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Multi-objective layout optimization of hospital outpatient clinics based on NSGA II

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This study utilizes an improved NSGA-II algorithm to conduct a multi-objective optimization of the hospital outpatient department layout. By simultaneously incorporating patient walking distance, hospital operating costs, patient waiting time, and medical staff work efficiency as optimization objectives, and adopting an adaptive population size adjustment strategy, this paper optimizes the existing outpatient layout in a case study of a three-story outpatient building at Panzhihua Central Hospital. The results show that the new plan reduces patient walking distance by 57.2%, shortens waiting time by 59%, and enhances medical staff collaboration efficiency, while only increasing costs by 5.6%. This demonstrates the effectiveness and feasibility of the improved NSGA-II method in handling complex multi-objective optimization problems for outpatient layouts. The research findings provide a reference for the rational allocation of hospital outpatient resources and the improvement of service quality. Additionally, this paper discusses the applicability and limitations of the study and proposes future research directions, including validating the method's effectiveness in hospitals of various types and sizes, incorporating dynamic optimization and real-time data, and deeply integrating with hospital information systems.

Keywords Hospital optimization, Hospital outpatient layout, NSGA II, Multi-objective algorithm

As an important part of the medical and health service system, the hospital outpatient department plays a crucial role in providing primary healthcare services. However, with population growth, accelerated urbanization, and increasing medical needs, hospital outpatient departments face numerous challenges, including inefficient space utilization, low service efficiency, and poor patient experience[1]. According to 2021 statistics, the total number of medical consultations in China's medical institutions reached over 5.44 billion, posing a significant challenge for hospital outpatient services[2]. In a country with a large population like China, county and township hospitals are unable to meet the demand for medical care, leaving renowned regional hospitals to shoulder the responsibility for major medical services[3].

As the first point of contact for patients, the layout of the hospital outpatient building is critical in determining patient treatment times, the speed of medical processes, and hospital costs[4,5]. Research indicates that a scientifically designed outpatient layout can optimize the medical service process, improve service efficiency and quality, enhance the patient experience, reduce medical costs, maximize the utilization of medical resources, and contribute to the sustainable development of healthcare services.

Current research on outpatient clinic layouts has yielded positive results. For instance, Sauli Karvonen conducted a case study on Tampere Heart Hospital, re-planning the hospital's functional areas, which reduced the patient's movement distance by 33%[6]. Wang Xiyuan improved the outpatient building layout of HBU Hospital, reducing the frequency of patient movement by 378 units and shortening the movement distance by 505 meters[2]. Farhood Rismanchian, studying the emergency department, used process data mining methods to reduce the movement distance of non-critical patients and critical patients by 42.2% and 47.6%, respectively, while also considering design preferences and minimizing relocation costs[7]. Sadeghi applied Computerized Relational Layout Planning (CORELAP) to the Beheshti Hospital in Iran, which reduced patient movement distances by 26%[8].

Karvonen creatively applied methods from cellular manufacturing and production flow analysis, techniques typically used in industrial production, to optimize hospital layouts[6]. He treated the movement of patients in heart hospitals as analogous to product transportation in industrial production, using methods that reduce transportation distance to optimize patient movement. Wang applied the Systematic Layout Planning (SLP) method, commonly used for logistics functional area planning, to the outpatient building's functional area

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design, which reduced patient movement by 505 meters[2]. Although SLP is effective for small-scale layouts, it is less effective for outpatient clinics with numerous functional areas. Munavalli used genetic algorithms to redesign the outpatient department, rearranging departments to minimize travel distances and time[5]. Although genetic algorithms are often applied to combinatorial optimization problems in manufacturing, they also yielded positive results in outpatient clinic layouts.

In the field of industrial production, there are two primary methods for solving multi-objective optimization problems: one involves using preference selection criteria to convert the multi-objective problem into a single-objective problem; the other retains the original objectives and employs selection strategies to iteratively choose individuals with optimal attributes[9,10]. The second method was proposed by Kalyanmoy Deb, Nidamarthi Srinivas, and others, and it has been proven to be more effective, forming the foundation of the NSGA-II method[11,12]. Since its introduction, NSGA-II has gained widespread recognition and has been successfully applied in engineering and academic research[13–16]. However, there are relatively few studies applying NSGA-II to hospital outpatient layout optimization.

In existing research on hospital outpatient layout, most studies focus on single-objective optimization, overlooking the conflicts between multiple objectives. In the field of multi-objective optimization, NSGA-II has been widely used in engineering and academic research. However, the application of NSGA-II to optimize hospital outpatient layouts is relatively limited. This study aims to fill this gap by applying the NSGA-II algorithm to optimize hospital outpatient layouts, addressing issues such as low space utilization and service inefficiency. Compared to traditional methods, NSGA-II offers significant advantages in handling multi-objective optimization problems, enabling the simultaneous optimization of multiple objective functions and providing more comprehensive and efficient solutions.

The unique aspect of using the NSGA-II method, compared to previous studies, lies in its ability to simultaneously optimize multiple objectives, particularly in balancing patient flow, operational costs, employee efficiency, and patient waiting times. Traditional hospital outpatient layout optimization tends to focus on a single objective, such as reducing patient movement distance or improving service efficiency, but often ignores the conflicts and trade-offs between these objectives. NSGA-II, through non-dominated sorting and crowding distance concepts, effectively handles the conflicts between multiple objectives, optimizing patient flow and reducing waiting times while considering operational costs and employee work efficiency, thus providing a more comprehensive and efficient solution. This multi-objective optimization method not only reduces patient waiting times and improves service quality but also maintains cost control and enhances employee work efficiency, minimizing unnecessary movement and workload. However, this also brings new challenges, such as how to reasonably quantify and balance the priorities of multiple objectives and how to address the computational complexity of the algorithm while ensuring optimal performance. These issues need to be further studied and refined in practice.

In conclusion, this paper proposes an improved NSGA-II algorithm to solve the multi-objective hospital outpatient layout problem, aiming to reduce patient movement distance, cut costs, enhance employee satisfaction, and simultaneously reduce patient waiting times. The main content of this paper is as follows:

"Introduction" section provides a literature review, discussing NSGA-II and existing research on hospital outpatient layouts.

"Problem description and model building" section presents the problem and model formulation, detailing the multi-objective characteristics of the hospital outpatient layout and constructing a four-dimensional multi-objective function with constraints.

"Algorithm design" section introduces the algorithm design, including improvements to NSGA-II through an adaptive population size.

"Case" section demonstrates a case application to showcase the effectiveness of the proposed method.

"Conclusion and discussion" section summarizes the research findings and provides suggestions for future research.

Problem description and model building

The outpatient departments of Chinese hospitals mainly include pediatrics, internal medicine, neurology, obstetrics and gynecology, cardiology and many other departments. In addition, the outpatient departments also include manual registration and fee offices, self-service machine registration and fee offices, pharmacies and other auxiliary departments. The outpatient layout optimization problem is an assignment problem, which is to assign all outpatient clinics to each room, as shown in Fig. 1.

In Fig. 1, six outpatient clinics, including pediatric outpatient clinic, neurology outpatient clinic, cardiology outpatient clinic, internal medicine outpatient clinic, registration and charging office, and pharmacy, need to be assigned to eight rooms. The hospital can add new outpatient clinics, such as pharmacies, internal medicine, neurology and other departments. For example, in Fig. 1, up to two outpatient departments can be added. Different results of the above assignments will lead to different outpatient layouts. Different outpatient clinic layouts will result in different lengths of patient walking paths, which affects the hospital's service level for patients. It is not difficult to see that the greater the number of new outpatient clinics, the shorter the walking distance for patients and the higher the hospital's service level, but the hospital's costs will increase. In summary, the hospital outpatient layout involves multiple conflicting objectives, and when optimizing the outpatient layout, hospitals need to fully consider the multi-objective optimization problem.

Symbol description

The corresponding meaning of the mathematical model is shown in Table 1.

