IIAI Open Conference Publication Series
IIAI Letters on Informatics and Interdisciplinary Research
Vol. 001, LIIR039
DOI: https://doi.org/10.52731/liir.v001.039

Bed Management for Inpatients Using Particle Swarm Optimization

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Abstract

We present a particle swarm optimization model in inpatient bed management. The management satisfies patient and hospital preferences in the allocation of beds in hospitals. The patient's interest is to be satisfied as much as possible with their bed preferences, such as private or general rooms. Meanwhile, hospitals prefer to receive patients from the same department in the same room, to minimize doctor and nurse movement and provide medical care efficiently. A formula is drawn out with the two interests in the objective function. The numerical results show the effectiveness of the proposed algorithm.

Keywords: 0–1 integer programming, Bed management, Particle swarm optimization

1 Introduction

In Japan, the efficient provision of high-quality medical care has become a challenge in anticipation of the increasing medical needs of an aging population. Specifically, medical needs are expected to accelerate after 2025 [1]. Efficient use of medical resources is required to efficiently provide quality medical care. Beds are essential among medical resources for satisfying the demand for medical care. Since 2014, the Ministry of Health, Labor, and Welfare (MHLW) has published an annual report on hospital bed functions (such as bed counts and occupancy rates) to better understand the state of hospital bed functions in each hospital in Japan [2]. MHLW also estimates medical care demand and the number of beds required in each region by 2025 for each medical institution and develops regional medical care plans [3]. Bed management also affects the response to emergency care. Specifically, if there are not enough beds, it is impossible to accept seriously ill patients, decreasing the demand response rate. It is necessary to establish an efficient bed management system not only to meet increasing medical needs but also to prevent a decline in the demand response rate to emergency transport.

In this study, bed management refers to the scheduling problem of determining which room bed to assign newly admitted patients. The number of beds varies depending on the size of the hospital, ranging from less than 100 to more than 1,000. Hospitals receive the number of patients in proportion to the number of beds; for example, a relatively large hospital receives 2,000 patients per month. Because bed management must consider many patients and beds, it is difficult, even for skilled personnel, to manually create optimal schedules that satisfy the constraints. Currently, actual bed management is performed ad hoc by the head nurse or department head.

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Bed management is a complex problem that requires the consideration of various types of beds, such as isolation, private rooms, and general beds. Therefore, many studies use simulations, and only a few studies provide mathematical models [4][5]. Mathematical models have the advantage that the objectives and conditions are clear, and the results are easy to interpret. Demeester et al. [6] used a mathematical modeling study to formulate the inpatient bed scheduling problem as a mixed-integer programming problem. The amount of violation is minimized using soft constraints, such as gender constraints, where men and women are in separate rooms. A hybrid tabu search algorithm was used to solve this problem. Bastos et al. [7] reformulated the problem in a simplified form as mixed-integer programming with an optimal solution based on the model of Demeester et al. [6]. Schafer et al. [8] defined the mixed-integer programming problem's objective function as utility maximization for stakeholders, such as patients, doctors, and nurses. Furthermore, a heuristic method was developed to apply the proposed model to allocate beds in a large hospital. Bed management has mainly been studied in Europe and the United States. Bed management differs between Japan and other countries. For example, while it is possible to temporarily admit a patient to a corridor outside the room in a foreign country, the patient must be admitted to a bed in the room in Japan. Therefore, foreign models cannot be applied directly to bed management in Japan.

We propose a particle swarm optimization (PSO) model for inpatient bed management. The proposed PSO model creates a bed schedule that satisfies both patient and hospital requirements. The patient requires to satisfy the bed preference, such as a private or general room, as much as possible. The hospital must rationalize the delivery of medical care by receiving patients from the same department in the same room to minimize doctor and nurse movement. Additionally, the schedule created satisfies the constraint of separate rooms for men and women, as well as the current bed occupancy of admitted patients. The effectiveness of the algorithm is verified using numerical analysis in the context of a hospital.

2 Bed Management

2.1 Mathematical Programming

We consider a model of bed management problem that satisfies patient and hospital preferences and assign patients to beds. Bed management is formulated as the following 0−1 integer programming model.

Notation

Index sets.

B: Set of beds.

I: Set of beds in a private room, where $I \subset B$.

P: Set of patients.

Parameters.

s_{bp} $(b \in B, p \in P)$: 1 if patient p can use bed b, and 0 otherwise. The parameter considers information, such as current bed status and gender restriction.

h_{ip} $(i \in I, p \in P)$: Penalty when a patient p who wants a private room is assigned to a general bed.

d_{bp} $(b \in B, p \in P)$: Penalty when patient p is admitted to bed b outside the department.

