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A Decision Support System for Skill-Based Nurse Scheduling in an Intensive Care Unit

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Highlights

- This paper focuses on a nurse scheduling model based on nurses' skill levels.
- The problem is modeled with 0-1 Goal Programming.
- An application is performed at a 3rd level of surgical intensive care of a general hospital.

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Abstract

The main target of health institutions is to provide the health services needed by society at the desired quality with the lowest possible cost. Considering the total number of employees in health institutions, nurse assignment and scheduling have an essential role in increasing efficiency and improving service quality due to the one-to-one interaction of nurses with patients. This study proposes a nurse scheduling model based on nurses' skill levels incorporated into a decision support system. The skill level of nurses is assessed using Analytic Hierarchy Process and Technique for Order Preference by Similarity to Ideal Solution method based on eight criteria. The nurse scheduling problem is then modeled with 0-1 Goal Programming, considering the skill assessment as a constraint. The practicality of the proposed model is examined for the assignment and scheduling conditions of nurses at the 3rd level of surgical intensive care in a general hospital, and the valuable aspects of the proposed approach are discussed. When the proposed solution is compared with the current situation, it is realized that one nurse is saved without worsening the constraints.

1. INTRODUCTION

Health institutions are constantly growing in complexity and capacity, thus having an increasing share of expenditure in national budgets [1]. Human resources management in health institutions, particularly hospitals, constitutes a significant part of the annual budget [2-4]. Despite that, hospitals largely have difficulty finding sufficient resources in terms of human resources, causing lower expected health service levels [5]. Because of this, hospital managers have no choice but to improve the hospitals' existing human resources, [6] but facing with pressure to plan available human resources efficiently [2, 7]. One possible method to alleviate this constraint is to enhance better decision support systems in human resource planning that meet hospital policies and staff expectations and provide insight into planning outcomes [5].

Nurses, playing a key role in the central workforce of hospitals, contribute to achieving high performance for patient satisfaction and health service quality [8-10]. Therefore, it is indispensable to apply studies to increase the productivity and quality of nurses working at the hospital. Nurse scheduling has a crucial role in increasing the productivity of nurses since it creates a model in line with the needs and choices of the nurses and ensures that the nurses and the relevant enterprise can provide health services in a planned and systematic way.

The nurse scheduling problem (NSP) is one of the topics that has been receiving attention in the literature for a long time [11, 12]. NSP has started to attract the attention of health researchers again because of the

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long working hours under stressful conditions during the COVID period, which greatly affects psychological, health, morale and work performance [13]. NSP is mostly made manually in many hospitals. However, a manually developed schedule that meets the requirements, ensures a fair distribution of shifts among employees, and takes into account employee preferences may be cumbersome [14]. NSP aims to establish a schedule for a number of nurses over a specified term (often two weeks or one month) while providing a certain level of healthcare and complying with hospital management guidelines [15]. More clearly, NSP means assigning a certain number of nurses to different work shifts with a set of hard and soft constraints, including the preferences of staff and the demands of hospitals, to balance the workload of nurses, increase hospital efficiency, reduce operating costs [11, 16-19], improve staff and patient safety and satisfaction to reduce the administrative workload of hospital administrators [11, 20-22].

In intensive care services offered in inpatient health facilities today, nurses are assigned with the number of work force per bed, regardless of the bed occupancy rate and the workforce qualifications of each nurse at all hours of the day. Day and night shift assignments for nurses assigned to the intensive care service are created manually as a result of the effort of the hospital manager [23]. This manual method is likely to ignore the skills of nurses, and due to the uneven and unbalanced workload, affecting the work peace among the nurses. This study investigates the solution to three fundamental problems that nurses face while delivering intensive care services.

(1) Nurses' assignment according to the actual number of beds, regardless of whether the bed is in use or not in health institutions. Facing idle capacity and inefficiency when the bed is idle or temporary.
(2) Failure to ensure a fair and balanced distribution of workload among nurses.
(3) Not minimizing the quality differences in service delivery arising from nursing services between shifts.

In this study, the following solutions have been sought to address the above problems:

(1) The number of nurses needed per patient in the day and night shifts in the intensive care unit is determined by integrating the minimum number of nurses needed for any time of the day, and the bed occupancy rate is predicted by the Holt-Winter method [24].
(2) Skill management, the evaluation of the right person at the right time, in the right place [25], plays an main role in increasing the hospital's performance and achieving a more efficient structure [26, 27]. With the integration of the Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), which are the Multi-Criteria Decision-Making Methods (MCDM), the workforce skill level of the selected hospital's intensive care unit nurses is determined based on criteria. Then, the obtained levels are added as constraints to the mathematical model.
(3) 0-1 Goal Programming (GP) model with the related constraints ensures that the workload is distributed fairly among the nurses and that the nurses' requests and the expectations of the hospital management are fulfilled.

The contribution of this paper is twofold. First, it is one of the few studies in NSP literature using skill levels [28-30] with MCDM methods in intensive care units (ICU). Second, while most studies on NSP are not estimated the number of nurses [30], this paper also attempts to forecast future nurse demand in the day and night shifts.

The remainder of this paper is arranged as follows: Section 2 reviews the latest and prominent literature on NSP, mainly focusing on skill factors. Section 3 presents the prediction of the bed occupancy rate, the AHP-TOPSIS approach for skill levels and the GP model, which are the cores of the skill-based nurse scheduling system (SBNSS). Section 4 presents an implementation of the proposed SBNSS from a decision support perspective. Finally, Section 5 points to results and aspects for future research.

2. RELATED WORK

NSP or Nurse Rostering Problem is one of the most widespread issues in personnel scheduling surveys [23, 31, 32] and has been widely studied over the last decades [33] using a few approaches, including operational research techniques and artificial intelligence.

In the literature, two kinds of NSP are generally presented:

(1) Cyclical or rotational scheduling [34]: A cyclic schedules consist of work scheduling turn round among a group of nurses over a set time. At the end of the programming time, each nurse would have completed each cycle exactly once [35, 36]. Cyclical scheduling usually produces good schedules, but cannot respond effectively to staffing and other demands [23]. Cyclic models can be useful for minimizing staffing to meet staffing demand.

(2) Non-cyclical scheduling: This scheduling consists of three parts: the first includes how many personnel must be employed to meet the demand, the second determines the number of personnel to work in each shift, and the third determines the duties of each shift [37]. Non-cyclical programs schedule the workforce for 2-4 weeks and revise the schedule as needed [36].

