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Multi-Objective Optimization and Decision-Making of Green Infrastructure Layout Considering Carbon Emission

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ABSTRACT

Green infrastructure (GI) is one of the important measures to deal with climate change. Under the call of carbon emission reduction, it is inevitable to find a combination scheme of green infrastructure with low cost, low carbon emission, and high efficiency. This study analyzes the carbon emission activities of three kinds of green infrastructure: biological retention pond(BR), green roof(GR), and permeable pavement(PP) in the whole life cycle. A three-objective optimization model is constructed by coupling Storm Water Management Model (SWMM) and Non-dominated Sorting Genetic Algorithm III (NSGA III), which is applied to a newly-build campus in China. According to different demands scenarios, the weight coefficient method is adopted to determine the optimal scheme. The optimal scheme takes carbon emission reduction as the most important objective consisting of 59.1%BR, 33.9% GR and 7% PP. The result shows that the suggested scheme has a larger GR area than PP. This study provides a method and framework for the optimal design of GIs from the perspective of reducing carbon emissions in the newly-build areas, which contribute to the general construction of Sponge City.

Keywords: Green infrastructure, Multi-objective optimization, Carbon emission, Numerical simulation

NONMENCLATURE

Abbreviations	
APEN	Applied Energy
Symbols	
n	Year

1. INTRODUCTION

Climate change is one of the significant challenges facing the world currently. Frequent rainstorms and floods have seriously threatened human life and property safety, such as the severe rainstorms that fell in Zhengzhou on 20th July 2021. One of the fundamental reasons is that the hydrological cycle changed due to global warming. In order to alleviate the trend of global warming, many countries have put forward low-carbon development strategies[1]. The Chinese government set a double carbon goal in 2020: strive to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. Studies have shown that cities account for 2% of the world's total area, but 75% of the world's energy is consumed and produces the most greenhouse gases[2, 3]. However, China's urbanization rate exceeded 60% in 2019, and the trend continues to increase[4]. Therefore, how to achieve low-carbon development in the process of rapid urbanization is a crucial issue concerned by the government and scholars at present.

To mitigate the impact of climate change on cities, China started implementing the Sponge City strategy in 2013. As an essential facility in Sponge City, Green Infrastructures (GIs) smooth the runoff process and reduce pollutant through infiltration, interception, and storage. The benefits of GIs in reducing runoff and pollutants have been demonstrated by experimental and simulation studies[5-7]. Studies have also analyzed the cooling and energy saving benefits of GIs [8, 9]. The relationship between GIs and greenhouse gases has recently attracted the attention of some scholars. Lin et al. [10] and Ma[11] analyzed the carbon emissions from GIs construction in the built area; Kavehei et al. [12] investigated the carbon accumulation effect of biological

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retention basins through field study; Luo et al.[13] studied the carbon sequestration of green roofs. Existing research provides a good basis for this study, but few studies consider the design of green infrastructure from the perspective of low carbon.

It is necessary to design the layout of GI before it is implemented. As a reliable and effective calculation method, multi-objective optimization is often used to determine the best scheme of GIs[14]. Rezaei et al. used the Multi-Objective Particle Swarm Optimization to determine the optimal LID type and combination so as to reduce peak runoff and pollutants[15]. Leng et al. determined the optimal combination of gray-green infrastructure by taking runoff, pollutants and cost as optimization objectives[16]. Obviously, besides hydrological and environmental benefits, the cost is a key factor for the optimal design of GIs in existing studies[17]. However, almost no planning and design considers that the construction of GIs will also cause carbon emissions. Moreover, fewer studies focused on the relationship between carbon emissions and carbon absorption of GIs.

In this study, an optimal design framework of the GIs from the perspective of reducing carbon emissions is conducted to fill the above-mentioned gaps. Firstly, the carbon emission of GIs was comprehensively analyzed during the whole life cycle. On this basis, a multi-objective optimization model considering carbon emission, cost and hydrological benefits is proposed. The optimal scheme based on different objectives is determined by taking a newly-build urban area in China as an example. In addition, the carbon sequestration benefit of the optimal scheme is also analyzed. This study could provide scientific support for the optimal layout design of GIs to contribute to the realization of low-carbon cities and dual carbon goals.