Variables.

x_{bp} $(b \in B, p \in P)$: 1 if patient p is admitted to bed b, and 0 otherwise.

Formulation

$$\text{Minimize} \quad \sum_{i \in I} \sum_{p \in P} h_{ip} x_{ip} + \sum_{b \in B} \sum_{p \in P} d_{bp} x_{bp} \tag{1}$$

subject to

$$\sum_{b \in B} x_{bp} \leq 1, \qquad \forall p \in P, \tag{2}$$

$$\sum_{p \in P} s_{bp} x_{bp} \leq 1, \quad \forall b \in B, \tag{3}$$

$$x_{bp} \leq s_{bp}, \qquad \forall b \in B, \forall p \in P, \tag{4}$$

$$x_{bp} = \{0, 1\}, \qquad \forall b \in B, \forall p \in P. \tag{5}$$

In the above formulation, the objective function (1) comprised two terms. The first term of the objective function satisfies the patient's request for a private bed as much as possible. The second term of the objective function accepts patients from the same department to the same room as much as possible. Constraint (2) ensures that patient i is admitted to bed b exactly once. Constraint (3) prevents double-booking of beds. Constraint (4) prevents assignment if patient p cannot use bed b. Constraint (5) is a binary constraint.

This study proposed a model that derives a solution to large-scale bed management in a reasonable time. Therefore, the bed management model described in this section as a 0–1 integer programming problem is reformulated as a PSO model.

2.2 Particle Swarm Optimization

Many combinatorial optimization problems are NP-hard, and finding exact optimal solutions for large systems is generally difficult. Here, we describe the application of learning techniques based on swarm intelligence to the automatic construction of hospital bed schedules. We use a PSO [8] method as the learning algorithm based on swarm intelligence.

PSO is an evolutionary optimization calculation technique based on the concept of swarm intelligence. The hypersurface of an objective function is searched in PSO as information s exchanged between swarms of search points. The next state of each individual is generated based on the optimal solution in its search history ("personal best"; ***xpbest***), the optimal solution in the combined search history of all individuals in the swarm ("global best"; ***xgbest***), and the current velocity vector. Briefly, assuming a population size N_p and problem dimension N_d, the position and velocity of an individual i (where $i = 1, ..., N_p$) at the $(t + 1)$-th step of the search, respectively, $\boldsymbol{x}_i^{(t+1)}$ and $\boldsymbol{v}_i^{(t+1)}$ are:

$$\boldsymbol{x}_i^{(t+1)} = \left(x_{i,1}^{(t+1)}, \dots, x_{i,j}^{(t+1)}, \dots, x_{i,N_d}^{(t+1)}\right) \tag{6}$$

$$\boldsymbol{v}_i^{(t+1)} = \left(v_{i,1}^{(t+1)}, \dots, v_{i,j}^{(t+1)}, \dots, v_{i,N_d}^{(t+1)}\right) \tag{7}$$

These two variables can be updated using the following equation, using the position and velocity at the t-th step, $\boldsymbol{x}_i^{(t)}$ and $\boldsymbol{v}_i^{(t)}$:

$$v_{i,j}^{(t+1)} = \gamma \cdot v_{i,j}^{(t)} + c_1 \cdot rand1_{i,j} \cdot \left(xpbest_{i,j}^{(t)} - x_{i,j}^{(t)}\right)$$
$$+c_2 \cdot rand2_{i,j} \cdot \left(xgbest_j^{(t)} - x_{i,j}^{(t)}\right) \tag{8}$$

$$x_{i,j}^{(t+1)} = x_{i,j}^{(t)} + v_{i,j}^{(t+1)} \tag{9}$$

Here, $\boldsymbol{xpbest}_i^{(t)}$ represents the optimal solution discovered during the search through the t-th step by individual i, whereas $\boldsymbol{xgbest}_i^{(t)}$ represents the optimal solution discovered during the search through the t-th step by the swarm to which individual i belongs. The term γ represents inertia, and it takes a value between [0, 1] (inertia factor); c_1 and c_2 are weighting factors, known as the cognitive learning and social learning factors (learning factors), respectively; and *rand*1 and *rand*2 are uniform random numbers in [0, 1].

In the proposed model, the numerical value of the j-th dimension of position vector $\boldsymbol{x}$ in the PSO represents the ID of the bed to which the j-th patient is assigned. We consider 1) not assigning women (men) to male (female) rooms and 2) not assigning more patients than the number of beds in each room, as hard constraints. We consider 3) not assigning a patient from one department to a bed in another department and 4) not assigning a patient who requests a private room to a general ward, as soft constraints. Then, we consider minimizing the total number of violations of those constraints, as an objective function. Here, we minimize the following evaluation function: $f(\boldsymbol{x})$.

$$f(x) = \sum_{k=1}^{4} w_k \cdot Npenalty_k \tag{10}$$

where $Npenalty_k$ is the number of violations of constraint k and w_k is a constant that represents the weight of constraint k. Note that the value of the weights for hard constraints should be set to be sufficiently larger than the value of the weights for soft constraints.

