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Multiobjective optimization using nondominated sorting genetic algorithm-II for allocation of energy conservation and renewable energy facilities in a campus

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ABSTRACT

For energy conservation and CO_2 emission reduction, renewable energy facilities, such as solar equipments and rooftop gardens, are considered effective for energy management of institutional buildings in a community. This study integrated an energy mixture facility model with a nondominated sorting genetic algorithm-II optimizer as a multiobjective optimal facility allocation model (MOFAM) for allocating renewable energy facilities on the rooftop of campus buildings.

A case study was conducted on a college campus to demonstrate the feasibility of MOFAM. MOFAM offers simple steps and provides more allocation plans to satisfy decision-makers' requirements for minimum investment cost, maximum CO_2 reduction, and maximum investment returns. In addition, the result demonstrates that the multiobjective optimal model considering three objectives resulted in optimal solutions that include the optimal solutions generated from two-objective optimization. In this campus case, MOFAM helped decision-makers optimize the installation area of solar photovoltaic panels, the installation area of solar water heaters, and the area of rooftop gardens on campus rooftops to perform effective management for institutional buildings for conserving energy and CO_2 reduction.

1. Introduction

In Taiwan, approximately 97% of energy is supplied by imported fuels [1]. Especially in central Taiwan, a coal-burning power plant provides most electricity for central urban and emits more than 37 million tons of CO_2 into the atmosphere each year so to be one of the power plants with the highest CO_2 emission in the world [2]. Therefore, the design of low-energy green buildings has been attracting increasing attention, and reducing the electricity consumption could be the effective and direct method to reduce the CO_2 emission in central Taiwan [3]. Since buildings are major energy consumers [4,5], Keoleian et al. calculated life cycle energy and CO_2 emissions of a standard house and an energy efficient house for improving CO_2 reduction of family house [6]. Literature reported that the linkage between building design, energy use and CO_2 emissions is dependent on climate and sociodemographic characteristics [7]. Campuses can be viewed as small communities due to their size, users and mixed complex activities, constructing campus buildings with low energy consumption can significantly reduce energy demand and CO_2 emission in an institution. For example, the introduction of rooftop gardens can reduce the annual energy consumption of buildings [8] and has the effect of CO_2 sequestration and reduction [9]. The use of solar photovoltaic panel facility and solar water heaters as an energy conservation measure in building is increasingly becoming widespread [10,11] . Therefore, Ho et al. systematically constructed an energy conservation and renewable energy structure optimization model for a campus [12].

However, planning a renewable energy and energy conservation system is very complicated duo to involving the effective distribution of limited resources multiobjective optimization [12]. Studies on optimal countermeasures for reducing CO_2 emphasized multiple objectives pertaining to economy, energy, and environment, as well as the interactions and constraints [13–15]. In such multiob-

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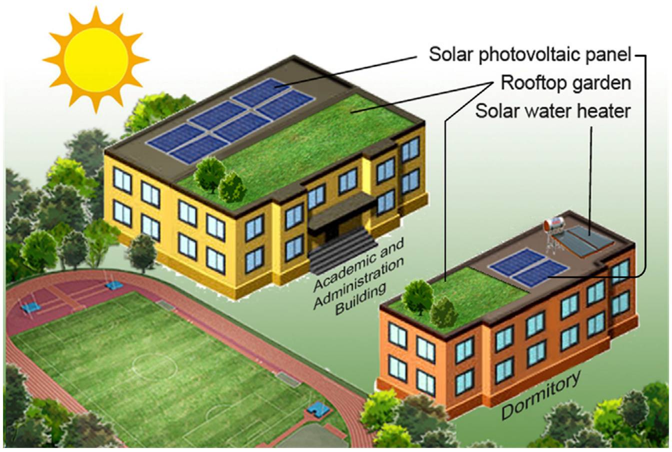

Fig. 1. Conceptual illustration and components of the MOFAM.

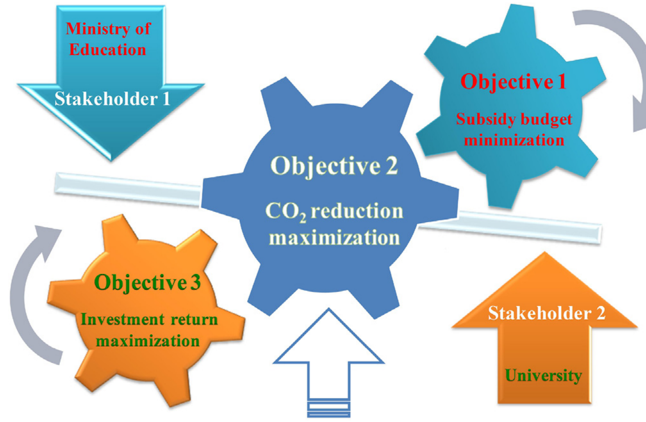

Fig. 2. Relationship among three objectives.

jective problems, decision-makers may consider the direct cost and indirect environmental impact of tasks as objectives, such as CO_2 reduction. However, often, there is conflict among such objectives [16]. In some practical problems involving multiple stakeholders and functionalities, it is also desirable to include as many objectives as possible and a decision-maker is required to maximize/minimize many-objectives simultaneously [17,18]. For example, Chantrelle et al. considered four objectives, including energy consumption, thermal comfort, cost, and CO_2 discharge, through nondominated sorting genetic algorithm-II (NSGA-II) to optimize the renovation of buildings [19]. Evins et al. employed the NSGA-II to optimize the cost and energy use of a modular building [20]. Multi-objective optimization should be a better method to evaluate the performance of zero energy building comprehensively [21], because it can provide many options [22]. The design variables of a design optimization in buildings usually describe the construction and the geometry of the building [23]. For example, Adamski optimized the shape of the building for getting minimum construction cost and minimum heating energy [24]. Diakaki et al. design optimally wall and window insulation of building to minimize simultaneously construction cost and energy consumptions [25]. Chantrelle et al. analyzed renovation options to optimize cost, energy use and comfort by varying constructions and control options [19]. Gange and Andersen design optimally facade element construction, geometry and shading of building for maximizing illuminance and minimizing glare [26]. Malatji et al. retrofitted optimally the facilities of building, and maximized the energy savings and minimized the payback period for a given fixed initial investment [15].