Solution methods for NSP are of two kinds:

(1) (1) Mathematical Programming: Here, the purpose is to research over a large resolution space to locate the best solution such that the objective function may be optimized [32]. Almost all of them use an objective function for mathematical modelling, mostly a single objective, optimized subject to certain constraints. However, some works have also been done with GP or multi-objective decision making. GP describes a goal level for each standard and relative preference to accomplish these targets [23]. Optimization methods are commonly used to solve linear, integer programming, or mixed-integer programming [36, 38-50], goal programming/multi-criteria approaches [19, 34, 51-59], stochastic programming [60, 61], non-linear programming [62], constraint programming [63, 64], fuzzy mathematical programming [2], branch-and-price algorithm [65, 66], minimum cost network flow [67].

(2) (2) Heuristic / Meta-heuristic / Hyper-heuristics / Matheuristics / Hybrid Approaches techniques: A heuristic methodology searchs feasible solutions, in a reasonable time, but concludes no guarantee of optimality [68]. Meta-heuristics struggle to acquire good solutions within an acceptable duration, even though they cannot be warranty to discover optimal solutions. Unlike heuristics, meta-heuristics can be problem-free [13]. Successful approaches to real-life NSP include metaheuristic [52, 69-90] procedures, including particle swarm optimization [91, 92], cyber swarm algorithm [93], adaptive neighborhood search [94], iterative local search [95], harmony search algorithm [96-98], bee colony optimization algorithm [99, 100], evolution algorithm [101], genetic algorithms, tabu search, simulated annealing [102], Population-Based local search [103], memetic algorithms, ant colony optimization, and variable neighborhood search [37, 104, 105]. Hyper-Heuristic is defined as an automated methodology for creating and selecting heuristics to solve computationally difficult problems [106, 107]. Matheuristic algorithms are the combination of meta-heuristic algorithms and mathematical optimization [108-112], which NSP is starting to become popular among health researchers [13]. Hybrid Approaches combine two or more methods in a single step [113-115].

In the literature, there are also practices using Artificial Intelligence (AI) methods to resolve the NSP [53, 116-119]. NSP provides a convenient environment to use constraint programming methods if multiple constraints are required. These practices occur from AI and are exact methods that guarantee feasible solutions for constraint satisfaction problems [12].

NSP, known as a Non-Polynomial (NP)-hard problem [85, 120], is frequent in health care management. The larger the size of the NSP, the more difficult it is to find the optimum solution in reasonable time [81]. Therefore, the ICU system with smaller problem size is chosen in this study to solve NSP.

NSP plays an important role in personnel resource planning of the intensive care unit. Good scheduling can improve nurses' peace of mind and workload distribution, as well as improve work efficiency and patient experience. More importantly, it enables decision makers in health institutions to plan more efficiently in the management of scarce personnel in intensive care. NSP is therefore for the benefit of patients, nurses and administrators.

Managing shift sequences for each nurse of different skills is solved as a hard or a soft constraint [15, 107, 121-124]. Although much research has been devoted to solving the NSP with several methods, the skills of nurses for the intensive care working conditions have not been considered yet. A large quantity of literature exists on NSP and skill management, but using them together has not been addressed in ICU. The following section presents a nurse assignment and skill management model to fill this space. The originality of the proposed model comes from incorporating this aspect directly into the problem formulation.

3. DEVELOPING THE SBNSS MODEL

In this chapter, we design the problem as a SBNSS model. Figure 1 defines a general view of the SBNSS, which includes three stages from macro-level planning for each 8-h shift and two shifts in a month. This essay differentiates itself from the former literature in the following aspects: (1) Estimating the bed occupancy rate according to the patient occupancy rate and determining the number of nurses, (2) Determining the relevant criteria according to their abilities in the appointment of nurses, weighting these criteria and scoring the nurses according to the criteria weights, (3) Modeling 0-1 GP considering Phase 1 and Phase 2.

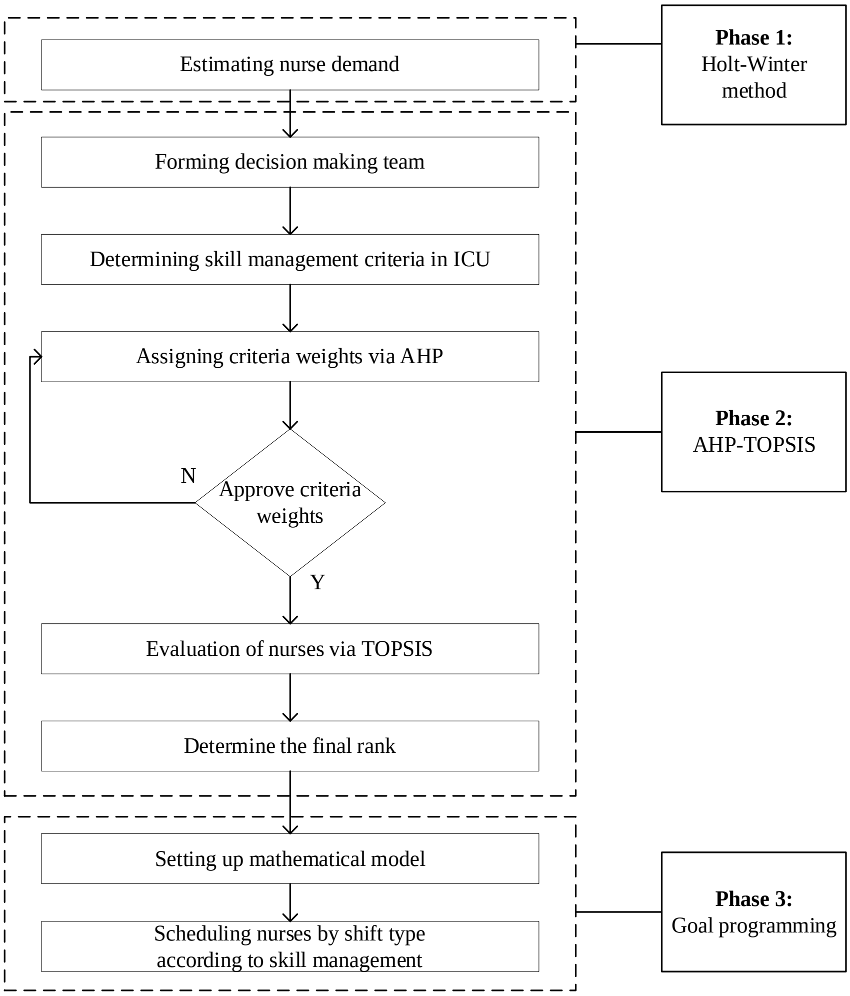

Figure 1. *The proposed SBNSS model*

3.1. Estimating Nurse Demand

Health managers must determine how many nursing to give work and how many to deploy each shift for ICU. An important hardship when planning nurses is the ambiguity around future workload. It usually matches the number of nurses per shift with the periodic average demand, which is one of the estimation methods. This averaging can be used for the Bed Occupancy Rate (BOR). Nursing demand here is estimated through The Holt-Winter method using BOR.