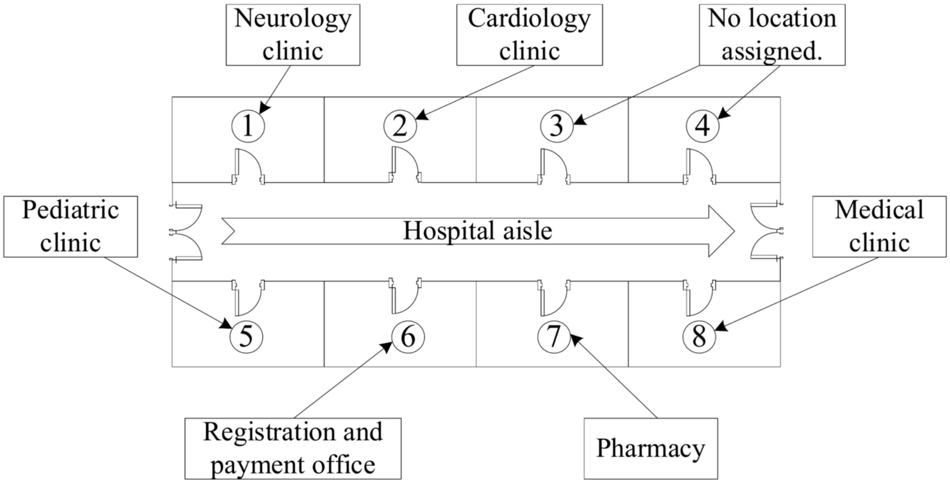

Fig. 1. Outpatient assigned to room.

Classification	Symbol	Description
Sets	P^m	The total number of people with m-disease
	OD_{ij}^m	Represents the distance traveled by a patient with *m* types of diseases from clinic *i* to clinic *j*. Here, *i* and *j* can also be other letters, representing different nodes
	OD_{ij}	OD_{ij} represents the distance between clinic *i* and clinic *j* in the outpatient layout plan
	x_i, y_i	The coordinate value of clinic *i*. *i* can be other letters, representing the coordinates of different points
	r_i, r_j	The numerical numbers of different floors where outpatient clinic *i* and outpatient clinic *j* are located. For example, $r_i = 1$ means clinic i is on the first floor. If clinic i and clinic j are on the same floor, $r_i = r_j$
	F_i	The fixed cost of outpatient clinic *i*
	V_i	Variable costs of outpatient clinic *i*
	w_{ij}	The intimacy weight between clinic *i* and clinic *j*
	n_{ij}	n_{ij} represents the central angle from clinic *i* to clinic *j*
Parameters	M	Total number of illnesses seen in outpatient clinics
	i, j	Clinic number
	S	Total number of outpatient clinics
	S_k	S_k represents the total number of *k* types of outpatient clinics. For example, in Fig. 11, there are two Obstetrics and Gynecology clinics, so S_k equals 2
	K	*K* represents the total classification of outpatient clinics
	h	Floor height of the outpatient building
	R	Radius
	D	Total walking distance of patients
	C	Outpatient operating costs
	Q	Patient queuing indicator
	E	Employee efficiency indicator
	L	Total available length of outpatient building
	W	The total available width of the outpatient building
	C_{max}	Maximum cost limit
	$S_{\max}$	Maximum number of outpatient clinics is limited
Decision variables	f_{ij}^m	0–1 decision variables. $f_{ij}^m = 1$ means that patients with m disease arrive at clinic *j* through clinic *i*. $f_{ij}^m = 0$ means that the patient did not reach clinic j through clinic *i*
	f_k^m	f_k^m represents that a patient with *m* diseases needs to pass through *k* types of outpatient clinics

Table 1. Symbol description.

Objective function

1. Walking distance

Most of the sick people are weak, and the shorter the moving distance, the better their experience. Especially for the sick elderly, who have difficulty walking, short-distance movement can bring them a very good hospital service experience. In China, it is a critical period of population aging. Public hospitals mainly serve the grassroots people, and the elderly who visit the hospital are the most served. Therefore, this paper adopts the minimum moving distance as one of the two goals. This model mainly considers that which clinic to go to is decided at the time of registration. There is no consolidated care model. The hospital outpatient layout refers to the total walking distance of all patients within a certain period of time. The total walking distance is mainly affected by the number of patients and the distance walked by a single person. Walking distance is shown in formula (1).

$$\min \quad D = \sum_{m=1}^{M} \sum_{i=1}^{S} \sum_{j=1}^{S} f_{ij}^{m} P^{m} OD_{ij}^{m} \tag{1}$$

OD_{ij}^{m} is a variable function with different criteria. Common criteria include walking distance for patients on the same floor, walking distance for patients on different floors, walking distance for patients in a circular building, and walking distance for patients in an irregular rectangular building. The OD_{ij}^{m} calculation function varies depending on the criteria, and the calculation formula can be adjusted according to practical situations. This section introduces the common criteria.

The OD_{ij}^{m} of the same floor is shown as the green line in Fig. 2, and the walking distance formula (2) is shown.

$$OD_{ij}^{m} = f_{ij}^{m} \left(|x_i - x_j| + |y_i - y_j| \right) \tag{2}$$

If there is a walking distance between different floors, the patient needs to first walk from clinic i to the elevator or stair position (x_e, y_e), then go up and down the stairs height h, and finally walk to clinic j. Different floors are shown by the green lines in Figs. 2 and 3. The formula of OD_{ij}^{m} is shown in Eq. (3).

$$OD_{ij}^{m} = f_{ij}^{m} \left((|x_i - x_e| + |y_i - y_e|) + (|x_e - x_j| + |y_e - y_j|) + h \times |r_i - r_j| \right) \tag{3}$$

If the floor has an irregular layout, OD_{ij}^{m} is calculated as irregular. Irregular buildings in hospital buildings are mainly rectangular and circular. As shown in Fig. 4a, it is an irregular rectangular layout, in which the walking distance of patients in outpatient clinic 1 and outpatient clinic 2 belongs to irregular paths, and the OD_{ij}^{m} calculation formula is shown in (4). For example, Fig. 4b is a circular layout, and the OD_{ij}^{m} calculation formula is shown in (5).

$$OD_{ij}^{m} = f_{ij}^{m} \left(OD_{ie}^{m} + OD_{ej}^{m} \right) \tag{4}$$

$$OD_{ij}^{m} = f_{ij}^{m} n_{ij} \pi R / 180 \tag{5}$$

2. Hospital operating costs

Hospital operating costs are the sum of variable costs and fixed costs per unit time for all outpatient departments. As shown in formula (6).

$$\min \quad C = \sum_{i=1}^{S} (F_i + V_i) \tag{6}$$

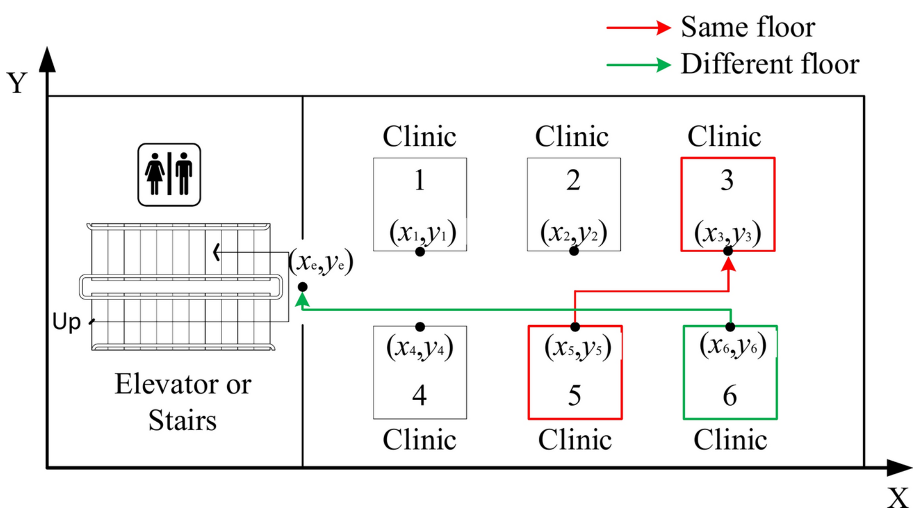

Fig. 2. Walking distance on the same floor.

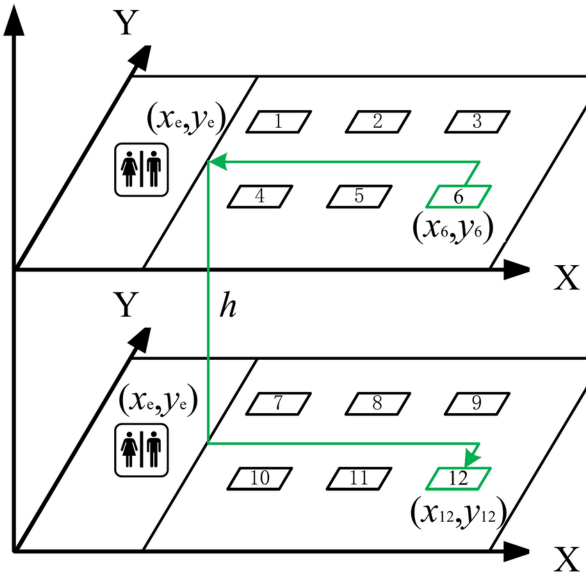

Fig. 3. Walking distance on different floors.