In common, two approaches can resolve multiobjective optimization problems, including preference-based procedure (or classical methods) and ideal procedure [27,28]. The preference-based procedure attempts to scalarize multiple objectives to find a set of Pareto solutions, when objectives satisfies an axiom on additivity property [28,29]. For example, Ren et al. used a constraint and weight method to optimize the operation strategy of a distributed energy resource system installed in a campus and minimize the energy cost and CO_2 emissions [30]. Karmellos et al. combined a mixed-integer non-linear program with weight method to minimize the primary energy consumption of building and the initial investment cost of building [31]. However, the weight method can only provide one optimal solution for certain weights [15,32]. When a large number of nondominated solutions are required for multiple conflicting objectives, such as improving building energy efficiency [33], ideal procedure metaheuristic multiobjective algorithms, such as NSGA-II, multi-objective evolutionary algorithms (MOEA), hybrid differential evolution algorithms (HDE), multiobjective particle swarm optimization (MOPSO), and multiobjective neighborhood field optimization algorithm (MONFO), offer higher performance rather than the preference-based procedure [34]. Kämpf and Robinson used the HDE to optimize building form for solar energy utilization [35]. An extended MOPSO was utilized to optimize the energy and comfort management in building automation and control [36]. A revised MOPSO algorithm was also applied to search for the tradeoff between life cycle costs and life cycle carbon emissions of building designs [37]. Several researches used NSGA-II to optimize energy performance of buildings and indoor thermal comfort [38,39]. Chantrelle et al. developed a multicriteria tool for the optimization of renovation operations, with an emphasis on building envelopes, heating and cooling loads and control strategies [19]. Hamdy et al. applied a modified genetic algorithm (GA) to get tradeoff solution of carbon dioxide equivalent emissions and the investment cost for a two-storey house and its heating, ventilation and air conditioning system [40]. Yang et al. used NSGA-II to optimize office building envelope design [41]. A steady ε-state evolutionary algorithm was combined with a multi-criterion decision making technique to support decision-makers in the process of designing hybrid energy systems [42]. The MONFO was utilized to find optimal retrofit strategies with conflicted objectives. If a single solution is preferred, analytic hierarchy process could be used to judge the best alternative in Pareto solutions [43]. Dufo-López and Bernal–Agustín employed the MOEA on a triple multi-objective design problem of solar photovoltaic panel–wind– diesel–hydrogen–battery system by minimizing three objectives, including cost, CO_2 emissions, and unmet load. [44]. NSGA-II is an improved MOEA and used to optimize the cost and energy consumption of a modular building [20], and sewerage rehabilitation planning [5]. However, Fallah-Mehdipour et al. reported that the capability of NSGA-II is superior to that of the MOPSO procedure in determining optimal alternatives for time-cost tradeoff (two-objective problems) and time-cost-quality tradeoff (three-objective problems) [45]; Brownlee et al. compared the performance of five multiobjective algorithms along with random search in solving a multi-objective building window placement problem, and NSGA-II was found to perform the best [45]. In summary, the NSGA-II is the most popular algorithm for multi-objective building design optimization between cost and various benefit objectives, such as reducing energy consumption and CO_2 emission [23].

In addition to economical consideration, CO_2 reduction is found as one important objective in building related-design optimization problems nowadays [23], especially for central Taiwan where electricity is supplied by a coal-burning power plant with huge CO_2 emission. To promote energy conservation and CO_2 reduction, Taiwan Ministry of Education plans to substantially reduce electricity subsidies in college campuses from 2016, and Taiwan Ministry of

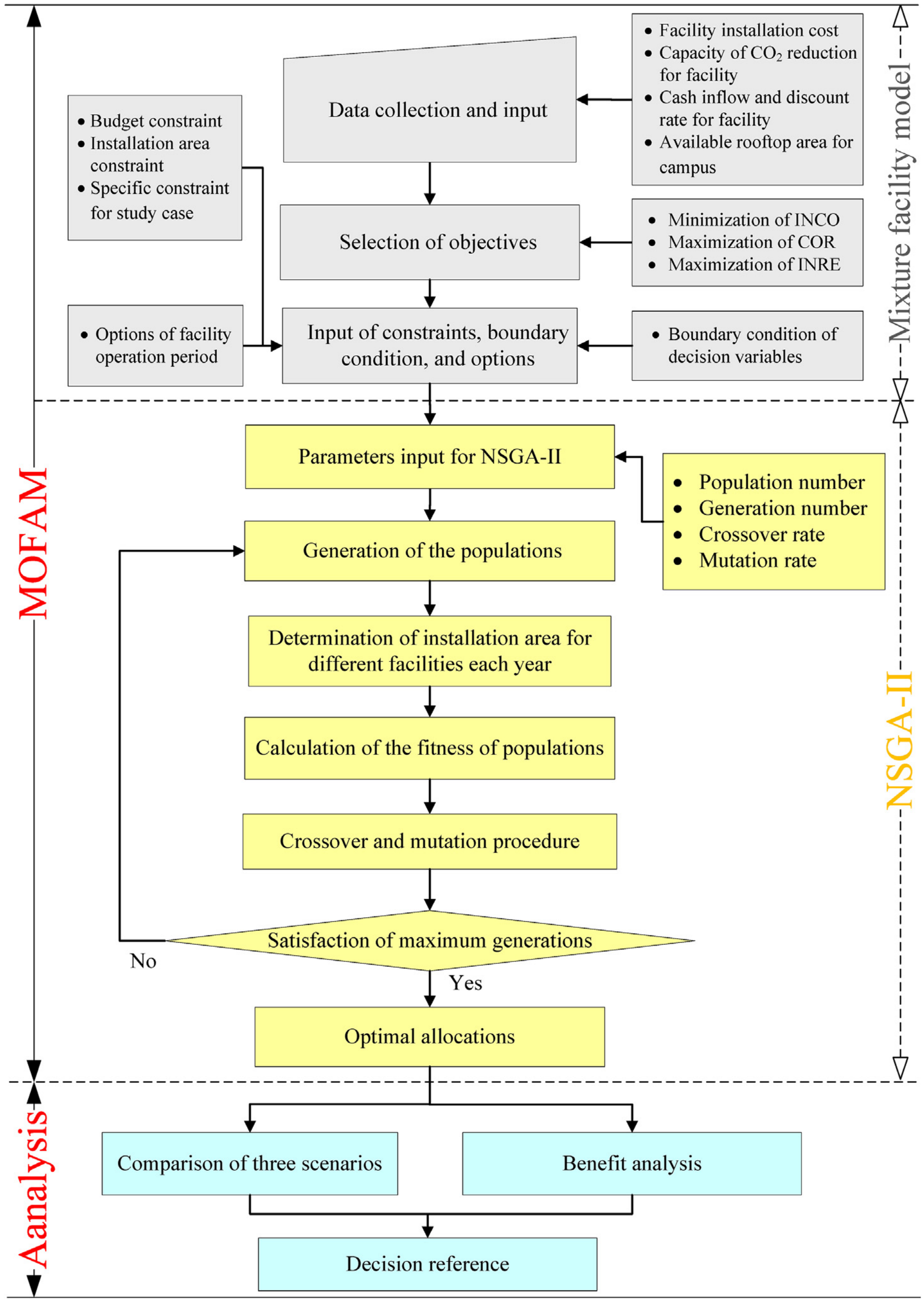

Fig. 3. Flowchart of this study.

Economic Affairs and Education both encourages and subsidies the energy conservation facility installation and operation. To design and operate sustainable institutional buildings, it is necessary to remodel the existing buildings for the purpose of energy conservation and renewable energy with the least disrupting effect on normal life. One feasible way is to install renewable energy facilities and improve the energy efficiency for the existing buildings in college campuses. Hence, this study is aimed at developing multiobjective optimal energy conservation and renewable energy mixture facility allocation model (MOFAM) for allocating renewable energy facilities in a campus. First, an energy mixture facility (energy conservation and renewable energy facility) model was built based on the previous study of Ho et al., and combined with the NSGA-II optimizer to form the MOFAM. The MOFAM was used to optimize the energy mixture facility allocation on the rooftop of building and obtain trade-off solutions for two or three conflicting objectives, namely minimizing investment cost of facility installation (*INCO*) and maximizing CO_2 reduction (*COR*) and investment returns (*INRE*). MOFAM was validated by a case study of a college campus, and benefit analysis was performed for three scenarios and preliminarily brings out the importance of considering different objectives by comparison of three scenarios. Furthermore, a sensitivity analysis was also performed to show the robustness of NSGA-II.