3 Numerical Experiments

Here, numerical results confirm the validity of the proposed algorithm.

3.1 Data

Based on hospital data, we set the parameters for numerical analysis [2]. We considered a 100-bed scheduling problem with 90 patients. However, considering the current bed occupancy by admitted patients, 30 patients shall be assigned to 40 beds, i.e., B = 40 and P = 30. Here, considering the ratio of the number of patients to be assigned to the number of available beds, a, as one indicator of the problem's difficulty, $\alpha = P/B = 0.75$ in this problem. The hospital has two departments, each with four private beds (i.e., I = 4) and eight male and female beds. In both departments, two male and one female patient request private rooms, whereas eight male and four female patients have no bed requests.

3.2 Results

Table 1 shows an example of the best bed assignment obtained using PSO. The solution search results in an assignment with an objective function value of zero, i.e., no constraint violations, thus all patient and hospital requirements are satisfied. The number of constraint violations during the solution search process using PSO and the number of constraint violations when random assignment is applied is shown in Figure 1. The number of constraint violations in PSO decreased quickly as soon as the solution search started, and a solution satisfying all constraints was obtained at 65 steps. Here, the number of individuals in PSO is 100,000, and the calculation of 500 search steps took approximately 50 s. The validity of the proposed algorithm was confirmed, as previously stated.

Table 1: An example of the best bed assignment obtained using PSO

				Number of patients							
				Department 1				Department 2			
				Request for private room		No request for private room		Request for private room		No request for private room	
				Male	Female	Male	Female	Male	Female	Male	Female
				2	1	8	4	2	1	8	4
Bed capacity	Department 1	Private	4	2	1	0	1	0	0	0	0
		Male	8	0	0	8	0	0	0	0	0
		Female	8	0	0	0	3	0	0	0	0
	Department 2	Private	4	0	0	0	0	2	1	0	0
		Male	8	0	0	0	0	0	0	8	0
		Female	8	0	0	0	0	0	0	0	4

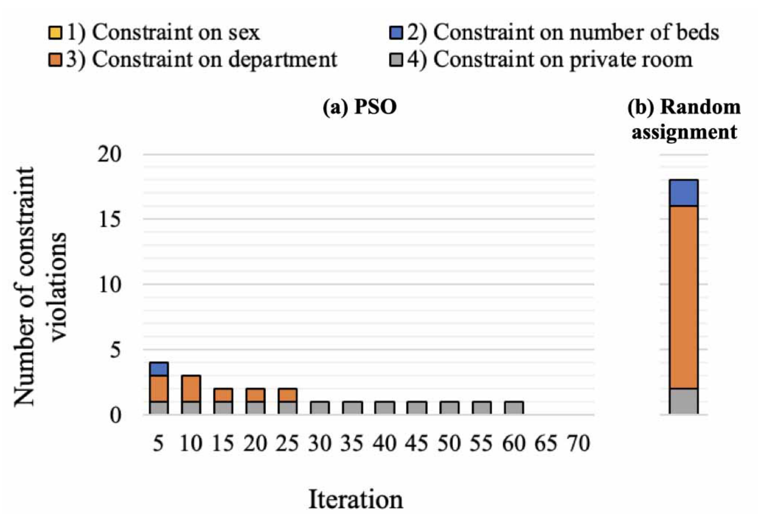

Figure 1: Comparison of the number of constraint violations: PSO vs. random assignment

4 Concluding Remarks

We proposed the PSO model for inpatient bed management. In the algorithm, we created a schedule that considers patient and hospital preferences while satisfying the current bed conditions and gender constraints. In the numerical analysis, a hospital instance was used to confirm the validity of the algorithm. Thus, we created a schedule that satisfies gender constraints and current bed status, as well as patient and hospital preferences.

Numerical experiments were performed under a scenario, where the ratio of the number of patients allocated to the number of available beds, α, was 0.75. Future work will include numerical analysis for scenarios with a larger number of patients to be assigned to available beds (i.e., larger values of α). This study proposed a model that derives a solution for large-scale bed management in a reasonable time. Therefore, we further verify the application of the algorithm to large instances. We compare our method to other meta-heuristic algorithms and explicit solution techniques. Additionally, numerical experiments with various objective functions describing different real situations in the hospital will be conducted in the future.

Acknowledgement

This work was partially supported by the Sasakawa Scientific Research Grant from The Japan Science Society.

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