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A LOCAL SEARCH HEURISTIC FOR NURSE ASSIGNMENT PROBLEMS WITH PERSONAL PREFERENCES

UMA HEURÍSTICA DE BUSCA LOCAL PARA O PROBLEMA DE DESIGNAÇÃO DE EQUIPES DE ENFERMAGEM COM PREFERÊNCIAS PESSOAIS

UNA HEURÍSTICA DE BÚSQUEDA LOCAL PARA PROBLEMAS DE ASIGNACIÓN DE ENFERMERAS CON PREFERENCIAS PERSONALES

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ABSTRACT

Recently, research into healthcare optimization has experienced exponential growth, arousing significant interest from researchers and healthcare organizations. This increase in interest is driven by the complexity and relevance of the challenges faced by society, and is directly related to the growing need to improve processes and the search for greater efficiency in healthcare systems on a global scale. The aim of this study is to develop an optimization approach, based on computational heuristic, to perform the planning and assignment of nurse professionals in hospital sectors in order to maximize both the personal preferences of the professionals and the efficiency of health care services. The proposed method uses a heuristic optimization algorithm based on local search with solution perturbation mechanisms and efficient search neighbourhoods. The computational results showed that the method could perform efficient assignments of nursing professionals in hospital sectors, optimizing job satisfaction and quality of service provided. In conclusion, the study evidenced that the developed method allows efficient management and assignment of nurse professionals in hospital settings, achieving scientific and practical contributions to the areas of healthcare optimization and hospital administration.

RESUMO

Recentemente, a pesquisa em otimização de saúde tem experimentado um crescimento exponencial, despertando o interesse significativo de pesquisadores e organizações de saúde. Esse aumento de interesse é impulsionado pela complexidade e relevância dos desafios enfrentados pela sociedade, estando diretamente relacionado à necessidade crescente de aprimoramento de processos e à busca por maior eficiência nos sistemas de saúde em escala global. O objetivo deste estudo é desenvolver uma abordagem de otimização, baseada em heurística computacional, para realizar o planejamento e a designação de profissionais de enfermagem em setores hospitalares, visando maximizar tanto as preferências pessoais dos profissionais, como a eficiência nos atendimentos de saúde. O método proposto utiliza um algoritmo heurístico de otimização baseado em busca local com mecanismos de perturbação de solução e vizinhanças de busca eficientes. Os resultados computacionais demonstraram que o método é capaz de realizar designações eficientes de profissionais de enfermagem em setores hospitalares, otimizando a satisfação profissional e a qualidade do serviço prestado. Concluindo, o estudo evidenciou que o método desenvolvido permite uma eficiente gestão e designação de profissionais de enfermagem em ambientes hospitalares, alcançando contribuições científicas e práticas para as áreas de healthcare optimization e administração hospitalar.

RESUMEN

En los últimos tiempos, la investigación en optimización sanitaria ha experimentado un crecimiento exponencial, despertando un gran interés entre investigadores y organizaciones sanitarias. Este aumento del interés viene motivado por la complejidad y relevancia de los retos a los que se enfrenta la sociedad, y está directamente relacionado con la creciente necesidad de mejorar los procesos y la búsqueda de una mayor eficiencia en los sistemas sanitarios a escala global. El objetivo de este estudio es desarrollar un enfoque de optimización, basado en heurísticas computacionales, para realizar la planificación y asignación de profesionales de enfermería en sectores hospitalarios, buscando maximizar tanto las preferencias personales de los profesionales como la eficiencia en la atención a la salud. El método propuesto utiliza un algoritmo heurístico de optimización basado en búsqueda local con mecanismos de perturbación de solución y vecindades de búsqueda eficientes. Los resultados computacionales mostraron que el método es capaz de realizar asignaciones eficientes de profesionales de enfermería en sectores hospitalarios, optimizando la satisfacción profesional y la calidad del servicio prestado. En conclusión, el estudio demostró que el método desarrollado permite una eficiente gestión y asignación de profesionales de enfermería en ambientes hospitalarios, logrando aportes científicos y prácticos para las áreas de optimización asistencial y administración hospitalaria.