2. Methodology

2.1. Development of MOFAM

An energy subsidy project was initiated by Taiwan Ministry of Education to promote the installation of energy conservation and renewable energy facilities in college campuses. Universities

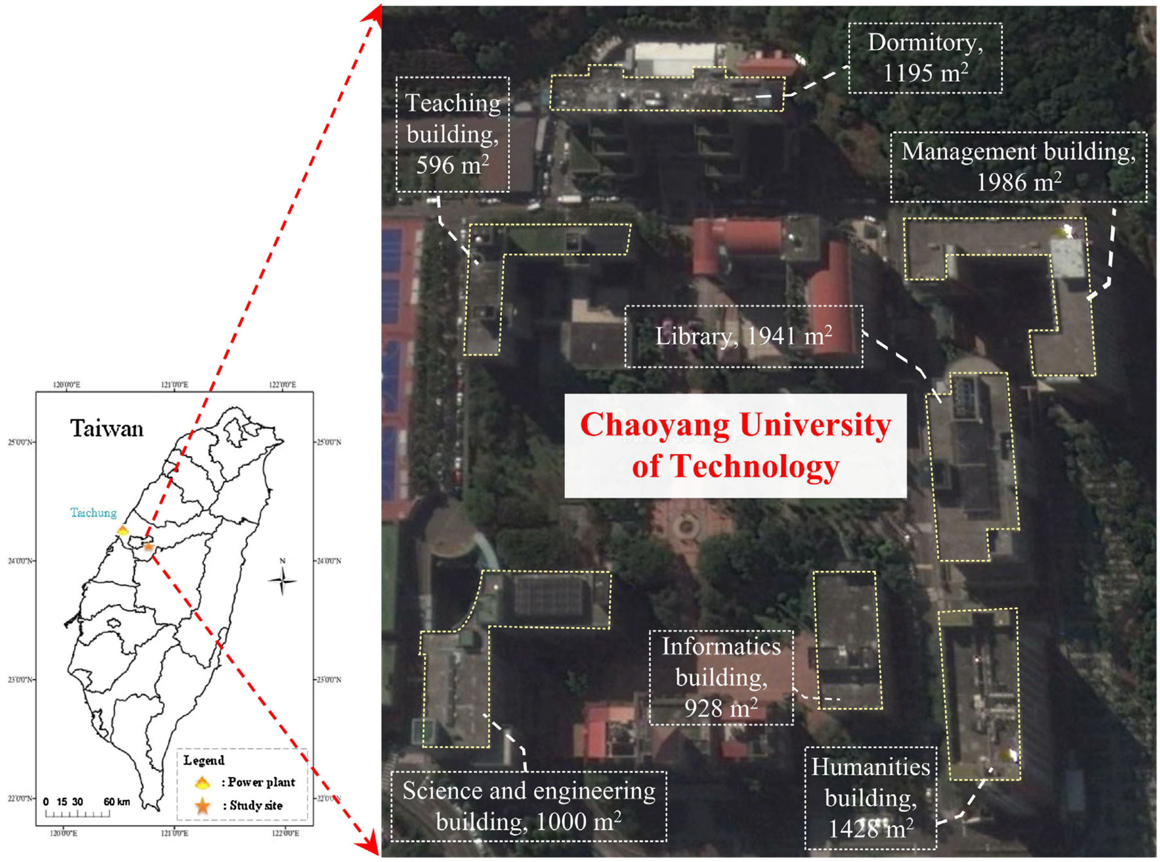

Fig. 4. Study site and available rooftop area of the campus buildings.

were encouraged to propose an optimized facility allocation plan to the Ministry of Education who has right to evaluate plans and grant applicant subsidy. In this case, both universities and the Ministry of Education are stakeholders playing roles of decision-makers and can settle an optimized energy project cooperatively based on the optimal solutions provided by the MOFAM. Fig. 1 presents a schematic of the MOFAM. Energy conservation and renewable energy facilities can comprise a rooftop garden, solar photovoltaic panel, and solar water heater; the installation area of these facilities is decision variables in the MOFAM. The objectives in the MOFAM were functions of facility installation areas. Compared with *INCO*, *COR* is associated with environmental impact and is hard to be quantified by currency; in other words, the objectives in the MOFAM can be set as a function of a quantifiable direct or indirect cost. To perform a science-based evaluation of *INCO* and *INRE*, present value (PV) and net present value (NPV) were used to analyze the cost benefit of these facilities installation.

The relationship between three objectives is shown in Fig. 2. Two stakeholders considered their individual objectives and one cooperative objective. The university considered the investment return and CO_2 reduction maximization after facilitation installation, and the investment return was derived from the saving of electricity expense and subsidy of electricity generated by solar photovoltaic panel. The Ministry of Education funded an energy conservation facility installation project for universities and expected the minimization of facility installation cost (*INCO*). From the aspects of two stakeholders, three scenarios were compared to show the advantage of the multiobjective optimal facility allocation model. Scenario I is designed from the aspect of the Ministry of Education who tends to obtain optimized allocations between minimum investment cost and maximum CO_2 reduction. The university tends to optimize allocation by considering investment returns and CO_2 reduction in scenario II. In scenario III, three objectives, including minimizing *INCO* and maximizing *COR* and *INRE*, was optimized to satisfy the requests from the Ministry of Education and the university that gives a whole picture of optimization solution distribution. Preferences of decision-makers, such as short construction period, special request for specific building, and diverse energy facility, possibly affect annual facility construction. The area occupied by each type of renewable energy facility must not exceed the available area on the rooftops of campus buildings. In addition, the finalized subsidy possibly limits the facility installation area each year, and energy generated by solar water heater is required for providing hot water to students residing in dormitories for bath.

The flowchart of this study shown in Fig. 3 includes the MOFAM implementation and result analysis. The MOFAM comprises the mixture facility model and NSGA-II. In the mixture facility model, the objectives are selected base on the consideration of stakeholders, and the preferences of stakeholders are expressed in constraints and boundary conditions. Once parameters in NSGA are set, the NSGA is executed to optimize the mixture facility model. The mathematics in the MOFAM can be described by the following equations:

$$\text{Minimize}INCO = \sum_{k=1}^{K}\sum_{t=1}^{T} C_{kt}xkt \quad (1)$$

$$\text{Maximize}COR = \sum_{k=1}^{K}\sum_{t=1}^{T} E_k x_{kt} DC_k \quad (2)$$

$$\text{Maximize}INRE = \sum_{k=1}^{K}\sum_{t=1}^{T} \frac{R_{kt} - C_{kt}}{(1+r_k)^t} x_{kt} \quad (3)$$

Table 1
Net present value of cost and benefit for each facility in each year.

Facility [Discount rate (r_k), %] [Capacity of CO_2 reduction (D_c), kg/m^2]	Year	Inflows (R_{kt})	PV of inflows	Outflows (C_{kt})	PV of outflows	NPV
	Initial	2100	2100	1816	1816	284
Rooftop garden	1	2100	1963	1816	1697	266
[$r_k = 7\%$]	2	2100	1834	1816	1586	248
[$D_c = 7.50\ kg/m^2$]	3	2100	1714	1816	1482	232
	4	2100	1602	1816	1385	217
	5	2100	1497	1816	1295	202
	Initial	20,000	20,000	18,000	18,000	2000
Solar photovoltaic panel	1	20,000	18,182	18,000	16,364	1818
[$r_k = 10\%$]	2	20,000	16,528	18,000	14,875	1653
[$D_c = 2.05\ kg/m^2$]	3	20,000	15,026	18,000	13,523	1503
	4	20,000	13,660	18,000	12,294	1366
	5	20,000	12,418	18,000	11,176	1242
	Initial	17,000	17,000	15,432	15,432	1568
Solar water heater	1	17,000	15,740	15,432	14,288	1452
[$r_k = 8\%$]	2	17,000	14,574	15,432	13,230	1344
[$D_c = 326.97\ kg/m^2$]	3	17,000	13,495	15,432	12,250	1245
	4	17,000	12,495	15,432	11,343	1152
	5	17,000	11,570	15,432	10,503	1067

$$A_k = \sum_{t}^{T} x_{kt} \quad k = 1, \ldots, K \tag{4}$$

Budget constraint

$$\sum_{k=1}^{K} C_{kt} x_{kt} \le B_t \quad t = 1, \ldots, T \tag{5}$$

Installation area constraint

$$\sum_{k=1}^{K} A_k \le R \tag{6}$$

Boundary condition

$0 \le x_{kt} \le BC \forall k, t$ (7)