2. MATERIAL AND METHODS

2.1 Multi-objective problems

The reasonable objective function and decision variable are the key factors to solve a multi-objective problem. Concerning the layout optimization of GIs, its hydrological benefits and costs are often considered as objectives. The objective functions of cost and carbon emission are calculated based on the life cycle, the hydrological benefits are expressed by runoff reduction rates. The area of a particular type of GI in a particular sub-catchment is a decision variable. GIs' types include bio-retention ponds (BR), green roofs (GR) and permeable pavements (PP). The research framework is shown in Figure 1.

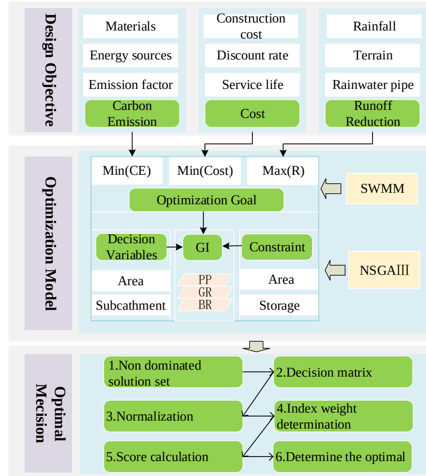

Fig. 1.The research framework

2.1.1 Carbon emission

A reasonable method is essential for estimating the carbon emission of GIs. In this study, the account boundary is determined by the life cycle of GIs, including construction, operation, maintenance, and recycling. The construction and maintenance processes are the major sources of carbon emissions. Due to the natural nature of GIs and the uncertainty of regional future planning, this study assumed that GIs would not produce carbon emissions during the recycling process. Therefore, the carbon emission of GIs can be calculated by equation (1). The construction of GIs includes raw material production, transportation and on-site construction. The carbon emission of these processes can be calculated by equation (2).

$$CE = C_C + C_{OM} - C_S \tag{1}$$

$$C_C = C_{ma} + C_{tr} + C_{os} \tag{2}$$

While CE is the total amount of carbon emissions during the whole life of GIs, C_C, C_{OM} represents the carbon emissions during the construction, operation and maintenance, respectively. C_{ma}, C_{tr}, C_{os} represents the carbon emissions in the raw material production, transportation and on-site construction, respectively.

The emission factor method proposed by IPCC is the most widely used method for estimating carbon emissions. Therefore, it is adopted to estimate the carbon emission in the construction phase. The calculation formula of the factor emission method is shown in Equation (3) [18].

$$CE = AD * EF \tag{3}$$

Where CE is the carbon emissions, AD is the activity data, EF is the emission factor.

The carbon emissions mainly come from the raw material during the material production process. For GIs, the material mainly includes gravel, geotextiles, waterproof materials, and concrete. The carbon emission can be calculated according to Equation (4).

$$C_{ma} = \sum_{i=1}^{n} M_i \times F_i \tag{4}$$

Where M_i is the consumption of the i-th material, t; F_i is the emission factors of the i-th material, kg CO_2/t.

In the transportation process, the carbon emission mainly depends on the mode and distance of the transportation. So the carbon emission during the transportation process can be calculated by Equation (5) [19].

$$C_{tr} = \sum_{i=1}^{n} M_i \times D_i \times T_i \tag{5}$$

Where D_i is the transport distance of the i-th material, km; T_i is the carbon emission factor of the unit distance under the i-th material transportation mode, kg CO_2/(t・km); M_i is the same as in equation (4).

There are many kinds of energy consumption in the on-site construction process, such as transportation and electricity. Therefore, the carbon emission during construction can be calculated by equation (6).

$$C_{os} = \sum_{i=1}^{n} E_i \times EF_i \tag{6}$$

Where E_i is the consumption of the i-th energy, kWh or kg; EF_i is the carbon emission factor of the i-th energy kgCO_2/kWh or kgCO_2/kg.

During the maintenance process, PPs need to be cleaned daily, and vegetated facilities need to be trimmed and decontaminated regularly. Different types of energy are consumed in this process so that the calculation method can refer to Equation (6).