BOR and Average Length of Stay (ALOS) are used to exhibit an inpatient's actual average stay consumed for a given period. These indicators exhibit changes required in the healthcare service and provide necessary data outcomes regarding beds utilized during the different periods [125].

The Holt-Winter method forecasts time series for which trend and seasonality are present [24]. The method is one of the exponential smoothing methods that takes into account trend, season and error terms in the time series [126]. To explain this method, we need to understand the following two definitions well. Let c=the number of periods in the length of the seasonal pattern and S_t be an estimate of a seasonal multiplicative factor for month t, obtained after observing x_t. The Holt-Winter method yields a forecast of the base level L_t and the per-period trend T_t of the series. Each period L_t, T_t, and S_t are updated with Equations (1), (2) and (3). At the end of period t, the estimate $f_{t,k}$ for month t+k is given by Equation (4). α, β and γ are smoothing constants, each of which is between 0 and 1 [24, 126]. The Holt-Winter method is be defined as follows:

$$L_t = \alpha \frac{x_t}{S_{t-c}} + (1-\alpha)(L_{t-1} + T_{t-1}) \quad (1)$$

$$T_t = \beta (L_t - L_{t-1}) + (1-\beta) T_{t-1} \quad (2)$$

$$S_t = \gamma \frac{x_t}{L_t} + (1-\gamma) S_{t-c} \quad (3)$$

$$f_{t,k} = (L_t + k\,T_t)\, S_{t+k-c} \ . \quad (4)$$

For forecast accuracy, MAD (Mean Absolute Deviation) and MSE (Mean Squared Error) in Equations (5-6) are considered [127]:

$$MAD = \frac{1}{O}\sum_{t=1}^{O} |\, y_t - f_t \,| ,\ t=1,2,3,\ldots,O \quad (5)$$

$$MSE = \frac{1}{O}\sum_{t=1}^{O} (y_t - f_t)^2 ,\ t=1,2,3,\ldots,O\ . \quad (6)$$

where y_t represents actual value, f_t forecasted value and O number of time points. By revising the estimated bed occupancy rate with the number of beds in the related service, the demand for nurses (ND) on the day and night shifts is calculated with Equation (7).

$$ND = nb_{it} \Big/ \left(\frac{100 * o_i}{bor_{it}}\right) \quad (7)$$

where nb_{it} represents the number of beds assigned to unit type i on month t, bor_{it} the estimated bed occupancy rate, and o_i, according to legislation for ICU, at least one nurse for every two beds at all-day hours.

3.2. Skill Management for Nursing Services

Healthcare managers must focus on nurses' skills that can important influence health organizations. These are very important for the health care of health institutions and are critical for the short-term and long-term health care success of the ICU.

Some studies support that there is a positive relationship between employees and organizations in health units in terms of implementing skill management strategies [128]. When the studies on skill management in nursing are examined, it has been determined that the application of skill management strategies improves the clinical skills of nurses, increases job satisfaction, and increases the rate of effective treatment of the institution for patients [129].

Here we followed a two-stage method for the skill criteria for nurses in an ICU. In the first stage, information is collected from the subjected related experts. In the second stage, the last decade of the literature is considered to focus on up-to-date studies. We conducted research involving health experts selected from different functional areas of several hospitals directly involved in ICUs. Criteria to be considered in selecting nurses' skills for ICU are determined by a team of health experts having long-term managerial experience. Four important scientific databases were chosen: ScienceDirect, Springer Link, Scopus, and Gale Reference Complete. We selected four standards, such as the article being published in academic research journal, written in English, published between 1995-2023, and having the whole text in at least one database. To manage a more productive and comprehensive search strategy, we utilized boolean expressions to combine three expressions: "standards for ICU" or "nursing skills for ICU" or "skill management". Table 1 presents criteria and definitions elicited from expert opinions and a systematic literature review.

Table 1. *Skill management criteria in ICU and their definitions*

Criterion	Definition
Certificate/Training [130-133]	Certificates for intensive care qualification and education
Experience [134, 135]	Total years each nurse worked in the healthcare system
Experience in ICU [133, 135]	Nurse's experience in ICU
Education status [132]	Graduate (high school, associate degree, undergraduate, postgraduate)
Teamwork [136]	The nurse's relationship with other healthcare providers ought to be professional and supported confidence and esteem.
Critical Thinking [137]	When defining and handling client responses to unexpected and unusual health events, the nurse uses critical thinking for problem-solving.
Therapeutic communication [138]	The nurse is liable for establishing a therapeutic nurse-client relationship, which focalizes on the client's needs. The relationship is relied on esteem, confidence, sincerity, and suitable use of power.
Safety [139]	The nurse is liable for taking actions to arrange safety for both patients and colleagues.

The proposed model for the skill-based management of nurse assignment problem in ICU, created of AHP and TOPSIS, occurs of three main stages:

(1) initiates to find out the weights of the criteria via the AHP,
(2) continues to rank the alternatives with the TOPSIS method,
(3) assessment of nurses' skills and determination of the final skill point.

AHP, improved by Saaty (1980), mentions determining the relative significance of a set of alternatives in a MCDM problem [140]. The four main steps of the AHP can be summarized as follows: first, establish the hierarchical system by separating the problem into a hierarchy of interrelated elements; second, contrast the relative weight between the bases of the decision elements to form the reciprocal matrix; third, synthesize the individual decision and forecast the relative weight; fourth, combine the relative weights of the elements to determine the best alternatives/strategies [141]. In the literature, several works determine the weights for nurse selection criteria using the AHP method [142-144]. AHP employed here are as follows [145]:

Let C= $\{C_j \mid j = 1,2,3, \dots, n\}$ be the set of criteria. The result of the pairwise comparison on n criteria can be sum up in an (n×n) assessment matrix A in which every element a_{ij} (i, j = 1,2, . . . , n) is the coefficient of weights of the criteria, as shown [140, 146]:

$$A = \begin{pmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \dots & a_{nn} \end{pmatrix}, a_{ij} = 1, a_{ji} = {}^{1}/_{a_{ij}}, a_{ij} \neq 0 \tag{8}$$