Specific constraints for the study case ($k = 3$)

$$\frac{QN}{J} \le BAT \le S_c \frac{QN}{J} \tag{8}$$

$$BAT = \sum_{t}^{T} E_{3t} x_{3t} \tag{9}$$

$$Q = C_p M (WT_2 - WT_1) \tag{10}$$

$$A_3 \le D \tag{11}$$

C_{kt} is the cash outflow per square meter of the kth facility in the tth year (in New Taiwan dollar per square meter, NTD/m^2), t is the time (year), and x_{kt} is a nonnegative decision variable denoting the installation area of the kth facility in the tth year (m^2). K is the number of energy conservation and renewable energy facilities, and was set to be three in this study. Furthermore, T is the installation or operation time of facilities and is determined by decision-makers; E_k is the energy generated per square meter of the kth facility (kWh/m^2); DC_k is the capacity (coefficient) of CO_2 reduction and varies from one facility to another; for example, DC_k is considered as the reduced CO_2 emission for the solar photovoltaic panel and solar water heater instead of coal-based power, whereas it is considered as the carbon sequestration capacity for the rooftop garden. R_{kt} is the cash inflow per square meter of the kth facility in the tth year (NTD/m^2), r_k is the discount rate (%) of the kth facility and is dependent on the environmental policy; A_k is the total installation area of the kth renewable energy facility (m^2).

These three objectives are subject to budget constraint, installation area constraints, boundary conditions of decision variables, and specific constraints for the study case [as Eqs. (5)–(11)]. B_t is the available budget for the construction of renewable energy facilities in the tth year; R is the total available rooftop area (m^2); BC is the upper boundary of decision variables (m^2). The Eqs. (8)–(11) pertain to renewable energy required for providing hot water to students residing in dormitories for bathing purposes. Parameter BAT is the thermal quantity required for the bathing water (kWh), Q is the thermal energy required for providing hot water to a single person (kJ/person), N is the number of people consuming water per day (persons), J is a coefficient that represents the conversion of thermal energy to electric energy (1/3600 kJ/kWh), C_P is the specific heat capacity of water (4.181 kJ/kg °C), M is the hot water consumption per person, WT_1 is the initial temperature of water used for bathing (°C), WT_2 is the final temperature of water used for bathing (°C), and S_c is a coefficient related to the steady supply of hot water. In this study, for the solar water heater, D is limited to the dormitory rooftop area.

2.2. Optimizer in the MOFAM

Typically, two general approaches can be used to resolve multiobjective optimization problems. One combines multiple objectives into a single composite function by using adaptive weights through optimizers, such as GA [46–48,25]; however, the weights are determined according to the prior knowledge, and the optimal result provides no information about the compromise between objectives [15,23]. The other approach involves a multi-objective algorithm for determining "Pareto front" (PF) solutions. NSGA-II is one of major heuristic multiobjective optimizer mainly based on a non-dominated sorting (NDS) and crowding distance sorting mechanisms to determine the PF. Such mechanisms ensure both the convergence and spreading of the population. The major procedures of NSGA-II include population generation, population fitness evaluation, population ranking according to crowding distance, elitist selection, bimodal crossover, and mutation. Parent populations are ranked in an NDS order for generating an offspring [49]. The NSGA-II input parameters include population size, number of generations, mutation probability, crossover probability, and number of objectives. Some of these parameters were used in a sensitivity analysis for demonstrating their effect on the trade-off

Table 2
Optimal allocations for scenario I.

Facility kind (k)	Installation year (t)	Decision variable (X_{kt})	Installation area (m^2)			
			A	B	C	D
Roof garden ($k=1$)	1	X_{11}	949	965	436	967
	2	X_{12}	907	966	566	967
	3	X_{13}	568	967	503	967
	4	X_{14}	967	967	471	965
	5	X_{15}	833	966	917	965
	Total	-	4224	4831	2893	4831
Solar Photovoltaic panel ($k=2$)	1	X_{21}	0	24	0	44
	2	X_{22}	1	66	1	29
	3	X_{23}	5	880	1	945
	4	X_{24}	2	55	1	938
	5	X_{25}	1	572	2	905
	Total	–	9	1597	5	2861
Solar water heater ($k=3$)	1	X_{31}	3	3	3	3
	2	X_{32}	9	9	2	9
	3	X_{33}	150	150	150	150
	4	X_{34}	22	22	2	2
	5	X_{35}	23	23	41	43
	Total	–	207	207	198	207
Total installation area/Total rooftop area			4440/9055	6635/9055	3241/9055	7899/9055
Total operation period (years)			4	4	9	9
CO_2 reduction (kg)			99,381.4	107,186.5	578,688.1	658,652.2
Investment cost ($NTD)			8,918,416	30,027,660	6,646,476	45,246,760
BR[a] (CO_2 kg/$NTD)			0.0036	0.0015	0.0314	0.0009
Investment return ($NTD)			1,252,939	3,638,618	39,635,744	277,885,730

[a] Benefit ratio of investment cost.

solution. In case study, 15 decision variables were encoded as integer numbers in NSGA-II, and the fitness of chromosomes in NSGA-II was expressed according to the objective values.

2.3. Case study

A college campus is an urban space that serves as an experimental location for implementing measures for promoting CO_2 reduction and sustainable development of a city. Chaoyang University of Technology (CYUT), which is located in Taichung City in central Taiwan, was selected as a pioneer and a case study. A solar photovoltaic panel and solar heater could be installed on rooftop gardens for promoting renewable energy use on campus. In this case, three facilities, including rooftop garden ($k=1$), solar photovoltaic panel ($k=2$), and solar water heater ($k=3$), can be selected and installed in campus. Because of limited availability of campus land, the renewable energy facilities were installed on the rooftop of campus buildings covering a total area of 9055 m^2 (R) as shown in Fig. 4. A local market survey was conducted to generate the R_{kt} and C_{kt} in the NPV in Table 1, including energy cost savings and facility installation cost provided by construction companies. The r_1, r_2, and r_3 were 7%, 10%, and 8%, respectively. A five-year project involving annual maximum subsidy of 20 million NTD (US$0.68 million) from Taiwan Ministry of Education could be finalized for CYUT, and thus the B_t is 20 million NTD each year during installation period. A high efficiency solar photovoltaic panel can generate 262 kWh/m^2 of electricity annually in Taichung City; the heat accumulation of a solar heater is related to the sunshine rate, and generates 2.22 kWh/day by 1 m^2 of a heat accumulating surface in the presence of solar radiation. According to statistical data provided by Taiwan Central Weather Bureau, the average sunshine duration per year in the study area is 87 days. Approximately 500 students ($M=500$) residing in the dormitory require hot water supply for 252 days and average hot water consumption for 50 kg/person/day. The WT_1 and WT_2 were 21 and 45 °C, respectively. In this case, shrubs will be selected to plant in the rooftop garden because they are the most effective plants for reducing building energy consumption [8], and carbon sequestration of the shrubs is 7.5 kg CO_2/m^2 [50]. In other words, the DC_1 value for the rooftop garden is 7.5 kg CO_2/m^2. The DC_2 and DC_3 value for solar photovoltaic panel ($k=2$) and solar water heater ($k=3$) is 2.05 and 326.97 kg CO_2/kWh, respectively. The D is 1195 m^2. The coefficient S_c for the solar water heater was 1.3 in the case study. Details of mixture facility model can also refer to Ho et al. [12]. To maintain normal operation in CYUT campus, a specific facility construction period is requested and limits annual installation area of the facilities. CYUT also prefers constructing diverse facilities to reduce unsteady recovery benefit of facility installation due to the variation of sunshine duration in central Taiwan. Therefore, the BC of each facility is set as 967 m^2 in the study case. In other words, the boundary condition could limit the maximum expense of facility installation.