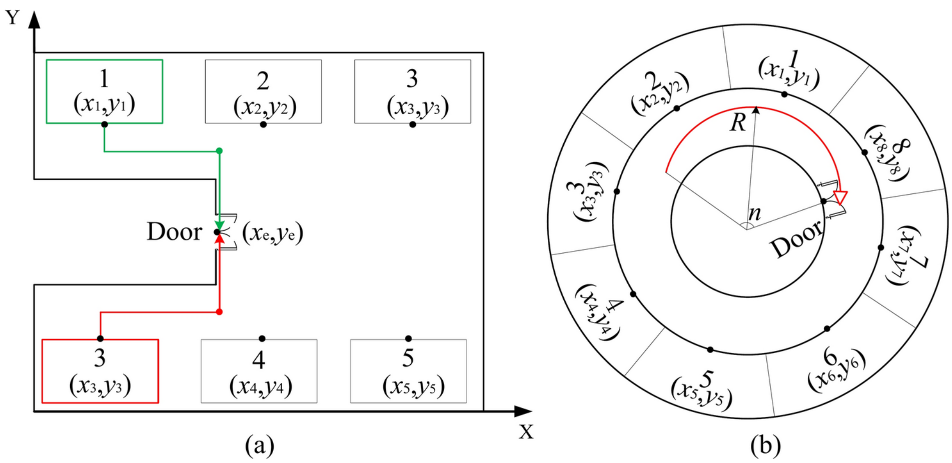

Fig. 4. Irregular outpatient clinic layout.

Formula (6) represents the operating cost of the hospital. The C value consists of the sum of fixed costs F_i and variable costs V_i. Fixed costs include the medical equipment, office equipment, and other items needed to establish the clinic. Variable costs represent the annual recurring costs, primarily consisting of staff salaries, medical consumables, and other related expenses.

3. Patient queueing

Patient queueing is a critical indicator of hospital service levels. When a hospital has a large number of patients and a limited number of outpatient departments, patients are likely to face long waiting times. In outpatient layout research, the number of outpatient departments directly affects patient waiting times. To minimize queueing times, this study uses the ratio of patient visits to the number of outpatient departments as a measure. A smaller ratio indicates shorter waiting times for patients. Patient queueing is shown in formula (7).

$$\min \quad Q = \sum_{k=1}^{K} \sum_{m=1}^{M} \frac{f_k^m P^m}{S_k} \tag{7}$$

4. Employee efficiency

Employee efficiency is also a crucial factor in outpatient layout design. For instance, medical staff working in the same department often need to collaborate closely, and if their workstations are not located near each other, it may lead to time wasted on communication, reducing overall efficiency. In outpatient layout, employee efficiency is represented using a product of distance and weight, similar to logistics and facility planning. The weight w_{ij} is categorized into five levels: A, E, I, O, and U, with corresponding weight values of 5, 4, 3, 2, and 1, respectively. The higher the weight value, the more crucial it is for the departments to be located near each other. Employee efficiency is shown in formula (8).

$$\min \quad E = \sum_{i=1}^{S} \sum_{j=i+1}^{S} (w_{ij} OD_{ij}) \tag{8}$$

Restrictions

The constraints are shown in formula (9).

$$\begin{cases} 0 < x_i < L \\ 0 < y_i < L \\ (x_i, y_i) \neq (x_j, y_j) \qquad \text{when} \qquad r_i = r_j \\ C \leq C_{\max} \\ S \leq S_{\max} \end{cases} \tag{9}$$

Formula (9) expresses the boundary constraints, non-overlapping constraints, maximum cost constraints and maximum outpatient number constraints of coordinate values.

Algorithm design

Genetic Algorithm (GA) was first proposed by John Holland of the United States in the 1970s. The algorithm was designed and proposed based on the laws of evolution of organisms in nature. It is a computational model of biological evolution that simulates the natural selection and genetic mechanism of Darwin's theory of biological evolution. It is a method of searching for the optimal solution by simulating the natural evolution process. The algorithm uses mathematical methods and computer simulation operations to convert the problem-solving process into processes such as crossover and mutation of chromosome genes in biological evolution.

NSGA II is a variant of Genetic Algorithm. Genetic Algorithm is mainly used to solve single objectives, while NSGA II is mainly used to solve multiple objectives. The main principle of NSGA II is similar to that of Genetic Algorithm, except that the selection strategy adopts the non-dominated sorting method.

Coding and population initialization

Symbol encoding is used. The number of numerical symbols corresponds to the number of rooms. The sequence of numerical symbols is ordered from the upper floors to the lower floors and from the back rows sequentially to the front rows. For example, the encoding in Fig. 3 is [1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12]. If there are 12 rooms, with 10 clinics already arranged. If there are 12 rooms, with 10 clinics already arranged and two vacant rooms represented by null, while maintaining the positional order, the encoding in Fig. 5 would be [1, 2, 3, 4, null, 5, 6, 7, 8, null, 9, 10].

Randomly generate an initial population of outpatient clinic layouts.

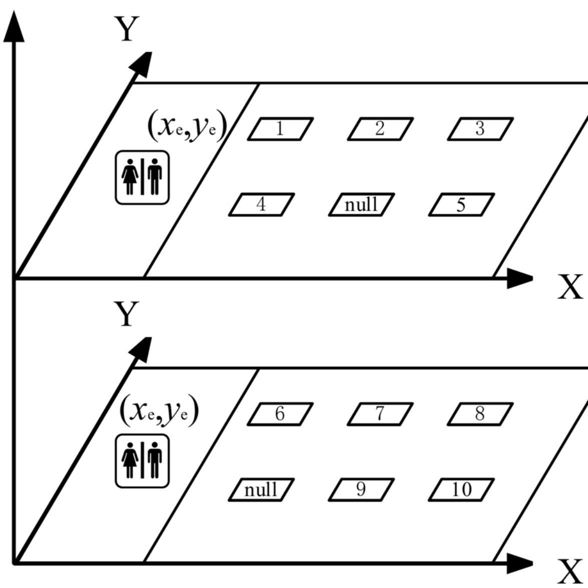

Fig. 5. Coding diagram.

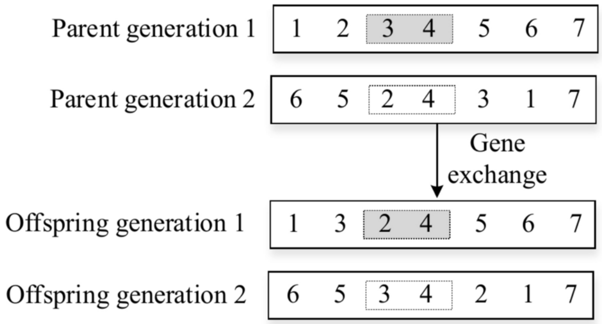

Fig. 6. Outpatient layout crossover.

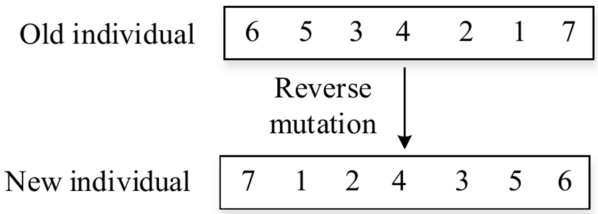

Fig. 7. Outpatient layout variation.

Crossover and mutation operations

The crossover operation of parent individuals is the main way for NSGA II to generate new individuals and form new populations. It is the exchange of gene segments between parent individuals according to the crossover probability, so that excellent genes can be continuously inherited. The outpatient layout adopts symbolic sequence coding. The gene segments of the layout individuals are intercepted based on two randomly selected points, and the gene segments are exchanged to form a new layout individual, as shown in Fig. 6.