In the last step, the mathematical transaction begins to normalize and get the relative weights for each matrix. The relative weights are given by the eigenvector (ω) corresponding to the largest eigenvalue (λ_{max}), as

$$A\omega = \lambda_{max}\,\omega \,. \tag{9}$$

If the pairwise comparisons are entirely steady, matrix A has a rank of 1 and λ_{max} =n. In this case, weights can be attained by normalizing any of the rows or columns of A. The consistency is identified by the relation between A's entries: $a_{ij} \times a_{jk} = a_{ik}$. The consistency index (CI) is:

$$CI = \left(\lambda_{max} - n \Big/ n-1 \right). \tag{10}$$

The final consistency ratio (CR) in Equation (11) is calculated as the ratio of the CI and the random index (RI) where RI refers to a random consistency index, which is obtained from a large specimen of accidentally created reciprocal matrices utilization the scale 1/9, 1/8,…,1,…,8, 9. The RI for different-sized matrices is indicated in Table 2.

$$CR = {CI}/{RI} \tag{11}$$

Table 2. *The RI for different size matrices [141]*

Number of elements	RI
3	0.52
4	0.89
5	1.11
6	1.25
7	1.35
8	1.40
9	1.45
10	1.49
11	1.51
12	1.54
13	1.56

The number 0.1 is the approved upper limit for CR. If the final CR surpassed this value, the consideration method must be repeated to improve consistency. The consistency dimensions can be used to assess the consistency of decision-makers and the consistency of the overall hierarchy [140]. Table 3 shows the ratio scale employed to contrast the significance weight between criteria according to the linguistic meaning from 1 to 9, denoting equal importance to extreme significance.

Table 3. *The nine-point intensity of importance scale and its description [141, 146]*

Definition	Intensity of importance
Equally important	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Extremely more important	9
Intermediate values	2,4,6,8

Yoon and Hwang [147] improved the TOPSIS predicate on the concept that the selected alternative should have the shortest Euclidean distance from the positive ideal solution and the farthest from the negative ideal solution. According to this technique, while the TOPSIS method takes a few input parameters from the user, the outputs are quite easy to understand. While solving a decision problem with the TOPSIS method, the selected. The alternative is anticipated to be close to the appropriate solution and far from the inappropriate solution. The TOPSIS method is used in many areas, such as supply chain management [148-150], financial applications [151] and health applications [152-154] to solve real-life problems.

Table 4 shows the main steps of the TOPSIS method [155, 156]. Following the notation, there are m alternatives $A_1, A_2, \ldots, A_m$ and n criteria $C_1, C_2, \ldots, C_n$ with weights $w_1, w_2, \ldots, w_n$. Let x_{ij} denote the m × n matrix of nurse performance ratings of each alternative at each criterion, and it is the score of nurse i under criterion j. The ranking of the alternatives in descending order on CC_i values.

***Table 4.** Steps of the TOPSIS method*

Description	Equation
Construct a decision matrix *D*	$D = (x_{ij})_{m \times n}$
Formulate a normalized decision matrix *R*	$R = (r_{ij})_{m \times n} = \left(x_{ij} / \sqrt{\sum_{i=1}^{m} x_{ij}^2}\right)_{m \times n}$
Build a weighted normalized decision matrix *V*	$V = (v_{ij})_{m \times n} = (w_j r_{ij})_{m \times n}$
Identify the positive ideal solution (V^+) $(A^+ = \{v_1^+, v_2^+, \ldots, v_n^+\})$ and negative ideal solution (V^-) $(A^- = \{v_1^-, v_2^-, \ldots, v_n^-\})$, J_b is a set of benefit criteria, and J_c is a set of cost criteria	$(V^+) = \left\{\left(\max_j v_{ij} \ / \ j \in J_b\right), \left(\min_i v_{ij} \ / \ j \in J_c\right) / \ i = 1,2, \ldots N\right\}$ $(V^-) = \left\{\left(\min_j v_{ij} \ / \ j \in J_b\right), \left(\max_i v_{ij} \ / \ j \in J_c\right) / \ i = 1,2, \ldots N\right\}$
Calculate the separation measure (S_i^+) and (S_i^-)	$S_i^+ = \left\{\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2\right\}^{0.5}$, i=1,2,…,N $S_i^- = \left\{\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2\right\}^{0.5}$, i=1,2,…,N
Determine the closeness coefficient (CC_i)	$CC_i = S_i^- / (S_i^+ + S_i^-)$

3.3. Goal Programming Model

Linear programming models are for one purpose. However, in real life, systems have multiple and often conflicting goals. GP is a multi-objective linear programming method that simultaneously minimizes the deviations in negative, positive, or both directions from many goals weighted according to their importance [19, 58]. The SBNSS involves scheduling several nurses for four weeks for the ICU while meeting employment necessity and other constraints. NSP model will also seek to meet various targets, such as decreasing overstaffing, incorporating nurses' leave preferences and skill management, and establishing foundations of justice among nurses. These offers using a 0-1 GP approach. The difference between the proposed 0-1 GP model and the previous NSP studies is that it predicts the number of nurses to work in a shift in Phase 1 and considers the nurses' skills in Phase 2. The above conditions have been added as constraints to the mathematical model, whose purpose and constraints are given below. This is the innovative aspect of the research.

The developed mathematical model is ground on the 0-1 GP model of Azaiez and Sharif (2005) for the NSP. In the new schedule, the shift hours have not been changed and are arranged in two shifts (Day Shift (DS): 08.00–16.00, Night Shift (NS)): 16.00-08.00). In determining the weekly working time, the legal regulations were considered. It was ensured that nurses were not assigned to the DS after the NS. Efforts were made to appoint as many shifts as feasible to each nurse. To increase the quality of health services in the ICU for each shift, the nurses were assigned considering the skill levels of the AHP-TOPSIS result. At the same time, if there are special requests of the nurses regarding the relevant period, these were also considered. The following notation is introduced in Table 5:

***Table 5.** Model parameters*

Indices, sets, parameters and decision variables	Definition
o	Number of days in a schedule

p	Number of nurses available for the unit of interest
t	Index for days, t= 1,2,3,…,o
k	Index for nurses, k= 1,2,3,…,p
D_t	Staff requirement for day shift of day t, t= 1,2,3,…,o
N_t	Staff requirement for night shift of day t, t= 1,2,3,…,o
P_k	AHP-TOPSIS skill value for nurse k, k= 1,2,3,…,p
D_{td}	1, if nurse d is assigned a day shift for day t, 0 otherwise
N_{td}	1, if nurse d is assigned a night shift for day t, 0 otherwise
R_{td}	1, if nurse d is assigned a day off for day t, 0 otherwise