The total annual electricity demand for CYUT is approximately 13,485,200 kWh; even if solar photovoltaic panels were installed on (mounted above) the all roof of the campus building, the generated annual electricity (2,372,440 kWh) can only support 17.6% of electricity demand in campus. Therefore, no surplus electricity exists and the insufficient capacity of electricity needs be supplied by the power company. The electricity generated by solar photovoltaic panel will also obtain a 10-year subsidy (maximum 9.4 NTD/kWh) from the Taiwan Ministry of Economic Affairs. The electricity generated by solar photovoltaic panel would obtain a 10-year subsidy from Taiwan Ministry of Economic Affairs. Therefore, the energy cost savings have been considered in R_{kt}, and C_{kt} is the total facility installation cost. Because all facilities would typically incur additional maintenance cost after 10 years of operation and the 10-year subsidy period of renewable energy, the benefit analysis was performed for an interval less than 10 years. The facilities could be installed completely during the first five years, and are expected to be operated in the following years after their installation until the end of the period of ten years. Once the facilities are installed during the first five years, the installed facilities start to operate in the next year and then the derived investment return and CO_2 reduction in the following year will be calculated continuously in the

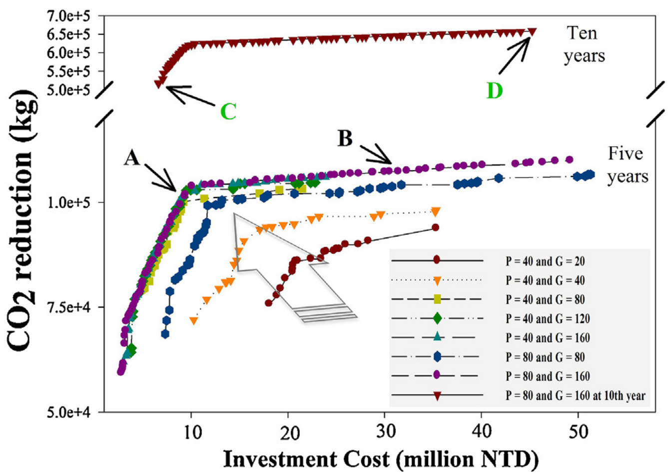

Fig. 5. Optimized solutions between investment cost and CO_2 reduction.

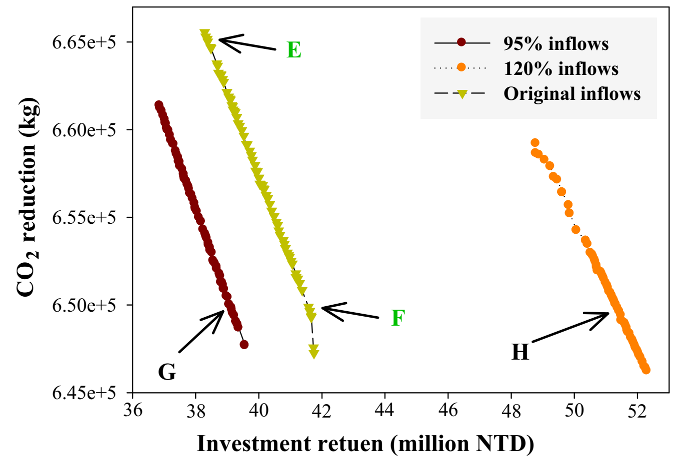

Fig. 6. Optimized solutions between investment return and CO_2 reduction.

objective functions until the tenth year. For example of allocation B in Table 2, solar photovoltaic panels with an area of 24 m^2 will be installed in the first year, and then starts to supply the power need of campus in the second year and continues operating until the tenth year. In other words, the derived investment return and CO_2 reduction from the installed solar photovoltaic panels in the first year will be calculated continuously in the following nine years (the 2nd to 10th year) in the objective functions.

3. Results and discussion

3.1. Influence of NSGA-II parameters for solutions

To investigate the robustness of NSGA-II, several MOFAM runs were executed for various NSGA-II parameters, different population (*P*) or generation sizes (*G*), a constant crossover rate of 0.85, and a mutation rate of 0.05. In Fig. 5, the number of feasible solutions increases with the number of generations because of the evolution and propagation of superior chromosomes. Moreover, improve of these solutions are decreased gradually and converged to a PF curve (as the direction of the arrow in Fig. 5). For a population of 40, the number of generations approaching a steady PF is approximately four times the population. When the population increases to 80, the number of generations is only two times of the population (G = 160) and more optimal solutions are obtained; moreover a PF curve similar to that calculated for the population of 40 was obtained. This result indicates that a large population with diverse chromosomes could facilitate the improvement of solutions. Specifically, a large population is more efficient than a large generation in enhancing the optimal PF outcome for the present case. However, such parameter set specifications for evolutionary algorithms may depend on the requirement in various stages for a given problem [51]. In scenario I and II, the parameters in NSGA-II optimization were sets as follows: population size of 80, generations of 120, crossover probability of 0.85, and mutation probability of 0.05. Overall, NSGA-II can provide a large number of nondominated solutions and avoids the complex steps of a fuzzy two-stage algorithm used in a previous study [12].

3.2. Scenario I: trade-off between minimum investment cost and maximum CO_2 reduction

Fig. 5 depicts the optimal trade-off allocations (solutions) of renewable energy facilities for achieving the objectives of minimum investment cost and maximum CO_2 reduction. Each PF comprises an optimal trade-off allocation, and each allocation represents a design associated with the maximum CO_2 reduction at a specific investment cost. Overall, the estimated investment cost ranges from 2 million to 50 million NTD, depending on the CO_2 reduction targeted. Fig. 5 shows that an increase in the CO_2 reduction increased the investment cost. These PFs can be used by decision-makers as decision reference and for performing benefit analysis for achieving optimal allocations.

In Fig. 5, two different benefit ratios (BRs) can be observed for the investment cost; during the first five years of facility installation, the BR for a cost between 2 million and 10 million NTD is high (0.0036 kg CO_2/NTD), and the corresponding CO_2 reduction is between 59 and 109 tons. The optimal allocation A in this range shows that the total rooftop garden area is 4224 m^2, the solar photovoltaic panel area is 9 m^2, and the solar water heater area is 207 m^2 (Table 2); a budget of 9 million NTD could lead to a CO_2 reduction of 104 tons in the fifth years. In other words, facility installation on building rooftops at CYUT can reduce approximately 104 tons of CO_2 over a period of five years. If the maximum CO_2 reduction targeted is greater than 104 tons, the BR decreases; the solar photovoltaic panel should be increased, which would increase the installation cost. For example, in allocation B (in which the BR is low), a larger solar photovoltaic panel (area: 1597 m^2) compared with that in allocation A would be installed (Table 2), The higher installation cost of the solar photovoltaic panel compared with that of the other facilities results in a low BR of 0.0015 kg CO_2/NTD. Allocations A and B have different BRs, but similar areas of roof garden and solar water heater; this result is consistent with the roof garden and solar water heater having greater capability to reduce CO_2. In Table 1, the solar water heater has the highest capability for CO_2 reduction, and it implies that the solar water heater will be installed preferentially. Moreover, the installation area of the solar water heater will be the upper limit of the constraint for providing a steady supply of hot water.