The crossover operation in the previous step allows NSGA II to generate a new set of individuals, and find better individuals in the set (an individual is equivalent to an outpatient layout plan). As the number of crossover generations increases, the individual set tends to be homogenized, and no matter how the crossover is performed, no new individuals can be generated, so it falls into a local optimal solution (this problem is very common in mathematical optimization). In order to avoid falling into the optimal solution, a mutation operation is designed. In each generation of iterative optimization, some individuals are mutated to increase population diversity. Mutation operation simulates genetic mutations in biological evolution. It can prevent the population from falling into the local optimal solution to a certain extent and increase the diversity of the population. It is more convenient and operable to use reverse sequence mutation in sequentially encoded individuals. This article adopts the reverse mutation operation, which is shown in Fig. 7.

Choose strategy

The most critical step in using NSAG II to solve the outpatient layout is to select a strategy. The core content of the selection strategy is as follows.

1. Non-dominated sorting

First define the vector F(X) = (f1(X), f2(X), f3(X),…, fM) composed of fi(i = 1,2,3,…, M) with M multi-objective problems (X)), where Xu and Xv represent any two decision variables, and U represents the decision space, then Xu, Xv ∈ U. The Pareto dominance relationship (minimum target value) is expressed as Eq. (10).

$$\begin{cases} X_u \text{dominate} X_v & f_i\left(X_u\right) < f_i\left(X_v\right) \quad \forall i \in (i=1,2,...,M) \\ X_u \text{weak dominance} X_v & f_i\left(X_u\right) \leq f_i\left(X_v\right) \quad \forall i \in (i=1,2,...,M) \\ X_u \text{do not dominate } X_v & f_i\left(X_u\right) < f_i\left(X_v\right) \quad \text{and} f_j\left(X_u\right) > f_j\left(X_v\right) \quad \exists i,j \in (i,j=1,2,...,M) \end{cases} \tag{10}$$

In order to further illustrate the dominance relationship of hospital layouts, a dual-objective Pareto dominance relationship diagram is shown in Fig. 8. As shown in Fig. 8, the two objectives are the hospital operating cost and the patient walking distance. A\B\C\D\E in the figure is a feasible solution. The feasible solution of this layout is that C dominates D, E weakly dominates D, and C and E do not dominate each other.

2. Elite retention strategy

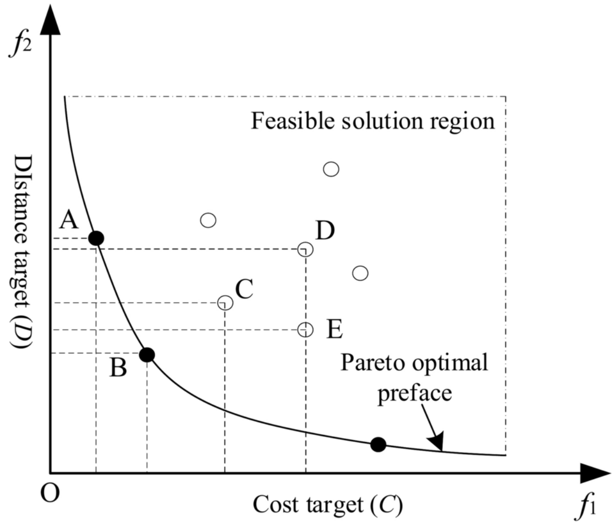

Fig. 8. Pareto dominance relationship.

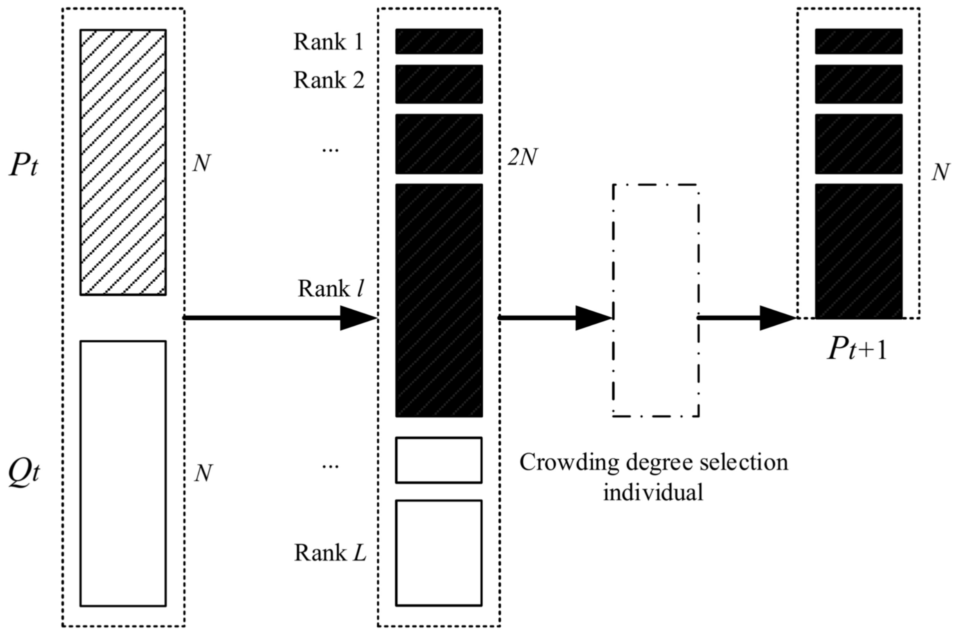

Fig. 9. Lite retention strategy.

The elite retention strategy is a key step to ensure the convergence of the outpatient layout population. The elite retention strategy is shown in Fig. 9.

As shown in Fig. 9, the parent population is assumed to be *Pt* and the offspring population is *Qt*. The parent population and offspring population are merged into a [*Pt*, *Qt*] population. The number of individuals in the new population is 2*N* (*N* represents parent/ The number of offspring populations), non-dominated sorting is performed on the new population [*Pt*, *Qt*], and the sorting result is [Rank 1, Rank 2, Rank 3,…, Rank *L*] layer, where Rank l is a column vector. If the total number of individuals in the Rank 1 to Rank l layers is equal to *N*, then select these *N* individuals as the next generation population Pt + 1; if the total number of individuals in the Rank 1 to Rank (*l*-1) layers is less than *N*, Rank 1 to Rank *l* If the total number of individuals in the layer is greater than *N*, individuals of Rank *l* need to be selected. The selection based on crowding degree is NSGA II.

Dynamic population size adjustment

The population size *N(t)* is adjusted according to the current evolutionary generation (number of iterations) *t*, and the population size gradually decreases as the number of iterations increases. Dynamic population size adjustment is shown in formula (11).

$$N_t = N_{\min} + (N_{\max} - N_{\min}) \left(1 - \frac{t}{T}\right) \quad (11)$$

N_t: The population size at generation t, $N_{\max}$: The initial maximum population size, $N_{\min}$: Minimum population size, T: The total number of evolutionary generations.

The improved NSGA II process is shown in Fig. 10, where the red dashed box represents Dynamic Population Size Adjustment.

NSGA II process

Figure 10 shows the main process of NSGA II solving the hospital outpatient layout problem.

Case

Hospital introduction

Panzhihua Central Hospital was founded in 1965. It is a modern large-scale comprehensive hospital integrating medical treatment, teaching, scientific research, preventive health care, health management, emergency rescue, maternal and infant health care, integrated medical and nursing care, elderly-friendly, and Internet hospital. The hospital has a wide range of services, and its medical staff ranks first in Panxi, with more than 300,000 patients treated annually.

Current layout of the outpatient building

The hospital's outpatient building has three floors in total. The outpatient building includes many departments and examination areas. The current layout of the three floors is shown in Fig. 11. The first floor includes Emergency Department, Pediatric, Obstetrics gynecology, pharmacy, Manual registration payment, Machine registration payment, etc., among which the Emergency Department is not within the scope of outpatient layout optimization. The second floor includes outpatient departments such as Cardiology, Neurology, Hepatobiliary Surgery, Medical, Ophthalmology, Rheumatology, Endocrinology, Nephrology, Surgery, Orthopedics, and Dental. The third floor includes Ultrasound Department, Dermatology, Otolaryngology, ECG, EEG, EMG and other outpatient departments.