2.1.2 Cost

Cost is one of the critical contents of GIs planning and design. The Technical Guide for Sponge Cities-Construction of Low Impact Development (for Trial Implementation)[20] provides references for different GIs in Beijing based on the floor space. But the data does not reflect the cost during the whole life cycle, such as construction and operation. The life cycle method is adopted to estimate the cost more reasonable. The detailed content of this method can refer to Mei[21] and Liao[22]'s paper.

2.1.3 Hydrological benefit

The hydrological benefit is one of the main functions of GIs. The runoff reduction rate is used to evaluate the hydrological benefit, calculated by equation (7).

$$R = \frac{V_{NG} - V_G}{V_{NG}} \times 100 \tag{7}$$

Where R is the runoff reduction rate, %, V_{NG} is the outflow volume before GIs are laid out, m^3; V_G is the outflow volume after GIs are laid out, m^3.

2.2 Optimization model

In order to acquire the optimal scheme that meets the requirements of low carbon, low cost and high runoff reduction rate, the optimization model was established. There are four steps to build an optimization model in this study.

(1) The multi-objective optimization algorithm

The Non-dominated Sorting Genetic Algorithm III (NSGA-III) has been proved to be successful in solving multi-objective optimization problems. Deb improved it based on NSGAⅡ in 2013[23]. Like NSGA and NSGAⅡ, it also needs to cycle the processes of selection, crossover and variation. However, the difference is that it retains the non-dominated individuals close to the reference point with the help of a set of predefined reference points. Given its advantages in multi-objective optimization and finding the optimal solution quickly, this method is selected for the optimization process.

(2) The hydrological and hydrodynamic model

In order to determine the location and scale of GIs and calculate the runoff reduction rate, it is necessary to construct a hydrological and hydrodynamic model. The Storm Water Management Model (SWMM) can simulate both surface runoff and pipe confluence, which is suitable for the hydrological and hydrodynamic process simulation in urban areas. In addition, SWMM is open source, which facilitates integration with optimization algorithms. So the SWMM model was constructed in this study.

(3) Integrated optimization algorithm and hydrological model

The PYSWMM corresponds to SWMM in Python, and the NSGA-III exists in the Geatpy toolkit. Since both the SWMM and NSGA-III algorithms can be found in python toolkits, the integration of the model and algorithm is completed in the PyCharm platform. By developing the interface, the optimization algorithm can call the hydrological model, and the simulation results can be fed back to the optimization target so as to realize the integration between the hydrological model and the optimization algorithm.

(4) Determine the optimal decision

As a set of Pareto optimal solutions is obtained after the above optimization, it is necessary to choose an appropriate method to determine the optimal solution. The Pareto solution set constitutes a decision matrix whose column number is equal to the number of objectives. The decision matrix should be normalized first because of dimensional disunity. For cost-type indicators, such as carbon emission and cost, the normalization formula is shown in equation (8), while for benefit-type indicators, such as runoff reduction rate, the normalization formula is shown in equation (9). If the weight of each target is given, the total score can be obtained by equation (10). The scheme corresponding to the maximum R_i value is the optimal scheme.

$$r_{ij}^{-}=\frac{\max\limits_{j} a_{ij}-a_{ij}}{\max\limits_{j} a_{ij}-\min\limits_{j} a_{ij}}(j=1,2) \tag{8}$$

$$r_{ij}^{+}=\frac{a_{i}-\min\limits_{j} a_{ij}}{\max\limits_{j} a_{ij}-\min\limits_{j} a_{ij}}(j=3) \tag{9}$$

$$R_i=\sum_{i=1}^{n} w_j \times r_{ij}(j=1,2,3) \tag{10}$$

Where, $a_{i,j}$ represents the value of the j-th objective in the i-th scheme; i is the number of schemes; j is the number of objectives, in this study, j=1 represents the cost, j=2 represents the carbon emission, j=3 represents the runoff reduction rate; r_{ij} represents the normalized value of the j-th objective in the i-th scheme, '-' represents the cost-type indicators, '+'represents the benefit-type indicators; w_j represents the weight value of the j-th objective; R_i is the total score of the i-th scheme.