In Fig. 5, the optimal tradeoff for the case where the installed facilities operate for the next five years is shown by the brown inverted triangle. The figure also shows two BRs; the higher BR corresponds to a cost between 6 million and 10 million NTD and is 0.0314 kg CO_2/NTD, and the corresponding CO_2 reduction ranges between 516 and 614 tons. In Table 2, in allocation C, which has a high BR, the total rooftop garden area is 2893 m^2, the solar photovoltaic panel area is 5 m^2, and the solar water heater area is 198 m^2. Compared with allocation A, allocation C shows an obvious increase in CO_2 reduction because of a longer operation time and different facilities have different capacity of CO_2 reduction, and the similar installation area and investment cost in allocation A and C demonstrate that the investment cost dominates the installation

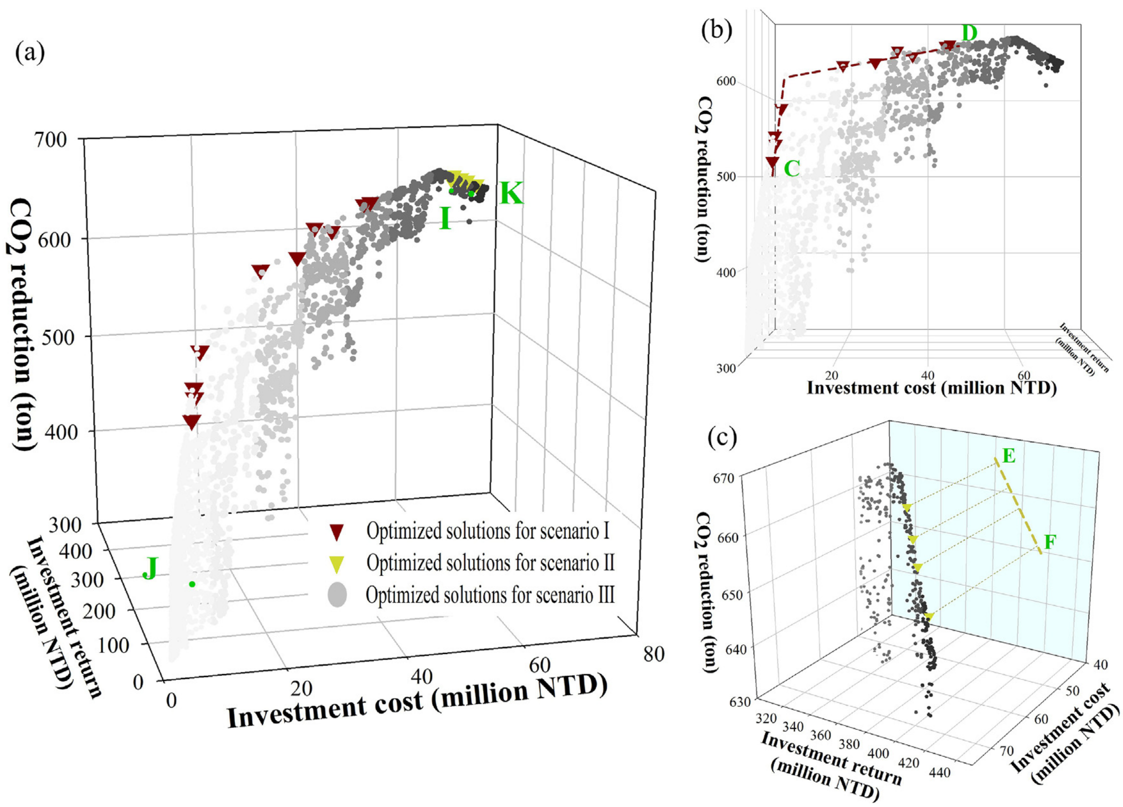

Fig. 7. (a) Optimized solution distributions on 3-D Pareto surface and (b) and (c) projected on 2-D plane.

Table 3
Optimal allocations for scenario II.

Facility kind (k)	Installation year (t)	Decision variable (X_{kt})	Installation area (m^2)			
			E	F	G	H
Roof garden	1	X_{11}	966	962	962	962
($k=1$)	2	X_{12}	962	905	851	954
	3	X_{13}	813	570	747	468
	4	X_{14}	888	786	609	843
	5	X_{15}	963	912	965	943
	Total	–	4592	4135	4134	4134
Solar	1	X_{21}	660	939	959	966
photovoltaic	2	X_{22}	959	958	965	958
panel	3	X_{23}	936	960	942	906
($k=2$)	4	X_{24}	732	917	957	929
	5	X_{25}	967	939	887	954
	Total	–	4254	4713	4710	4713
Solar	1	X_{31}	115	79	44	58
water heater	2	X_{32}	13	7	6	8
($k=3$)	3	X_{33}	23	103	122	124
	4	X_{34}	48	17	8	16
	5	X_{35}	8	1	27	1
	Total	–	207	207	207	207
Case inflow			original	original	95% original	120% original
Total installation area/Total rooftop area			9053/9055	9055/9055	9051/9055	9054/9055
Total operation period (years)			9	9	9	9
CO_2 reduction (kg)			665,016	650,091.9	650,009.9	650,046.0
Investment return ($NTD)			383,849,604	415,365,879	390,711,841	513,065,995
BRR[a] (CO_2 kg/$NTD)			0.0016	0.0016	0.0016	0.0016
Investment cost ($NTD)			67,105,464	73,237,528	73,226,632	73,268,960

[a] Benefit ratio of investment return.

area. Decision-makers could spend approximately 6.6 million NTD for building the facilities in the first five years, and the investment returns would approach 5.3 million NTD after 9 years of operation.

When the maximum CO_2 reduction exceeds 614 tons, the BR decreases and the installation cost of the solar photovoltaic panel increases sharply to slightly increase CO_2 reduction, such as allocation D (Table 2). Although a high BR can be achieved by the MOFAM, approaching the maximum CO_2 reduction could be set as a target to develop a zero energy community. These results demonstrate the MOFAM enabling a complete tradeoff allocation of energy conservation and renewable energy facilities on rooftops in a low-carbon campus.

Table 4
Optimal allocations for scenario III.

Facility	Installation area (m^2)		
	I	J	K
Roof garden	4276	1427	4639
Solar photovoltaic panel	4532	11	3961
Solar water heater	206	165	206
Total installation area/Total rooftop area	9014/9055	1603/9055	8761/9055
Total operation period (years)	9	9	9
Investment return ($NTD)	402,464,693	24,897,980	358,156,183
CO_2 reduction (kg)	652,250.6	388,051.4	661,015.4
Investment cost ($NTD)	70,219,220	4,501,398	63,427,280

3.3. Scenario II: design of trade-off between investment returns and CO_2 reduction

Fig. 6 depicts the optimal allocation of facilities after 10 years of operation for maximum investment returns and CO_2 reduction. An increase in CO_2 reduction decreases the investment returns. Each of the allocations represents a design associated with the maximum CO_2 reduction for specific investment returns. For example, for the original inflows, allocation E (shown in Table 3) in the PF corresponds to a total rooftop garden area of 4592 m^2, solar photovoltaic panel area of 4254 m^2, and solar water heater area of 207 m^2. Other allocations in scenario II have similar areas and almost occupy the entire installation area. Unlike scenario I, allocations in scenario II are based on maximum investment returns. The parallel and linear PFs in scenario II indicate that the benefit ratio of investment returns is almost constant for different case inflows. Specifically, if the cash inflow of investment returns (R_{kt}) decreases (or increase) to 95% (or 120%) of the original inflow, the PF moves to the left (or right). For example, three allocations in Fig. 6(F–H) are shown in Table 3; an increase in the case inflow directly increases the investment returns. For similar CO_2 reduction values, the investment returns differ but the total installation area of facilities is similar, indicating that the case inflow has a negligible effect on facility allocation. In addition, the total installation area is similar for all years but the installation areas for different facilities differ from year to year, showing that the consideration of the NPV would contribute to the yearly variation of the installation area. Unlike scenario I, the rooftop area in scenario II would be fully occupied by different renewable energy facilities to satisfy maximum investment returns, and the allocation of these facilities is determined by their DC_k for maximizing CO_2 reduction.