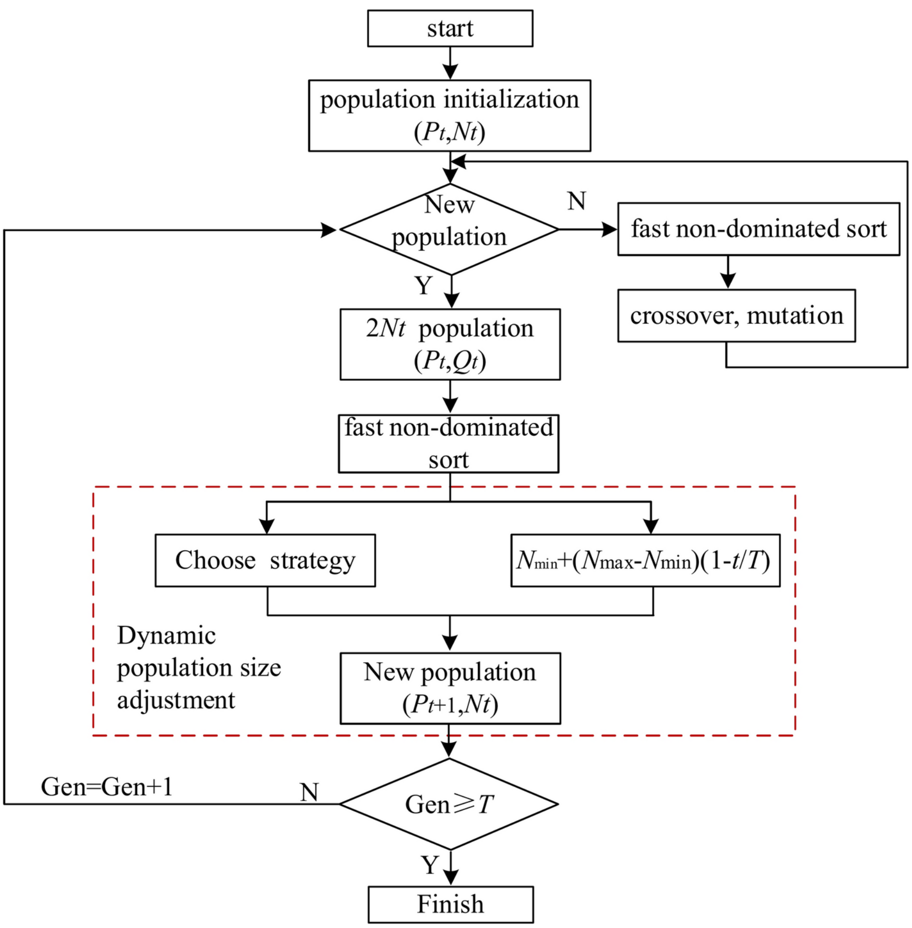

Fig. 10. Improved NSGA II algorithm flow.

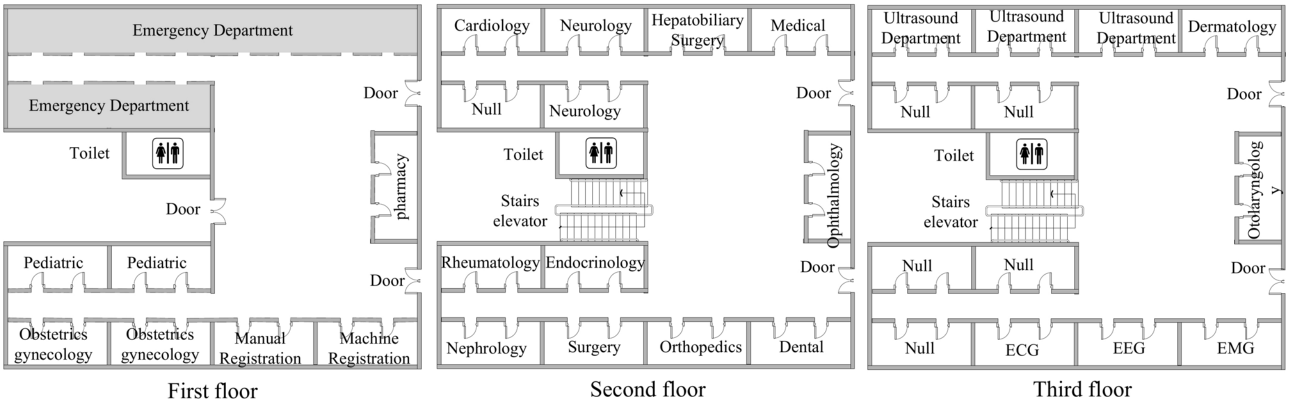

Fig. 11. Current layout of hospital outpatient department.

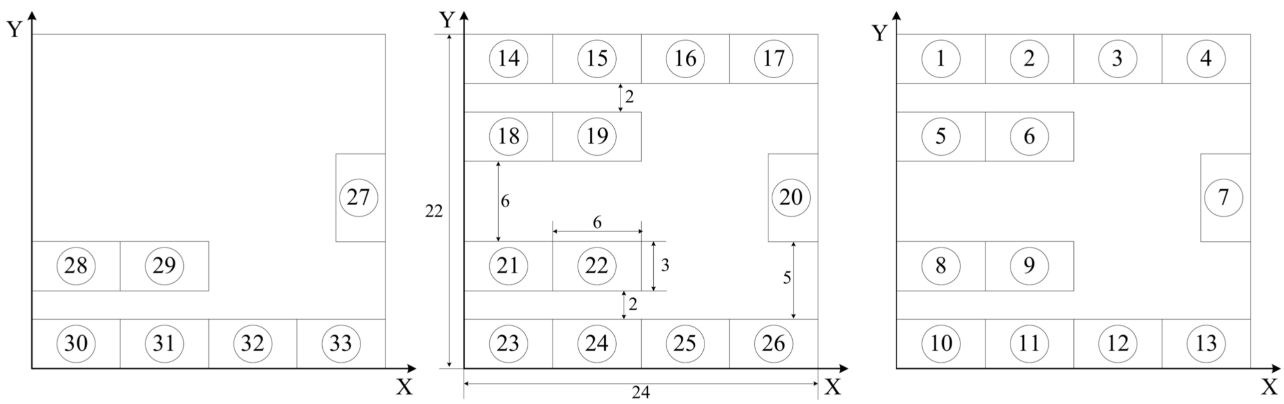

Fig. 12. Schematic diagram of hospital outpatient room numbering.

Outpatient clinic	Number	Outpatient clinic	Number
Pediatrics	1	Nephrology	13
Obstetrics and gynecology	2	Surgical	14
Manual charging	3	Orthopedics	15
Machine charges	4	Dentistry	16
Pharmacy	5	Ultrasound department	17
Cardiology	6	Dermatology	18
Neurology	7	Otolaryngology	19
Hepatobiliary surgery	8	ECG	20
Internal medicine	9	EEG	21
Ophthalmology	10	EMG	22
Rheumatology	11	Vacant room	null
Endocrinology	12		

Table 2. Clinic number.

The outpatient building has a total of 33 rooms. For the convenience of research, the rooms in the above-mentioned outpatient building are numbered as shown in Fig. 12.

Each clinic is represented by letters as shown in Table 2. If there are two same outpatient clinics, they are represented by a combination of letters and numbers. For example, if there are two pediatric departments, they are represented by 1a and 1b.

In summary, the current layout coding of the hospital outpatient building can be obtained as[17,17,17,18,null,null, null,null, null,20,21,22,6,7,8,9,null,7,10,11,12,13,14,15,16,5,1,1,2,2,3,4]. The values for Distance, Cost, Queueing, and Employee are as follows: Distance = 45,320,658, Cost = 2095.5, Queueing = 39,577,858.7, and Employee = 91,256.

Data

The medical treatment process and number of patients with major diseases in the hospital outpatient department are shown in Table 3.

As shown in Figs. 11 and 12, it can be seen that the calculation of OD_{ij} uses formula(2)-(5). The obtained OD_{ij} is shown in Table 4.

The intimacy weight w_{ij} between outpatient departments is shown in Table 5.

Note: The letters in Table 5 represent ranking values, where A = 5, B = 4, C = 3, D = 2, and U = 1.

The operating costs are shown in Table 6.

Parameters and environment settings

Since NSGA II is well-established in the field of facility layout engineering, but less so in hospital outpatient layouts, this paper adopts the parameters from references such as Zhang , Melek and Ding for the application in this case[17–19]. The parameters and environment are shown in Table 7.

Performance analysis of NSGA II

This case involves 33 rooms that need to be assigned outpatient departments. A total of 27 outpatient departments must be assigned to these 33 rooms, while the remaining 6 rooms can be assigned between 0 and 6 additional outpatient departments from the 27 available ones. The large scale of the problem presents a significant challenge for solving it.