2.3 Case study overview

Taiyuan, as a rapidly developing city, is located in Shanxi Province, North China. In order to solve the problem of water shortage and waterlogging, it is making efforts to build a sponge city. The Dongshan campus of Shanxi University, located in the southeast of Taiyuan city, is chosen as the study area. The planned construction area of the first phase is about 0.52km^2, and the terrain is high in the northeast and low in the southwest. The total amount of the input rainfall event is 70.55 mm with a profile of Chicago, and the rainfall duration is 24 hours.

3. RESULTS

3.1 The optimization schemes set

When the number of iterations is 60, and the population size is 200, the Pareto solution set contains 190 non-dominated solutions, as shown in Figure 2(a). The range of runoff reduction rate is 25.8% - 26.3%, the average annual cost range is (0.84 -1.8) $\times 10^6$ yuan, and the average annual carbon emission range is (0.4-1.4) $\times 10^5$kg. As shown in Figure2(b), the more the annual average cost is, the less obvious effect of increasing unit cost on runoff reduction is, which indicates that there is a law of diminishing marginal utility between investment and runoff reduction. The carbon emission of GIs increases with the increase of cost, and the increase rate also increases, as shown in Figure2(c).

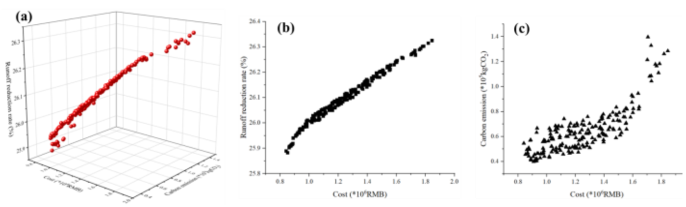

Fig. 2. Pareto solution set

3.2 The optimal scheme under different scenarios

How to find the most suitable solution from the Pareto solution set requires consideration of practical requirements. This study sets up three scenarios according to different needs:

(1) For areas with limited cost budgets, a scheme that achieves the maximum hydrological benefit and produces the least carbon dioxide at the minimum cost is desirable. The weight coefficients corresponding to cost, carbon emission and runoff reduction rate are 0.8,0.1,0.1, respectively.

(2) For regions that need to achieve the carbon reduction target, CO_2 emissions are the primary limiting factor, with little pressure on the budget and runoff control. The weight coefficients corresponding to the cost, carbon emission and runoff reduction rate are 0.1,0.8,0.1, respectively.

(3) For areas with severe waterlogging, runoff control is the primary consideration in GIs' planning, with little pressure on the economy and carbon emission. The weight coefficients corresponding to the cost, carbon emission and runoff reduction rate are 0.1,0.1,0.8, respectively.

The scores of each scheme obtained by equation (10) under the three scenarios are shown in Figure 3(a). The one marked by the arrow is the highest score, which is the best solution. The best plan for scenario (1) is 6 with a runoff reduction of 25.9%, scenario (2) is 42 with a runoff reduction of 26%, and scenario (3) is 89 with a runoff reduction of 26.3%. The area of GIs corresponding to the three optimal schemes is shown in Figure 3(b).

From Figure 3(b) and table 1, runoff reduction requires a larger GI area and cost investment and produces the most carbon emissions at the same time. In table 1, the cost of scheme 42 is higher than scheme 6, but the carbon emission is smaller than scheme 6, which is contrary to the previous analysis that "carbon emission increases with the increase of the cost." Combined with Figure3(b), the main reason is that in scheme 42, the area of GR is larger than that of PP, and the carbon emission generated by GR is smaller than that of PP. When planning to reduce carbon emissions, consideration should be given to increasing the area of facilities with vegetation systems rather than permeable paving. Similarly, if the goal is to reduce costs, more permeable paving with lower costs should be set, rather than green roofs with higher costs.