3.4. Scenario III: trade-off curve for investment cost, investment returns, and CO_2 reduction

Scenario III considered three conflicting objectives, namely *INCO*, *COR*, and *INRE*, for determining the appropriate facility allocation in the case study. To comprehensively construct the Pareto surface (PS) as shown in Fig. 7(a), a population of 3400 and a generation size of 10200 were adopted in the NSGA-II optimization. These optimal tradeoff allocations form a three-dimensional (3D) PS, and depending on the requirements of decision-makers, the visualized PS can provide them with various appropriate allocation choices. A high investment cost is incurred for simultaneously satisfying the objectives of maximum investment returns and maximum CO_2 reduction. For investment cost less than 10 million NTD, a high surface gradient indicates that allocations in this range have high investment efficiency, which is consistent with the high BR in scenario I. Because R_{kt}, C_{kt}, and r_k are constants for the facility k, the linear relationship between investment cost and investment returns can be predicted using Eqs. (1) and (3). An increase in the investment cost proportionately increases the investment returns, and the investment efficiencies for the three objectives are dominated by the investment efficiency of the objective of maximum CO_2 reduction. Specifically, decision-makers can select the design of facility allocation in the range of higher investment efficiencies for promoting renewable energy use on campus within a limited budget.

Table 4 shows some allocations in the PS in Fig. 7(a). In allocation I, the maximum investment cost (approximately 70 million NTD) is incurred for achieving maximum investment returns (approximately 40 million NTD) and maximum CO_2 reduction. Unlike allocations in scenario II, allocation I, which involves a smaller total installation area, involves the consideration of minimum investment cost. Allocation J has the smallest total installation area in scenario III. In addition, allocation K involves higher CO_2 reduction, investment returns, and investment cost compared with allocation D in scenario I. The PS in Fig. 7(a) can be projected on two dimensional (2D) panels as shown in Fig. 7(b) and (c) to yield 2D optimal tradeoff curves for comparison with two-objective optimization. A slice of the PS as the dark red front in Fig. 7(b) covers the optimized allocations from *INCO* and *COR* optimization, such as allocation C and D in Fig. 5. Similarly, the blackish dash line in Fig. 7(c) is consistent with the distribution of allocations in Fig. 6, and covers allocation E and F generated from *INRE* and *COR* optimization. Specifically, the result demonstrates that the multiobjective optimal model considering three objectives optimization resulted in optimal solutions that include the optimal solutions generated from two-objective optimization. The MOFAM was proven to provide the Ministry of Education and CYTU with more allocation plans for decision reference by considering simultaneously three-objective optimization according to the comparison with two-objective optimization.

4. Conclusions

The MOFAM provides useful decision information on renewable energy facility allocation and the optimal installation areas of solar photovoltaic panels, solar water heaters, and rooftop gardens for achieving the desired objectives. The case study of a college campus for achieving the conflicting objectives *INCO*, *COR*, and *INRE* was conducted for demonstrating the feasibility of MOFAM. In the case study, the MOFAM could provide more allocation plans for satisfying the decision-maker's requirements, including minimum investment cost, maximum CO_2 reduction, and maximum investment returns. Meanwhile, some allocations with high investment efficiencies were obtained, and decision-makers can choose his preferred plan from these allocations when the budget is limited and the CO_2 reduction is not considered preferentially. For example, CYUT can spend 4 million NTD to obtain 509 tons of CO_2 reduction and investment return of 2 million NTD. The results show that high investment cost was incurred in simultaneously satisfying the objectives of maximum investment returns and maximum CO_2 reduction. The facility allocation of solar photovoltaic panel, solar water heater, and rooftop garden in different scenarios is dominated by the CO_2 reduction capacity of the facilities, for achieving the objective of maximizing CO_2 reduction. The solar water heater with the highest CO_2 reduction capability is preferred, and is followed by the rooftop garden with the second highest CO_2 reduction capability. If necessary, decision-makers could further utilize justice methods, such as analytic hierarchy process, on these allocation plans to determine an acceptable solution. The consideration of additional objectives could possibly provide more allocation solutions helpful for decision-making within a limited budget.

The MOFAM searched a Pareto front hyper-plane of allocation plans approaching either high benefit return from an economical aspect or high CO_2 reduction for environmental sustainability. In this paper, the MOFAM provided a useful optimization reference for allocating solar photovoltaic panels, solar water heaters, and rooftop gardens in a campus. The result showed that the optimal solutions from three-objective optimization cover the optimal solutions generated from two-objective optimization and provide comprehensive description about the solution space. In the future, more objectives can be considered in the MOFAM to achieve the optimal allocation for various renewable energy facilities for performing effective energy management for institutional buildings. The MOFAM can help optimize energy conservation and renewable energy mixture facilities in a community towards a zero carbon community.