Requirements in modeling the SBNSS and their corresponding constraints are stated as follows:

$$\sum_{d=1}^{p} D_{td} = D_t,\ t=1,\ \dots,\ o \tag{12}$$

$$\sum_{d=1}^{p} N_{td} = N_t,\ t=1,\ \dots,\ o \tag{13}$$

$$D_{t+1,d} + N_{td} \leq 1,\ t=1,\dots,o-1 \text{ and } d=1,\dots,p \tag{14}$$

$$R_{6d} + R_{7d} + R_{13d} + R_{14d} + R_{20d} + R_{21d} + R_{27d} + R_{28d} \geq 4,\ d=1,..,p \tag{15}$$

$$R_{6d} + R_{7d} \geq 1,\ d=1,..,p \tag{16}$$

$$R_{13d} + R_{14d} \geq 1,\ d=1,..,p \tag{17}$$

$$R_{20d} + R_{21d} \geq 1,\ d=1,..,p \tag{18}$$

$$R_{27d} + R_{28d} \geq 1,\ d=1,..,p \tag{19}$$

$$N_{t+1,d} + N_{td} \leq 1,\ t=1,\dots,\ o-1 \text{ and } d=1,\dots,p \tag{20}$$

$$\sum_{d=1}^{p} (P_d * D_{td}) \geq 6,\ t=1,\dots,o \tag{21}$$

$$\sum_{d=1}^{p} (P_d * N_{td}) \geq 6,\ t=1,\ \dots,o \tag{22}$$

$$\sum_{t=1}^{o} 8 * D_{td} + \sum_{t=1}^{28} 16 * N_{td} \geq 160,\ d=1,..,p \tag{23}$$

$$\sum_{t=1}^{o} D_{td} = 6,\ d=1,..,p \tag{24}$$

$$\sum_{t=1}^{o} N_{td} = 7,\ d=1,..,p \tag{25}$$

$$D_{td} + N_{td} + R_{td} = 1,\ t=1,\dots,o \text{ and } d=1,\dots,p \tag{26}$$

$$\sum_{t=1}^{7} D_{t3} = 0 \tag{27}$$

$$\sum_{t=1}^{o} N_{t5} = 0 \tag{28}$$

$$D_{td}+D_{t+1,d}+D_{t+2,d}+D_{t+3,d} \leq 3,\ t=1,\dots,o \text{ and } d=1,\dots,p \tag{29}$$

$$N_{td}+N_{t+1,d}+N_{t+2,d}+N_{t+3,d} \leq 3,\ t=1,\dots,o \text{ and } d=1,\dots,p \tag{30}$$

Equations (12-13) meet the personnel requirements for night and day shifts. Equation (14) avoid any two consecutive shifts. With Equation (15), the constraint allows each nurse at least four days off on weekends in a 4-week schedule. Equations (16)-(19) allow any nurse not to work consecutive weekends. Equation (20) allows each nurse to work one-NS in a row at most. Equations (21)-(22) ensure the appointment of at least one senior nurse (very qualified and qualified) in the day and night shifts. With Equation (23), each nurse works 40 hours a week, at least 160 hours a month. Equations (24)-(25) provide an equal number of day and night shifts assigned to each nurse. Equation (26) allows only one shift to be worked or day off per day. Equation (27) ensures that the month is not assigned to the DS in the first week. Equation (28) restricts nurses who cannot work the NS due to a particular excuse. With Equations (29)-(30), the constraints are provided to ensure that a nurse will not work more than three consecutive days in the day and night shifts.

Two target constraints were considered while solving the NSP. The first is the target constraints in Equations (12)-(13), where the number of nurses is necessary to fulfill the need for the day and night shifts, and the total number of shifts each nurse assigned during the monthly period is as equal as possible. Another constraint is the target constraint Equations (24)-(25), where the total hours assigned to the day and night shifts must be equal. In this context, optimization of both target constraints was aimed, and the model was solved accordingly using the General Algebraic Modeling System (GAMS) [157]. The objective function minimizes the sum of the deflections from the corresponding goals. In Equation (31) $d1$ and $d2$ are related to Equations (12)-(13), $d10$, and $d11$ are related to Equations (24)-(25). The mathematical notation of the objective function is given as:

$$\min\ \left[\sum_{t=1}^{o} d1_t^- + \sum_{t=1}^{o} d1_t^+ + \sum_{t=1}^{o} d2_t^- + \sum_{t=1}^{o} d2_t^+ + \sum_{d=1}^{p} d10_d^- + \sum_{d=1}^{p} d10_d^+ + \sum_{d=1}^{p} d11_d^- + \sum_{d=1}^{p} d11_d^+ \right]. \qquad (31)$$

4. APPLICATION FOR SBNSS MODEL

This study was conducted in a public health institution (Hospital D), one of Turkey's largest hospitals, established 50 years ago. The BOR of the ICUs was 91,6 % and 92 % in 2017 and 2018, respectively. A proposed SBNSS model for the NSP was implemented in one of the ICUs of Hospital D. The number of nurses working in the selected unit is 13. Nurses have an average of seven years of experience in the health system and four years of experience in the ICU. Currently, managerial staff prepares a manual schedule with a trial and error approach in ICU. This approach is not only costly, but also does not produce efficient schedules. Besides, these manual schedules do not satisfy several vital criteria for efficient scheduling, including balanced schedules, justice in considerations and nurses' preferences, skill management, and staffing requirements in quality and size. SBNSS ensures critical improvements in this regard besides offering a practical computerized tool.

The objective of this section is to show step by step the applicability of the proposed SBNSS model (Figure 1) in the ICU. SBNSS was implemented with C# (Intel Core i7-8565U CPU, 1.80 GHz, memory: 16 GB, Operating System: Windows 10).0-1 GP model was resolved by GAMS's solver. Under the SBNSS platform, (Figure 2), eight modules are provided: Skill Management (SM), Rest (Day off), Settings, Scheduling, Export, Archive, Help and Exit. With the SM module, the number and abilities of nurses in the ICU are described. With the rest module, nurses' monthly day off is entered. The constraints of mathematical modeling are set in the Settings module. GAMS is run with the scheduling module. It also gives excel output by using the export module after monthly scheduling. All schedules are recorded according to years and months in the Archive.