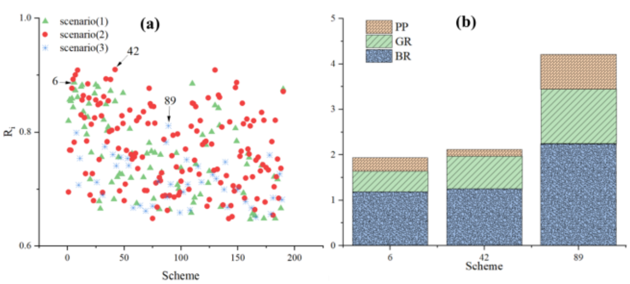

Fig. 3. Optimal schemes under different scenarios

Table1 Life cycle cost and carbon emission of optimal decision under different objectives

Scheme	Cost(*10^6yuan)			Carbon emission (10^5kgCO_2)		
	6	42	89	6	42	89
BR	9.86	10.37	18.60	3.65	3.84	6.88
GR	4.13	6.65	11.06	0.56	0.91	1.51
PP	1.19	0.59	3.06	2.69	1.33	6.95
GIs	15.18	17.61	32.73	6.9	6.08	15.34

4. DISCUSSION

4.1 Carbon sequestration of GIs

According to the existing references[24, 25], it is assumed that the carbon sequestration rate of the BR is 3 kgCO_2/(m^2*year), GR is 2 kgCO_2/(m^2*year). In the 16th year of scheme 6, it will reach carbon neutralization, and the net carbon sequestration at the end of the life cycle (carbon absorbed minus carbon emitted) is 2.03 $\times 10^5$ kgCO_2; Scheme 42 will achieve carbon neutralization in the 12th year, and the net carbon sink at the end of the life cycle is 4.33 $\times 10^5$ kgCO_2; In scheme 89, carbon neutralization will achieve in the 17th year, and the net carbon sink at the end of the life cycle is 2.94$\times 10^5$ kgCO_2. It can be seen that the scheme with the minimum carbon emission as the optimization goal also shows great advantages in carbon emission reduction, compared with the other two schemes. It is worth noting that the carbon sink rate dramatically influences the calculation results, while the value used in this study is small.

4.2 Limitations

How to rapidly promote the realization of carbon neutrality in Sponge City construction is the primary problem faced by the Chinese government and researchers. From the perspective of GIs, this study proves that the construction of Sponge City is conducive to realizing carbon neutrality with the support of data. However, only the carbon sequestration effect of plants and soil of GIs is considered, and the carbon emission reduction benefits of runoff pollution removal, runoff reduction, indoor temperature reduction and energy consumption should also be taken into account.

Although this study established a GIs optimization design model considering carbon emission, GIs is just the source regulation and storage part of Sponge City construction. The stormwater sewer system and the terminal storage system of the Sponge City system also need to be taken into account, especially at the planning and design stage. In addition, due to the diversity of vegetation and soil types of GIs, if the monitoring of carbon sink of GIs can be carried out as soon as possible, it will be helpful to promote better the construction of Sponge Cities and the realization of carbon neutrality.

5. CONCLUSION

Based on the analysis of carbon emissions in the service life of three green infrastructures, this study constructed a three-objective optimization design model coupled with NSGA Ⅲ and SWMM. In the optimal solution set, the marginal cost-benefit of runoff reduction effect decreases, while carbon emission increases with cost. According to different target scenarios, the optimal schemes are determined, respectively. When cost is the most important objective, the optimal scheme consists of 61.5% BR, 23% GR and 15.5% PP; when carbon reduction is the most important objective, the proportion of BR / GR / PP in the optimal scheme is 59.1%, 33.9% and 7%, respectively; When runoff reduction is the most important objective, the proportion of BR / GR / PP in the optimal scheme is

53.3%, 28.4% and 18.3%, respectively. The optimal scheme with carbon emission as the most important optimization objective showed a larger GR area than PP.

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REFERENCE

[1] McCormick K, Anderberg S, Coenen L, Neij L. Advancing sustainable urban transformation. J Clean Prod. 2013;50:1-11.

[2] Maleki MZ, Zain MFM. Factors that influence distance to facilities in a sustainable efficient residential site design. Sustain Cities Soc. 2011;1:236-43.

[3] Muneera T, Celikb AN, Caliskanc N. Sustainable transport solution for a medium-sized town in Turkey—A case study. Sustain Cities Soc. 2011;1:29-37.