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References

[1] W.T. Tsai, Current status and development policies on renewable energy technology research in Taiwan, Renew. Sustain. Energy Rev. 9 (3) (2005) 237–253.
[2] J. Tollefson, Countries with highest CO_2-emitting power sectors (tonnes per year), Nature 450 (7168) (2007) 327.
[3] Y.-H. Lin, K.-T. Tsai, M.-D. Lin, M.-D. Yang, Design optimization of office building envelope configurations for energy conservation, Appl. Energ. 171 (2016) 336–346.
[4] C.A. Balaras, K. Droutsa, E. Dascalaki, S. Kontoyiannidis, Heating energy consumption and resulting environmental impact of European apartment buildings, Energy Build. 37 (5) (2005) 429–442.
[5] Y.-H. Lin, Y.-P. Chen, M.-D. Yang, T.-C. Su, Multiobjective optimal design of sewerage rehabilitation by using the nondominated sorting genetic algorithm-II, Water Resour. Manage. 30 (2) (2016) 487–503.
[6] G.A. Keoleian, S. Blanchard, P. Reppe, Life-cycle energy, costs, and strategies for improving a single-family house, J. Ind. Ecol. 4 (2) (2000) 135–156.
[7] A. Atmaca, N. Atmaca, Life cycle energy (LCEA) and carbon dioxide emissions (LCCO2A) assessment of two residential buildings in Gaziantep, Turkey, Energy Build. 102 (2015) 417–431.
[8] N.H. Wong, D. Cheong, H. Yan, J. Soh, C. Ong, A. Sia, The effects of rooftop garden on energy consumption of a commercial building in Singapore, Energy Build. 35 (4) (2003) 353–364.
[9] L.J. Whittinghill, D.B. Rowe, R. Schutzki, B.M. Cregg, Quantifying carbon sequestration of various green roof and ornamental landscape systems, Landscape Urban Plann. 123 (2014) 41–48.
[10] C. Dharuman, J.H. Arakeri, K. Srinivasan, Performance evaluation of an integrated solar water heater as an option for building energy conservation, Energy Build. 38 (3) (2006) 214–219.
[11] S.-Y. Liu, Y.-H. Perng, Y.-F. Ho, The effect of renewable energy application on Taiwan buildings: what are the challenges and strategies for solar energy exploitation? Renew. Sustain. Energy Rev. 28 (2013) 92–106.
[12] Y.-F. Ho, C.-C. Chang, C.-C. Wei, H.-L. Wang, Multi-objective programming model for energy conservation and renewable energy structure of a low carbon campus, Energy Build. 80 (2014) 461–468.
[13] G.J.Y. Hsu, F.-Y. Chou, Integrated planning for mitigating CO_2 emissions in Taiwan: a multi-objective programming approach, Energy Policy 28 (8) (2000) 519–523.
[14] A. Alarcon-Rodriguez, G. Ault, S. Galloway, Multi-objective planning of distributed energy resources: a review of the state-of-the-art, Renew. Sustain. Energy Rev. 14 (5) (2010) 1353–1366.
[15] E.M. Malatji, J. Zhang, X. Xia, A multiple objective optimisation model for building energy efficiency investment decision, Energy Build. 61 (2013) 81–87.
[16] R. Evins, A review of computational optimisation methods applied to sustainable building design, Renew. Sustain. Energy Rev. 22 (2013) 230–245.
[17] K. Deb, H. Jain, An evolutionary many-objective optimization algorithm using reference-point-based nondominated sorting approach, part I: solving problems with box constraints, IEEE Trans. Evol. Comput. 18 (4) (2014) 577–601.
[18] D. Brockhoff, D. Saxena, K. Deb, E. Zitzler, On handling a large number of objectives a posteriori and during optimization, in: J. Knowles, D. Corne, K. Deb, D. Chair (Eds.), Multiobjective Problem Solving from Nature, Springer, Berlin Heidelberg, 2008, pp. 377–403.
[19] F.P. Chantrelle, H. Lahmidi, W. Keilholz, M.E. Mankibi, P. Michel, Development of a multicriteria tool for optimizing the renovation of buildings, Appl. Energ. 88 (4) (2011) 1386–1394.
[20] R. Evins, P. Pointer, R. Vaidyanathan, S. Burgess, A case study exploring regulated energy use in domestic buildings using design-of-experiments and multi-objective optimisation, Build. Environ. 54 (2012) 126–136.
[21] Y. Lu, S. Wang, Y. Zhao, C. Yan, Renewable energy system optimization of low/zero energy buildings using single-objective and multi-objective optimization methods, Energy Build. 89 (0) (2015) 61–75.
[22] C. Diakaki, E. Grigoroudis, N. Kabelis, D. Kolokotsa, K. Kalaitzakis, G. Stavrakakis, A multi-objective decision model for the improvement of energy efficiency in buildings, Energy 35 (12) (2010) 5483–5496.
[23] V. Machairas, A. Tsangrassoulis, K. Axarli, Algorithms for optimization of building design: a review, Renew. Sustain. Energy Rev. 31 (2014) 101–112.
[24] M. Adamski, Optimization of the form of a building on an oval base, Build. Environ. 42 (4) (2007) 1632–1643.
[25] C. Diakaki, E. Grigoroudis, D. Kolokotsa, Towards a multi-objective optimization approach for improving energy efficiency in buildings, Energy Build. 40 (9) (2008) 1747–1754.
[26] J. Gagne, M. Andersen, A generative facade design method based on daylighting performance goals, J. Build. Perform. Simul. 5 (3) (2012) 141–154.
[27] G. Narzisi, Multi-Objective Optimization, A quick introduction. New York University lectures, 2008.
[28] P.K. Shukla, K. Deb, S. Tiwari, Comparing classical generating methods with an evolutionary multi-objective optimization method, Lect. Notes Comput. Sci. 3410 (2005) 311–325.
[29] S. Albright, W. Winston, C. Zappe, Data Analysis and Decision Making, Cengage Learning, 2010.
[30] H. Ren, W. Zhou, K.i. Nakagami, W. Gao, Q. Wu, Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects, Appl. Energ. 87 (12) (2010) 3642–3651.
[31] M. Karmellos, A. Kiprakis, G. Mavrotas, A multi-objective approach for optimal prioritization of energy efficiency measures in buildings: model, software and case studies, Appl. Energ. 139 (2015) 131–150.
[32] B. Wang, X. Xia, J. Zhang, A multi-objective optimization model for the life-cycle cost analysis and retrofitting planning of buildings, Energy Build. 77 (2014) 227–235.
[33] Z. Wu, X. Xia, B. Wang, Improving building energy efficiency by multiobjective neighborhood field optimization, Energy Build. 87 (2015) 45–56.
[34] H. Ghiasi, D. Pasini, L. Lessard, A non-dominated sorting hybrid algorithm for multi-objective optimization of engineering problems, Eng. Optim. 43 (1) (2011) 39–59.
[35] J.H. Kämpf, D. Robinson, Optimisation of building form for solar energy utilisation using constrained evolutionary algorithms, Energy Build. 42 (6) (2010) 807–814.
[36] R. Yang, L. Wang, Multi-objective optimization for decision-making of energy and comfort management in building automation and control, Sustain. Cities Soc. 2 (1) (2012) 1–7.
[37] S. Liu, X. Meng, C. Tam, Building information modeling based building design optimization for sustainability, Energy Build. 105 (2015) 139–153.
[38] F. Ascione, N. Bianco, C. De Stasio, G.M. Mauro, G.P. Vanoli, A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance, Energy Build. 88 (0) (2015) 78–90.
[39] W. Yu, B. Li, H. Jia, M. Zhang, D. Wang, Application of multi-objective genetic algorithm to optimize energy efficiency and thermal comfort in building design, Energy Build. 88 (0) (2015) 135–143.
[40] M. Hamdy, A. Hasan, K. Siren, Applying a multi-objective optimization approach for design of low-emission cost-effective dwellings, Build. Environ. 46 (1) (2011) 109–123.
[41] M.-D. Yang, M.-D. Lin, Y.-H. Lin, K.-T. Tsai, Multiobjective optimization design of green building envelope material using a non-dominated sorting genetic algorithm, Appl. Therm. Eng. (2016), http://dx.doi.org/10.1016/j.applthermaleng.2016.01.015 (in press).
[42] A.T.D. Perera, R.A. Attalage, K.K.C.K. Perera, V.P.C. Dassanayake, A hybrid tool to combine multi-objective optimization and multi-criterion decision making in designing standalone hybrid energy systems, Appl. Energ. 107 (2013) 412–425.
[43] T.L. Saaty, Decision making with the analytic hierarchy process, Int. J. Serv. Sci. 1 (1) (2008) 83–98.
[44] R. Dufo-López, J.L. Bernal-Agustín, Multi-objective design of PV–wind–diesel–hydrogen–battery systems, Renew. Energ. 33 (12) (2008) 2559–2572.
[45] E. Fallah-Mehdipour, O. Bozorg Haddad, M.M. Rezapour Tabari, M.A. Mariño, Extraction of decision alternatives in construction management projects:

application and adaptation of NSGA-II and MOPSO, Expert Syst. Appl. 39 (3) (2012) 2794–2803.
[46] M.-D. Yang, T.-C. Su, Automation model of sewerage rehabilitation planning, Water Sci. Technol. 54 (11–12) (2006) 225–232.
[47] M.-D. Yang, T.-C. Su, An optimization model of sewage rehabilitation, J. Chin. Inst. Eng. 30 (4) (2007) 651–659.
[48] M.-D. Yang, A genetic algorithm (GA) based automated classifier for remote sensing imagery, Can. J. Remote Sens. 33 (3) (2007) 203–213.
[49] K. Deb, A. Pratap, S. Agarwal, T. Meyarivan, A fast and elitist multiobjective genetic algorithm: nSGA-II, IEEE Trans. Evol. Comput. 6 (2) (2002) 182–197.
[50] M.o.t.I. Construction and Planning Agency, Design and Technique Specifications for Greenery of Site, Construction and Planning Agency, Ministry of the Interior, 2012.
[51] H. Ishibuchi, Y. Shibata, Mating scheme for controlling the diversity-Convergence balance for multiobjective optimization, in: K. Deb (Ed.), Genetic and Evolutionary Computation—GECCO 2004, vol. 3102, Springer, Berlin Heidelberg, 2004, pp. 1259–1271.