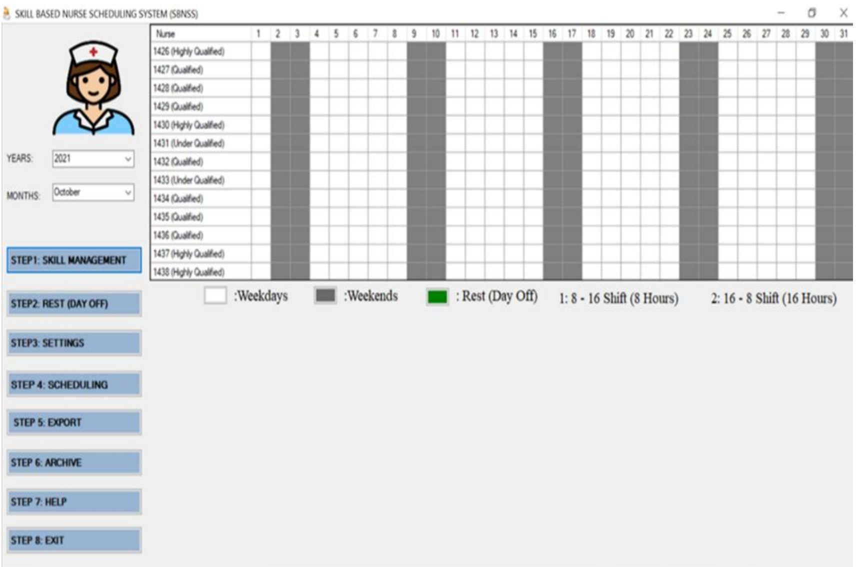

Figure 2. *Interface for SBNSS*

Estimating nurse demand for each shift in the ICU of Hospital D is based on BOR. Data were obtained from the Health Government of Turkey from January 2016 to April 2019. The Holt-Winter method is applied based upon mathematical notation below Equations (1)- (4). The smoothing parameters and starting values were chosen following Chatfield and Yar [158]. The conclusions acquired after applying the method to the 24 months of BOR (using α=0,99, β=0,03, γ = 0,99) are shown in Table 6. The Holt-Winters' model was built in MS Excel Solver add-in to devise values for α, β, and γ [159]. Solver is a non-linear optimizer, minimizing MAD considering the constraints α, β, and γ that should be between 0 and 1. Forecasting accuracy calculated according to Equations (5) and (6) was as follows:

Table 6. *The Holt-Winter Method for the ICU*

Month (2019)	Estimated BOR (%)	Actual BOR (%)
January	82.94	84.3
February	83.7	81.6
March	90.69	82.5
April	89.36	82.4

(MAD:4.65, MSE: 30.42)

As previously mentioned in Section 3.1, the forecasting BOR aims to estimate nurse demand for ICU from historical data. By revising the BOR estimated by the Holt-Winter method with the number of beds in the relevant service, the number of nurses who should be on the day and night shifts at all day hours is calculated in Equation (7) presented in Table 7. The minimum requirement of nurses per shift is three nurses for all day and night shifts (Figure 5).

Table 7. *Number of nurses for ICU*

Month (2019)	Estimated BOR (%)	Number of Beds	Number of Nurses
January	82.94	7	2.9
February	83.7	7	2.93
March	90.69	7	3.17
April	89.36	7	3.13

The proposed model for nurse skill management in ICU comprises AHP and TOPSIS methods stated in Section 3.2.1. Three levels in the decision hierarchy are structured for nurse skill management in ICU. The overall target of the decision process defined as "the selection of the skilled nurse in ICU" is the first level in the hierarchy. As described in Table 1, the criteria are at the second level, and alternative nurses are at the third level in the hierarchy. After forming the decision hierarchy for the problem, the weights of the criteria used in the assessment process were calculated using the AHP method according to Equations (8-11). In this phase, eight health experts with at least five-year experience in ICU-related works, including nursing and health management, were tasked with forming the individual pairwise comparison matrix using the scale given in Table 3. Geometric means of these values were then obtained. The results obtained from the calculations based on the pairwise comparison matrix for criteria are presented in Table 8. The C8 (Safety), C3 (Experience in ICU), and C6 (Critical thinking) were defined as the three most significant criteria in the nurse assignment selection process by AHP. CR of the pairwise comparison matrix was calculated as 0.00459 < 0.1. So, the weights are shown to be consistent and can be used in the selection process.

Table 8. *Results obtained with AHP*

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	Weights (ω)	CR
C1	1	1.92	2.35	1.47	1.65	2.49	1.97	2.8	0.063	
C2		1	1.9	1.5	1.04	1.42	1.11	1.81	0.108	
C3			1	2.3	1.39	1.16	1.34	1.08	0.171	
C4				1	1.3	1.76	1.29	2.28	0.083	0.00459
C5					1	1.48	1.07	1.92	0.108	
C6						1	1.2	1.42	0.148	
C7							1	2.65	0.113	
C8								1	0.207	

The results of AHP-TOPSIS analyses are summarized in Table 9 according to Table 4. Based on P_i values, the ranking of the alternatives in descending order are N1, N13, N5, N12, N9, N2, N3, N11, N10, N4, N7, N8 and N6. The proposed model results indicate that N1 is the best alternative with P_i value of 0.905.

Accordingly, the nurses were ranked depending on their abilities, with 1 to 3 points as "less qualified", 4 to 6 points "qualified", and 7 to 10 points "highly qualified".

Table 9. *AHP-TOPSIS based workforce skill management in ICU results*

Alternatives (Nurse work in ICU)	S_i^+	S_i^-	P_i	Skill point	Skill category
N1	0.009	0.083	0.905	10	Highly qualified
N2	0.047	0.044	0.483	5	Qualified
N3	0.054	0.046	0.461	5	Qualified
N4	0.056	0.035	0.38	4	Qualified
N5	0.028	0.063	0.689	8	Highly qualified
N6	0.079	0.018	0.187	2	Underqualified
N7	0.073	0.043	0.373	4	Qualified
N8	0.076	0.033	0.304	3	Underqualified
N9	0.046	0.049	0.514	6	Qualified
N10	0.055	0.036	0.396	4	Qualified
N11	0.053	0.038	0.416	5	Qualified
N12	0.029	0.06	0.672	7	Highly qualified
N13	0.027	0.063	0.695	8	Highly qualified

After the skill-based score and skill category of each nurse were determined by AHP-TOPSIS, it was shown through the application (Figure 3). Before using SBNSS, nurses' skills must first be maintained using the SM module.