To solve the large-scale multi-objective hospital layout problem, we applied adaptive population iteration adjustment to NSGA-II to ensure both population diversity and convergence. Detailed content can be found in the "Algorithm Design" section. To verify the effectiveness of the improved algorithm, we compared it with the multi-objective particle swarm optimization (MOPSO) and multi-objective ant colony optimization (MOACO) algorithms, with parameters referenced from[20–22]. The computational results were based on 100 satisfactory solutions, and the multi-objective values are plotted in Fig. 13.

The results in Fig. 13 show that the improved NSGA-II performs excellently in solving Cost, Distance, and Employee Efficiency compared to other methods. It also slightly outperforms MOPSO and MOACO in Patient Queueing, Distance, and Cost. Figure 14 shows the standard deviation of the four objective values $[D, C, Q, E]$ from the computation results. From Fig. 14, it can be observed that the results of NSGA-II are superior. However, the improved NSGA-II algorithm has the disadvantage of longer solving times and higher computational resource usage. Since changes to hospital outpatient layouts do not occur frequently (usually between a few years to several decades), real-time solving is not required, and there is no concern about the heavy consumption of computational resources.

From the analysis, it can be concluded that using the improved NSGA-II to solve the multi-objective problem of hospital layouts is highly feasible and meets our solving requirements.

Disease	Process	People	Disease	Process	People
Flu	[3, 5, 9]	2625	Eye disease	[3,10,3,5]	1855
	[4, 5, 9]	23,626		[4,10,4,5]	16,692
Muscle atrophy	[3,15,22,15,3,5]	5287	Chronic kidney disease	[3,13,17,13,3,5]	3135
	[4,15,22,15,4,5]	5287		[4,13,17,13,4,5]	7315
Periodontitis	[3,,16,3,5]	5176	Epilepsy	[3,7,21,7,3,5]	2355
	[4,16,4,5]	7765		[4,7,21,7,4,5]	5496
Cholecystitis	[3,8,17,8,3,5]	3562	Irregular menstruation	[3,2,17,2,3,5]	1211
	[4,8,17,8,4,5]	8311		[4,2,17,2,4,5]	10,897
Arthritis	[3,7,3,5]	4624	Pregnant woman	[3,2,17,2,3,5]	675
	[4,7,4,5]	4624		[3,1,3,5]	6076
Cervical spondylosis	[3,15,3,5]	4725	Pediatrics	[3,1,3,5]	1302
	[4,15,4,5]	11,025		[4,1,4,5]	11,722
Anorectal disease	[3,14,3,5]	4158	Rhinitis	[3,19,3,5]	1025
	[4,14,4,5]	9703		[4,19,3,5]	9223
Skin disease	[3,18,3,5]	1431	Coronary heart disease	[3,6,17,20,6,3,5]	4571
	[4,18,4,5]	12,878		[4,6,17,20,6,4,5]	4571
Thyroid disease diabetes	[3,12,17,12,3,5]	2913	Hypertension	[3,6,17,6,3,5]	6084
	[4,12,17,12,4,5]	11,654		[4,6,17,6,4,5]	9126
	[3,12,3,5]	10,024	Stroke	[3,7,17,7,3,5]	2526
	[4,12,4,5]	10,024		[4,7,17,7,4,5]	5895
Fatty liver	[3,9,17,9,3,5]	1527	Rheumatic heart disease	[3,11,17,20,11,3,5]	2106
	[4,9,17,9,4,5]	13,746		[4,11,17,20,11,4,5]	2106

Table 3. Medical treatment process and number of people.

OD_{ij}	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
1	0	6	12	18	2	8	26	32	26	34	28	28	34	62	56	56	62	60	54	54	62	56	60	54	56	62	58	66	60	64	58	60	66
2	6	0	6	12	8	2	20	26	20	28	22	22	28	56	50	50	56	54	48	48	56	50	54	48	50	56	52	60	54	58	52	54	60
3	12	6	0	6	14	8	14	26	20	28	22	16	22	56	50	50	56	54	48	48	56	50	54	48	50	56	52	60	54	58	52	54	60
4	18	12	6	0	20	14	8	32	26	34	28	22	16	62	56	56	62	60	54	54	62	56	60	54	56	62	58	66	60	64	58	60	66
5	2	8	14	20	0	6	24	30	24	32	26	26	32	60	54	54	60	58	52	52	60	54	58	52	54	60	52	60	54	58	52	54	60
6	8	2	8	14	6	0	18	24	18	26	20	20	26	54	48	48	54	52	46	46	54	48	52	46	48	54	50	58	52	56	50	52	58
7	26	20	14	8	24	18	0	24	18	26	20	14	8	54	48	48	54	52	46	46	54	48	52	46	48	54	50	58	52	56	50	52	58
8	32	26	26	32	30	24	24	0	6	2	8	14	20	62	56	56	62	60	54	54	62	56	60	54	56	62	58	66	60	64	58	60	66
9	26	20	20	26	24	18	18	6	0	8	2	8	14	56	50	50	56	54	48	48	56	50	54	48	50	56	52	60	54	58	52	54	60
10	34	28	28	34	32	26	26	2	8	0	6	12	18	60	54	54	60	58	52	52	60	54	58	52	54	60	56	64	58	62	56	58	64
11	28	22	22	28	26	20	20	8	2	6	0	6	12	54	48	48	54	52	46	46	54	48	52	46	48	54	50	58	52	56	50	52	58
12	28	22	16	22	26	20	14	14	8	12	6	0	6	56	50	50	56	54	48	48	56	50	54	48	50	56	52	60	54	58	52	54	60
13	34	28	22	16	32	26	8	20	14	18	12	6	0	62	56	56	62	60	54	54	62	56	60	54	56	62	58	66	60	64	58	60	66
14	62	56	56	62	60	54	54	62	56	60	54	56	62	0	6	12	18	2	8	26	32	26	34	28	28	34	54	62	56	60	54	56	62
15	56	50	50	56	54	48	48	56	50	54	48	50	56	6	0	6	12	8	2	20	26	20	28	22	22	28	48	56	50	54	48	50	56
16	56	50	50	56	54	48	48	56	50	54	48	50	56	12	6	0	6	14	8	14	26	20	28	22	16	22	48	56	50	54	48	50	56
17	62	56	56	62	60	54	54	62	56	60	54	56	62	18	12	6	0	20	14	8	32	26	34	28	22	16	54	62	56	60	54	56	62
18	60	54	54	60	58	52	52	60	54	58	52	54	60	2	8	14	20	0	6	24	30	24	32	26	26	32	52	60	54	58	52	54	60
19	54	48	48	54	52	46	46	54	48	52	46	48	54	8	2	8	14	6	0	18	24	18	26	20	20	26	46	54	48	52	46	48	54
20	54	48	48	54	52	46	46	54	48	52	46	48	54	26	20	14	8	24	18	0	24	18	26	20	14	8	46	54	48	52	46	48	54
21	62	56	56	62	60	54	54	62	56	60	54	56	62	32	26	26	32	30	24	24	0	6	2	8	14	20	54	62	56	60	54	56	62
22	56	50	50	56	54	48	48	56	50	54	48	50	56	26	20	20	26	24	18	18	6	0	8	2	8	14	48	56	50	54	48	50	56
23	60	54	54	60	58	52	52	60	54	58	52	54	60	34	28	28	34	32	26	26	2	8	0	6	12	18	52	60	54	58	52	54	60
24	54	48	48	54	52	46	46	54	48	52	46	48	54	28	22	22	28	26	20	20	8	2	6	0	6	12	46	54	48	52	46	48	54
25	56	50	50	56	54	48	48	56	50	54	48	50	56	28	22	16	22	26	20	14	14	8	12	6	0	6	48	56	50	54	48	50	56
26	62	56	56	62	60	54	54	62	56	60	54	56	62	34	28	22	16	32	26	8	20	14	18	12	6	0	54	62	56	60	54	56	62
27	58	52	52	58	52	50	50	58	52	56	50	52	58	54	48	48	54	52	46	46	54	48	52	46	48	54	0	24	18	26	20	14	8
28	66	60	60	66	60	58	58	66	60	64	58	60	66	62	56	56	62	60	54	54	62	56	60	54	56	62	24	0	6	2	8	14	20
29	60	54	54	60	54	52	52	60	54	58	52	54	60	56	50	50	56	54	48	48	56	50	54	48	50	56	18	6	0	8	2	8	14
30	64	58	58	64	58	56	56	64	58	62	56	58	64	60	54	54	60	58	52	52	60	54	58	52	54	60	26	2	8	0	6	12	18
31	58	52	52	58	52	50	50	58	52	56	50	52	58	54	48	48	54	52	46	46	54	48	52	46	48	54	20	8	2	6	0	6	12
32	60	54	54	60	54	52	52	60	54	58	52	54	60	56	50	50	56	54	48	48	56	50	54	48	50	56	14	14	8	12	6	0	6
33	66	60	60	66	60	58	58	66	60	64	58	60	66	62	56	56	62	60	54	54	62	56	60	54	56	62	8	20	14	18	12	6	0

Table 4. OD_{ij} distance (Meters).

