in Table 2. Each of these decision variables represents a possible selection from a set of feasible alternatives, as shown in Fig. 1. The identified list of decision variables represents housing design and construction decisions that have an impact on the aforementioned three objectives of the model and their metrics, and it covers the possible selection of the HVAC system, building envelope, lighting fixtures, appliances, water fixtures, occupant control, US Environmental Protection Agency (EPA) recommended air quality control, mechanical ventilation rate, and neighborhood quality as shown in Table 2.

3.3. Objective functions

The present model integrates three objective functions to maximize the operational environmental performance of single-family housing units, maximize the social quality of life for their residents, and minimize their life cycle cost.

3.3.1. Maximizing operational environmental performance

Residential units in the United States account for 18% of greenhouse gas emission, and 58% of public-supply water use [21,38,64]. These environmental challenges can be overcome by providing energy and water efficient design and construction decisions [19,39,62,69]. Accordingly, the first objective function in the model (see Eq. (1)) is designed to quantify and maximize the operational environmental performance of a single-family housing unit that represents the collective performance of the housing unit in the identified two operational environmental performance criteria: carbon footprint index (CFI), and water usage index (WTI). The objective function of ENV and its two criteria of CFI and WTI are calculated using multi-attribute utility theory (MAUT) to eliminate the impact of varying units and enable an

Table 1
Model criteria and metrics.

Objectives	Criteria	Metrics	Research studies
1. Operational environmental performance (ENV)	1.1 Carbon footprint index (CFI)	cf_1: Total amount of greenhouse gas (GHG) emissions caused by energy consumption of the housing unit and expressed in CO_2 equivalent emissions (CO_2e)	[20,73]
	1.2 Water usage index (WTI)	wt_1: Total amount of housing water consumption (US gal)	[67]
2. Social quality of life (SQOL)	2.1 Thermal comfort index (TCI)	tc_1: Predicted percentage of dissatisfied (PPD) index (%)	[26]
	2.2 Indoor lighting quality index (LQI)	lq_1: Annual average daylighting illuminance level (Lux)	[42]
		lq_2: Total hours exceeding glare comfort level in a year (hours)	[8,70]
	2.3 Indoor air quality index (AQI)	aq_1: Points achieved by performing the EPA recommended air quality control decisions	[24]
		aq_2: Percentage of dissatisfied people (PD) from indoor air quality caused by ventilation rate (%)	[3,25]
	2.4 Neighborhood quality index (NQI)	nq_1: Education level (%)	[1,11,14,48,59]
		nq_2: Safety level (%)	
		nq_3: Health conditions (%)	
		nq_4: Level of service and amenities (%)	
		nq_5: Economic conditions (%)	
		nq_6: Environmental conditions (%)	
3. Life cycle cost (LCC)	3.1 Life-cycle cost (LCC)	lc_1: Initial investment cost (US $)	[30,54]
		lc_2: Operation and maintenance costs (US $)	
		lc_3: Energy and utility costs (US $)	
		lc_4: Capital replacement cost (US $)	
		lc_5: Residual value (US $)	