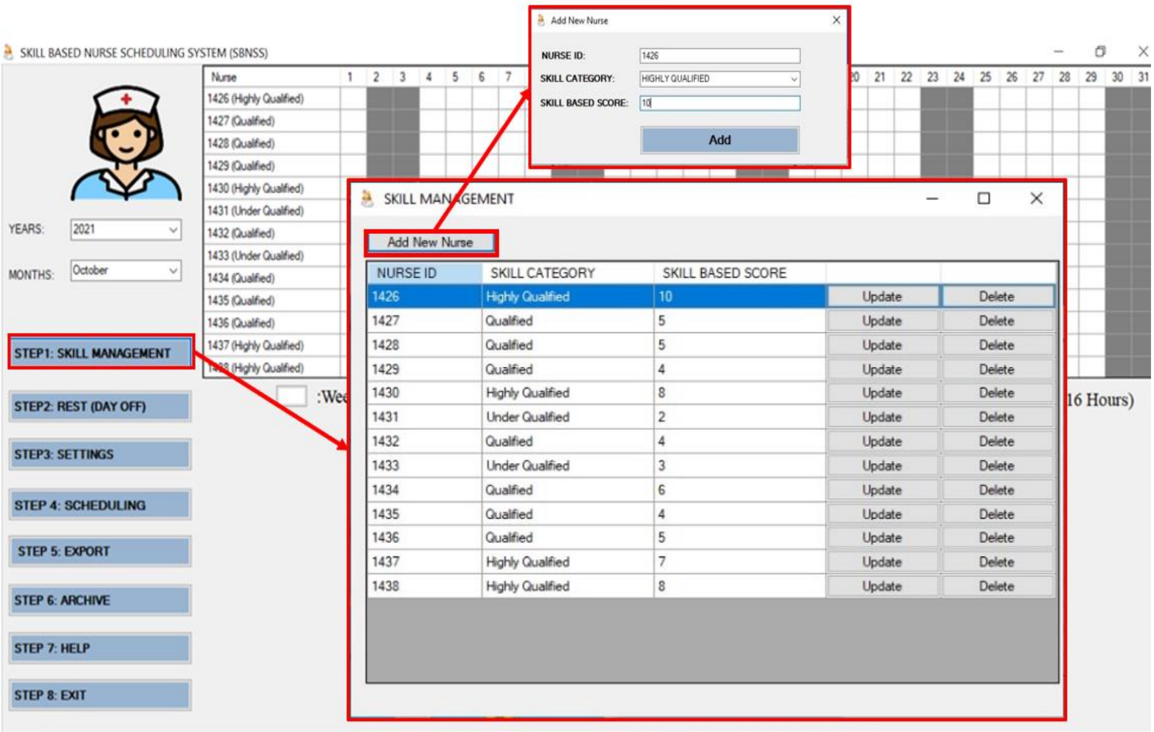

Figure 3. *Interface for SM Module*

Table 10 illustrates the schedule prepared by the head nurse manually. Accordingly, the manually prepared schedule was not balanced for day and night shifts. Nurses' day and night shifts varied between 20% and 100%. The preferences of nurses on Day Off (DO) were not considered. The constraint of avoiding a DS followed by a NS in the next day was violated more in the manual schedule. It was not to maximize the total satisfaction of all the nursing with the manually prepared schedule.

Table 10. *Monthly manual schedule for ICU*

Nurse	Total Hours Worked	Day Shifts	Night Shifts	Number of Weekends Worked
N1	120	3	6	3
N2	152	11	4	2
N3	160	8	6	4
N4	208	6	10	4
N5	0	0	0	0
N6	176	8	7	3
N7	160	10	5	3
N8	152	13	3	2
N9	136	3	7	2
N10	136	7	5	2
N11	48	6	0	0
N12	64	6	1	0
N13	8	1	0	0

In general, such a nurse preference schedule determines the combinations of each nurse’s preferred work shift and DO (as described in Figure 4) during the schedule planning to ensure Equations (27-28) is considered.

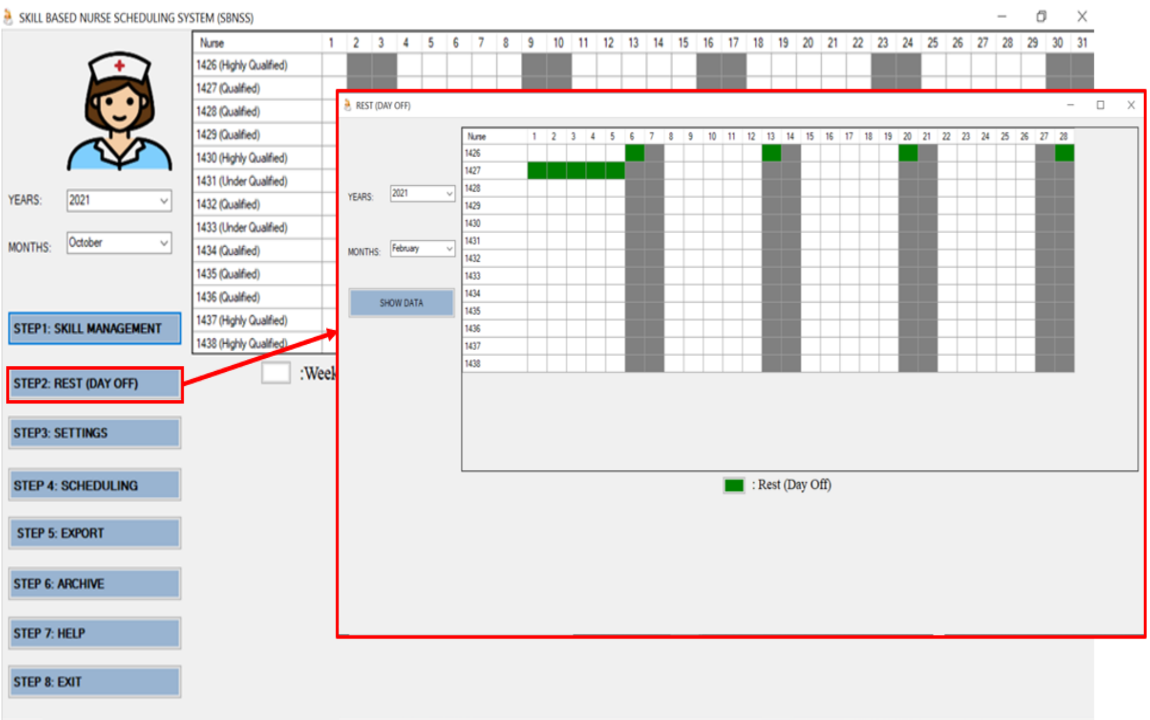

Figure 4. *Interface for Rest Module*

Settings Module (Figure 5) will permit the user to add the minimum daily necessity for each day and night shift, plan worked hours, disallow assigning two consecutive shifts, assign each nurse for each day a DS, a NS or a DO, assign an expert nurse per shift and avoid assigning a day shift followed by a NS on the next day.