[4] Wang K, Lin C, Wu C. Trends and planning choices after china's urbanization rate reaching above 60%. City Planning Review. 2020;44:9-17.

[5] Jiang C, Li J, Li H, Li Y, Zhang Z. Low-impact development facilities for stormwater runoff treatment: Field monitoring and assessment in Xi'an area, China. J Hydrol. 2020;585.

[6] Eckart K, McPhee Z, Bolisetti T. Performance and implementation of low impact development - A review. Sci Total Environ. 2017;607-608:413-32.

[7] Liu W, Chen W, Peng C. Assessing the effectiveness of green infrastructures on urban flooding reduction: A community scale study. Ecol Model. 2014;291:6-14.

[8] Lazzarin RM, Castellotti F, Busato F. Experimental measurements and numerical modelling of a green roof. Energ Buildings. 2005;37:1260-7.

[9] Li J, Wang Y, Ni Z, Chen S, Xia B. An integrated strategy to improve the microclimate regulation of green-blue-grey infrastructures in specific urban forms. J Clean Prod. 2020;271.

[10] Lin X, Ren J, Xu J, Zheng T, Cheng W, Qiao J, et al. Prediction of Life Cycle Carbon Emissions of Sponge City Projects: A Case Study in Shanghai, China. Sustainability. 2018;10.

[11] Ma J. Carbon source analysis and carbon emission study of typical measures for Sponge City construction. Jinzhong: Shanxi Agricultural University; 2018.

[12] Kavehei E, Iram N, Rezaei Rashti M, Jenkins GA, Lemckert C, Adame MF. Greenhouse gas emissions from stormwater bioretention basins. Ecol Eng. 2021;159.

[13] Luo H, Liu X, Anderson BC, Zhang K, Li X, Huang B, et al. Carbon sequestration potential of green roofs using mixed-sewage-sludge substrate in Chengdu World Modern Garden City. Ecol Indic. 2015;49:247-59.

[14] Wang J, Liu J, Wang H, Mei C. Approaches to Multi-Objective Optimization and Assessment of Green Infrastructure and Their Multi-Functional Effectiveness: A Review. Water. 2020;12.

[15] Rezaei AR, Ismail Z, Niksokhan MH, Dayarian MA, Ramli AH, Yusoff S. Optimal implementation of low impact development for urban stormwater quantity and quality control using multi-objective optimization. Environ Monit Assess. 2021;193:241.

[16] Leng L, Jia H, Chen AS, Zhu DZ, Xu T, Yu S. Multi-objective optimization for green-grey infrastructures in response to external uncertainties. Sci Total Environ. 2021;775.

[17] Jiang C, Li J, Gao J, Lv P, Yao Y, Li H. Advances in research of optimal rainwater infrastructure configuration in sponge city construction. Journal of Hydroelectric Engineering. 2021;40:19-29.

[18] Qin H. Urban water system and carbon emission. Beijing: Science Press; 2014.

[19] Development MoHaU-R. Building carbon emission calculation standard. 2019.

[20] MHURD. Technical Guide for Sponge Cities-Construction of Low Impact Development (for Trial Implementation). Ministry of housing and urban-rural development.2014.

[21] Mei C, Liu J, Wang H, Yang Z, Ding X, Shao W. Integrated assessments of green infrastructure for flood mitigation to support robust decision-making for sponge city construction in an urbanized watershed. Sci Total Environ. 2018;639:1394-407.

[22] Liao Z, Chen H, Huang F, Li H. Cost–effectiveness analysis on LID measures of a highly urbanized area. Desalin Water Treat. 2014:1-7.

[23] Deb K, Jain H. An Evolutionary Many-Objective Optimization Algorithm Using Reference-Point-Based Nondominated Sorting Approach, Part I: Solving Problems With Box Constraints. IEEE T Evolut Comput. 2014;18:577-601.

[24] Shafique M, Xue X, Luo X. An overview of carbon sequestration of green roofs in urban areas. Urban for Urban Gree. 2020;47.

[25] Kavehei E, Jenkins GA, Adame MF, Lemckert C. Carbon sequestration potential for mitigating the carbon footprint of green stormwater infrastructure. Renewable and Sustainable Energy Reviews. 2018;94:1179-91.