Optimal decoding and analysis

The optimal solution selected in the above calculation is [1, 1, 15, 20, 2, 2, 5, 11, 16, Null, 14, 4, 18, 13, 6, 17, 17, 19, 17, 5, 21, 7, 22, 7, 4, 3, 5, 10, 9, 8, 12, 4, 3]. The decoded hospital outpatient layout is shown in Fig. 15, and the correspondence between the numbers and the outpatient departments is provided in Table 2.

The values for Distance, Cost, Queueing, and Employee are as follows: Distance = 22,699,860, Cost = 2213.5, Queueing = 16,210,017, and Employee = 130,736.The improvements in Fig. 15, compared to the original layout in Fig. 12, not only involve changes in position but also the addition of five new outpatient departments, including Manual Charging, Machine Charges, and Pharmacy, as indicated by the green markings in Fig. 15. Although the increase in the number of outpatient departments resulted in a 5.6% rise in hospital costs, the walking distance for patients was reduced by 57.2%, and patient queueing time improved by 59%. Additionally, the outpatient departments that are closely related are positioned adjacently, which enhances staff efficiency.

Conclusion and discussion

Conclusion

This study successfully implemented multi-objective optimization of hospital outpatient layouts using the NSGA-II algorithm, significantly reducing patient walking distances and effectively controlling hospital operational costs. In the empirical case study of Panzhihua Central Hospital, the optimized layout plan, while adding five new outpatient departments, resulted in only a 5.6% increase in total operational costs. Concurrently, the total patient walking distance was reduced by 57.2%, patient waiting times improved by 59%, and staff efficiency was enhanced. These results demonstrate the high effectiveness and feasibility of the NSGA-II algorithm in addressing the multi-objective optimization problems of hospital outpatient layouts.

When compared with traditional methods, the NSGA-II algorithm provides a superior approach to balancing multiple conflicting objectives. While conventional optimization models often focus on reducing walking

w_{ij}	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	A	I	I	I	O	O	I	E	I	E	E	E	I	I	O	E	E	O	O	O	O	O
2	I	A	I	I	E	E	O	I	E	I	E	E	E	I	I	O	E	E	O	O	O	O
3	I	I	A	E	E	I	I	I	1	I	1	I	I	1	I	O	I	I	O	I	I	I
4	I	I	E	A	I	1	1	I	1	I	1	I	I	1	I	O	I	1	O	1	1	I
5	O	E	E	I	A	I	I	I	I	I	I	I	I	I	I	O	I	I	O	I	I	I
6	o	E	I	I	I	A	E	E	E	I	E	E	E	E	I	O	E	I	E	E	E	E
7	I	O	I	1	I	E	A	E	E	I	E	E	E	I	I	O	E	I	E	E	E	E
8	E	I	I	I	I	E	E	A	I	I	I	I	I	E	I	O	I	I	E	I	I	I
9	I	E	I	I	I	E	E	I	A	I	I	I	I	I	I	O	I	I	E	I	I	I
10	E	I	I	1	I	I	1	I	1	A	1	I	1	1	I	O	I	1	I	1	1	I
11	E	E	I	I	I	E	E	I	I	I	A	E	E	I	I	O	I	I	E	I	I	I
12	E	E	I	I	I	E	E	I	I	I	E	A	E	I	I	O	I	I	E	I	I	I
13	I	E	I	1	I	E	E	I	1	I	E	E	A	I	I	O	I	I	E	I	1	I
14	I	I	I	I	I	E	I	O	I	I	I	I	I	A	E	O	I	I	E	I	I	I
15	O	I	I	I	I	I	I	I	I	I	I	I	I	E	A	O	I	I	E	I	I	I
16	E	O	O	O	O	O	O	O	O	O	O	O	O	O	O	A	O	O	O	O	O	O
17	E	E	I	I	I	E	E	I	I	I	I	I	I	I	I	O	A	I	E	I	I	I
IS	O	E	I	1		1	1	I	1	I	I	I	1	1	I	O	I	A	E	1	1	I
19	O	O	O	O	O	E	E	O	E	I	E	E	E	I	I	O	E	E	A	I	I	I
20	O	O	I	I	I	E	E	I	I	I	I	I	I	E	E	O	I	I	I	A	E	E
21	O	O	I	1	I	E	E	I	I	I	1	I	I	1	I	O	I	I	I	E	A	E
22	O	O	I	I	I	E	E	I	I	I	I	I	I	I	I	O	I	I	I	E	E	A

Table 5. w_{ij} (A,E,I,O,U).

Outpatient clinic	1	2	3	4	5	6	7	8	9	10	11
F	19	32	5	1	25	21	23	19	20	42	23
V	42	44	20	0.5	20	50	60	55	54	45	42
Outpatient clinic	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
F	22	21	61	31	72	95	21	32	57	109	61
V	46	50	57	45	55	18	43	45	14	17	15

Table 6. Operating cost (10,000 Yuan).

Name	Environment	Name	Parameters
Programming languages	Python	Population size	$N_{\max} = 1000$ $N_{\min} = 100$
Computer hardware	Intel(R) Core(TM) i7-9750H CPU, RAM 24 GB	Max generations	1000
Computer system	Win 10	Crossover probability	0.9
Libraries/Frameworks	Numpy, Pandas, Deap	Mutation probability	0.05

Table 7. Parameters and environment.

distance, they may overlook other factors like operational costs or patient queuing times. In contrast, the NSGA-II algorithm in this study efficiently addresses all four critical objectives: walking distance, hospital operating costs, patient queueing, and employee efficiency. This balanced approach offers a more comprehensive solution for outpatient layout optimization, ensuring that hospitals not only improve patient experience but also enhance operational efficiency.

The results demonstrate the high effectiveness and feasibility of the NSGA-II algorithm in multi-objective optimization tasks, providing a robust framework for addressing the complex and often conflicting goals of healthcare facility management. By optimizing service levels and costs simultaneously, the study supports sustainable hospital development.

Discussion

1. Impact of practical application

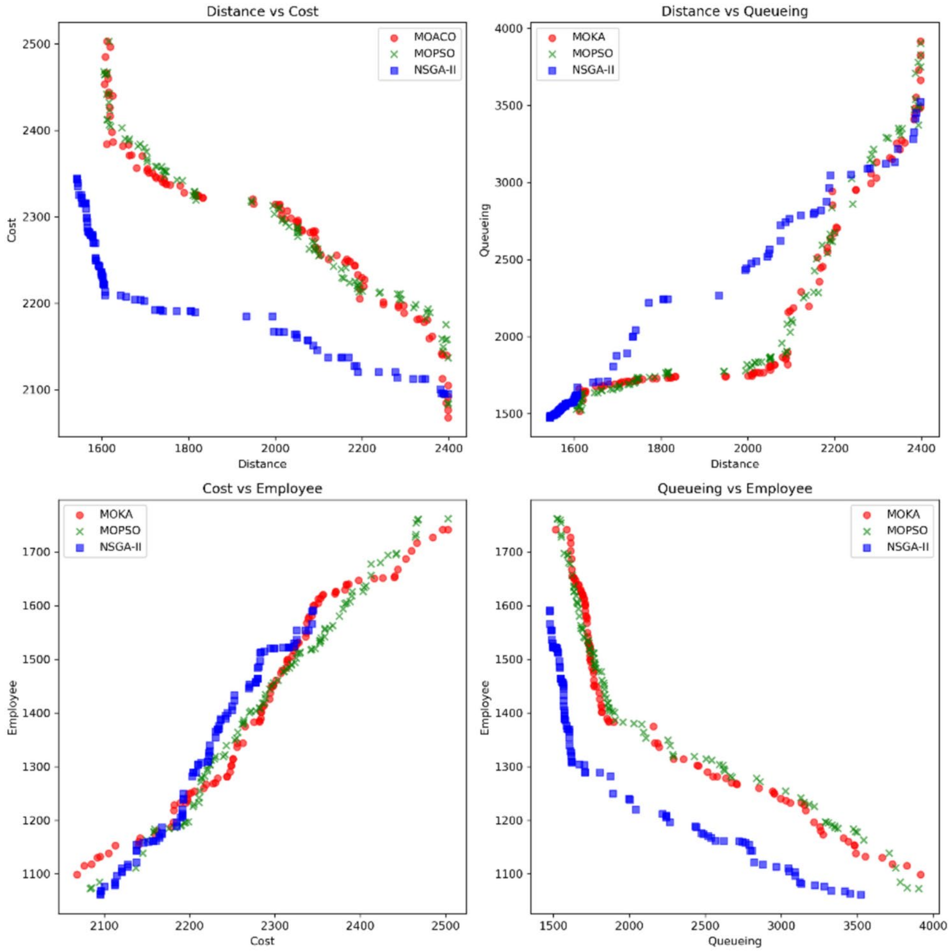

Fig. 13. Comparison of algorithm solution quality.