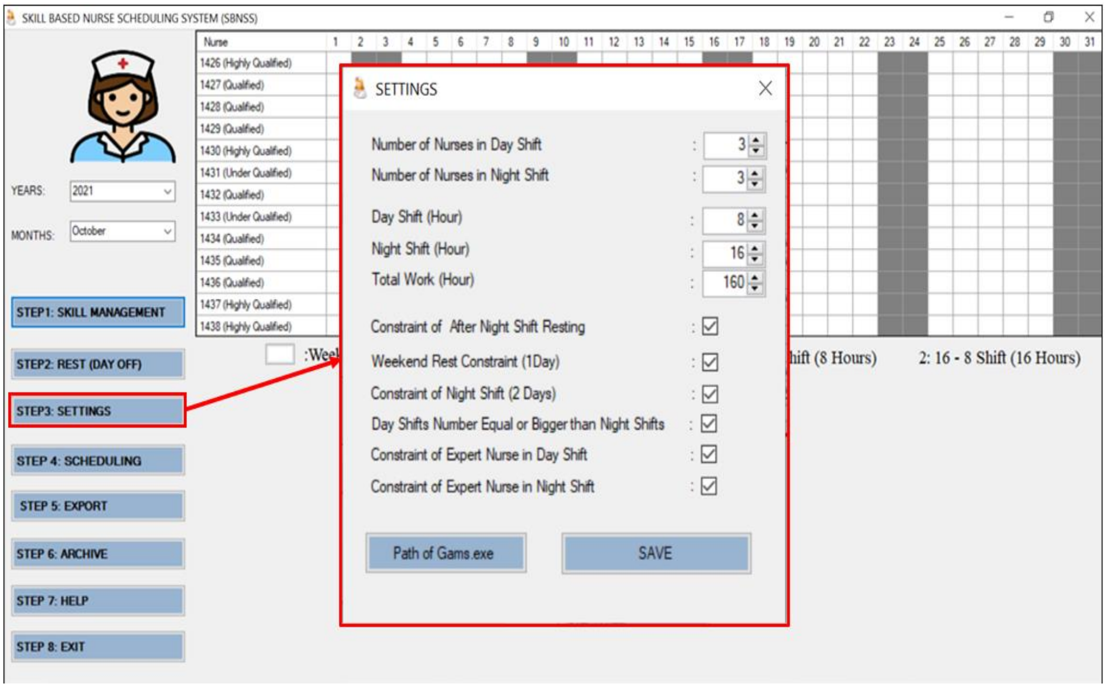

Figure 5. *Visualized Display of Settings Module*

The proposed mathematical model is introduced in Section 3.3. Table 11 shows the scheduling results for d=13 nurses and t=28 days. In this context, 'N' indicates the nurse working NS on a relevant day; 'D' indicates the nurse working DS on a relevant day, and the blank cells indicate that the nurse was on vacation (not working) day. The 'R' symbol indicates that the nurse was on vacation at the weekend. In addition, the number of days the nurses worked in day and night shifts and the total number of days they worked were stated throughout the schedule.

A balanced and fair assignment of nurses has been ensured. As it is known, 13 nurses work in the ICU under normal conditions. Assuming that there are 12 nurses in the unit, a new alternative schedule was obtained. When the system fell below 12 nurses, a solution could not be obtained in line with the desired target constraints in the mathematical model. The current situation of 13 nurses and the alternative situation of 12 nurses given in Table 12 are compared in terms of total hours and shifts.

Table 11. *Skill-based monthly shift table created for ICU*

Nurse \ Day	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
1			D		N	R	N			N			R	D	N		N		N	R	D		N		D	D	D	R
2	N		D	D		N	R				N		R	D	D	N		D		N	R	N		N			D	R
3		N		N		N	R	D	D	D	N		D	R		N			N	R	N				D		R	D
4				D	D	D	R	N			D	N	R	N		D				N	R	D	N			N	R	N
5	D	D	D		D	D	R	D	D		D	D	D	R	D	D	D		D	D	R	D	D		D	D	D	R
6		D		D		D	R	N		N		D	R	N				N		R	N		D	N		N	R	D
7		D		N		N	R	D	D				N	R	N		N			R	D	N		D		D	R	N
8	N		N			R	D			D	D	D	N	R	D	N		N		R	D	N					N	R
9			N		N	R	N		N		N		D	R			D	D	N	R	R		D	D	N		D	R
10	D			N		D	R	N		D	D		N	R	D		N		D	R	N				N		N	R
11	D	N			N	R	N		N		D		R	R	D	D	D	N		N	R			N			R	D
12		N			D	R	D			N		N	R	D	N				D	D	R	D	N		N		N	R
13	N		N			R	D		N		D	N	R	N		D		D		D	R			D		N	R	N

Higly Qualified (rows 1, 5, 12, 13) Qualified (rows 2, 3, 4, 7, 9, 10, 11) Under Qualified (rows 6, 8)

When Table 11 was examined, it was determined that there was no change posing a severe problem for each nurse during the day and night shifts. Thus, it is thought that the tension arising from the workload that might occur among nurses was prevented. In alternative scheduling, we can emphasize that the determined number of nurses will maintain the balance in workload for the current situation.

Table 12. *Comparison of the current situation and alternative schedules*

Nurse	Current Situation (Hours)	Alternative Situation (Hours)	Day Shift (CS)	Night Shift (CS)	Rest (CS)	Day Shift (AS)	Night Shift (AS)	Rest (AS)
N1	160	160	6	7	4	6	7	5
N2	160	152	6	7	4	5	7	4
N3	160	160	6	7	4	6	7	5
N4	160	160	6	7	4	6	7	5
N5	160	160	20	0	4	20	0	4
N6	160	160	6	7	4	6	7	4
N7	160	160	6	7	4	6	7	4
N8	160	160	6	7	4	6	7	4
N9	160	160	6	7	5	6	7	4
N10	160	160	6	7	4	6	7	4
N11	160	160	6	7	5	6	7	4
N12	160	160	6	7	4	6	7	4
N13	160	-	6	7	4	-	-	-

5. CONCLUSION

The use of NSP has expanded in recent years because of providing flexibility and cost-effectiveness in managing health personnel. Determining balanced schedules and assigning skilled nurses to suit patient needs are necessary since they impact the running costs, the quality of care offered to patients, and the job satisfaction of nurses. The present study describes the development of SBNSS to address the real-world nurse scheduling and skill management challenges encountered by ICUs. The SBNSS employs a zero-one GP model that considers bed occupancy, nursing skills, nurse preferences, and a well-balanced schedule. Other aspects of the problem, such as overstaffing, can also be handled using the SBNSS. The SBNSS enables sensitivity analyses and quick responses to new scheduling demands while decreasing the time and uncertainty associated with the manual method. Because most of the time is devoted discovering a feasible solution, the head nurse's scheduling load is expected to be significantly reduced. This model provides a practical method for analyzing a health system's human resource planning decision-making process. In the future, The SBNSS could also be used with slight modifications in other departments apart from ICU. Another future work to focus on is team relation and coordination in terms of social network perspective while nurse scheduling.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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