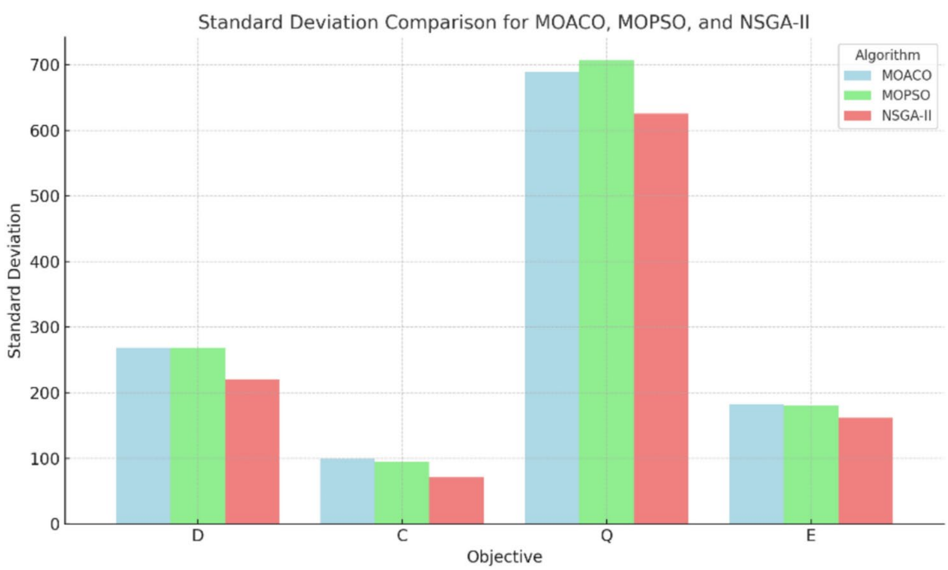

Fig. 14. Comparison chart of the standard deviations of the results from the three algorithms (*Note*: *D* represents patient walking distance, *C* represents hospital operating costs, *Q* represents patient queueing, and *E* represents employee efficiency).

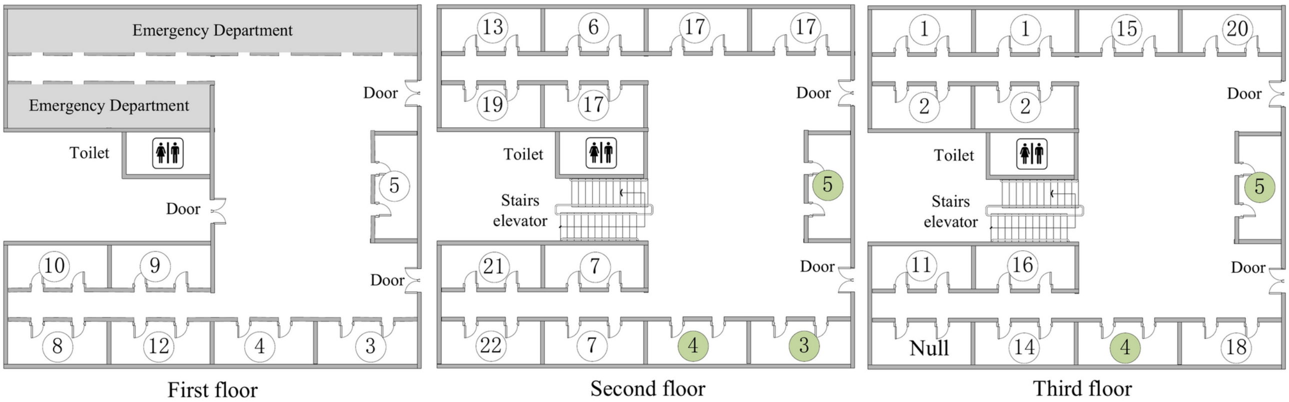

Fig. 15. Optimal layout diagram of outpatient clinic.

The optimized outpatient layout holds significant practical value in hospital management. Firstly, reducing patient walking distances directly enhances patient satisfaction and their overall healthcare experience, contributing to a positive reputation and strong brand image for the hospital. Secondly, operational cost control achieved through layout optimization can save resources, allowing further investment in medical equipment upgrades and service quality improvements. Furthermore, a rational layout design helps increase the utilization rate of medical resources, minimize conflicts and resource wastage between departments, and promote overall operational efficiency of the hospital.

2. Limitations of the study

Despite the notable achievements of this study, certain limitations exist. Firstly, the research case is limited to Panzhihua Central Hospital, and the generalizability of the results needs to be validated across a broader range of hospitals with varying types and sizes. Secondly, the model may need to incorporate more real-world factors in practical applications, such as dynamic changes in patient flow and the requirements for responding to sudden public health emergencies. Additionally, the data used in this study are primarily based on existing patient flow, operational costs, staff efficiency, and patient queuing. One of the challenges faced during the study was the difficulty in acquiring accurate and comprehensive data, particularly with regard to patient flow patterns and operational costs, which can vary significantly across different hospitals. Moreover, the computational demands of the proposed approach can be substantial, especially when dealing with large datasets or more complex hospital layouts, which may require significant computational resources and time. Furthermore, scalability concerns may arise when applying the model to larger hospital networks, where the complexity of the layout and operational factors increases. Future research should consider addressing these challenges by incorporating more variables, optimizing the computational efficiency of the model, and exploring solutions for scalability to make the model more practical for real-world applications in larger hospital networks.

3. Application in actual management and model constraints

In actual management, applying the NSGA-II algorithm to optimize outpatient layouts requires adjustments tailored to the specific circumstances of each hospital. For instance, different hospitals have varying department configurations, building structures, and patient needs, necessitating adjustments to the model parameters based on real conditions. Moreover, the model may face challenges such as difficulties in data acquisition and high computational resource demands during practical application. Therefore, when promoting its application, it is essential to integrate the algorithm with the hospital's information management systems to ensure data accuracy and real-time updates while optimizing the algorithm's computational efficiency to meet management needs.

4. Future research directions

Future research can further deepen the study from the following aspects: Firstly, expanding the research cases to include hospitals of different types and sizes to verify the applicability and effectiveness of the NSGA-II algorithm in a wider range of scenarios. Secondly, integrating real-time data and dynamic optimization methods to enhance the model's responsiveness to changes in patient flow and emergency events. Additionally, exploring the integration of the optimized model with the hospital's information management systems for intelligent outpatient layout management. Finally, considering the introduction of more objectives, such as environmental comfort and emergency response capabilities, to further improve the comprehensive effectiveness of layout optimization.

In summary, this study not only validated the effectiveness of the NSGA-II algorithm in optimizing hospital outpatient layouts but also provided practical and feasible solutions for actual management. However, as the healthcare environment continues to evolve, optimization models must be continuously refined and adjusted to better meet the developmental needs of hospitals.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions

Conceptualization, YZ and GJ; methodology, YZ; software, YZ and GJ; validation, JG and YZ; formal analysis, JG and YZ; investigation, YZ; resources, YZ; data curation, JG and YZ; writing—original draft preparation, YZ; writing—review and editing, JG and YZ; visualization, JG; supervision, YZ; project administration, YZ; funding acquisition, YZ All authors have read and agreed to the published version of the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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