INTRODUCTION

In times of major epidemics and pandemics, when the scarcity of resources is accentuated, mathematical and computational solutions that provide better management efficiency become even more critical. In recent years, research in healthcare optimization has grown exponentially. The theme has gained attention from researchers and health organizations due to the complexity and relevance of its problems in society, directly interconnected with the growing demand for process improvement and greater efficiency in health systems worldwide (Liu et al., 2018).

Several optimization approaches have been proposed for the theme (Gür & Eren, 2018). As better results are being achieved, the demand for new methods has increased in search of high levels of efficiency in healthcare management and services provided. Thus, in recent years, practical applications have been proposed in many different healthcare optimization problems, such as nurse scheduling (Burke et al., 2018; Constantino, 2014; Strandmark et al., 2020), patient scheduling (Rahimian et al., 2017; Abdalkareem et al., 2021), staffing programming (Millard et al., 2018; Chen et al., 2022), among others (Du et al., 2013; Mutingi & Mbohwa, 2014; Castaño & Velasco, 2020).

The capacity of hospital networks to develop a good schedule for professional teams is fundamental to balancing the organization's needs with better use and satisfaction of the groups of employees. In this sense, problems involving the allocation, assignment, and scheduling of nursing teams are some of the most researched problems in healthcare optimization (Wong et al., 2014) due both to the mathematical and computational complexity of solving such problems and the high impact on the overall performance of healthcare organizations.

Knowing that the management of nursing teams is directly linked to the quality and level of patient satisfaction, it is necessary to plan the scheduling of professionals to promote higher satisfaction rates, productivity, and, consequently, higher approval rates in the care provided (Chen et al., 2020). Some recent studies highlight the importance of information technology in nursing processes and supporting hospital activities in general (Gür & Eren, 2018; Abdalkareem et al., 2021; Camargo et al., 2018; Mendonca & Tachinardi, 2018; Soares et al., 2018).

The planning must involve an efficient method of managing employees to satisfy the demands of the hospital environment, from the programming of their performance, so that they fulfil the needs of patients, saving staff time and effort, or maximizing the quality of the services provided (Awadallah et al., 2015). The assignment process must be performed by analysing several issues, such as the availability of human and material resources and the preferences and skills of employees to work in a specific sector where the demand originated.

Such problems have a significant mathematical complexity to solve (Bilgin et al., 2012). With this, optimization approaches focused on allocating nurse professionals have received increasing attention from researchers and hospital networks. Its correct application allows for an adequate definition of shifts and/or work sectors, ensuring that constraints are satisfied and the objectives are optimized. The results can represent significant impacts on organizational performance and the quality of services provided (Mohd Rasip et al., 2015).

When discussing the management of nurse resources in hospital networks, it is necessary to mention the dimensioning of a human capital forecasting method in several aspects: Quantity and professional qualification (skills); Personal preferences; Demands by sectors of the organization; As well as aspects related to hospital structure and patient requirements, providing adequate demand assistance. Adequate staffing to meet the needs of nursing care to patients leads organizations to achieve a higher quality of care and safe and humanized care (Zhong et al., 2017).

A nursing team is usually composed of professionals with different backgrounds, specializations, and unique experiences, each possessing skills obtained from their professional and academic experience (You & Hsieh, 2021). In addition, each professional has particular preferences regarding working hours and shifts, which may be associated with their best professional performance or life routine, for example. On the other hand, hospital environments or surgical centers are composed of several sectors, each with its procedure directed to a specific condition, thus requiring a good health team to satisfy each demand with its peculiarities.

In the problem considered in this work, each nursing professional has distinct preferences and specialties for working in each sector, and scores from 0 to 10 can be assigned regarding their fittingness for the alternative workstations. These scores represent the nurses' adherence to their respective sectors, according to their level of specialties and personal preferences.

An optimal assignment of nursing professionals to the various sectors should maximize overall preference and specialty. To better illustrate the problem described, Table 1 presents an example of a simple problem in a hospital, with three sectors and four professionals that must be assigned, with their respective scores per sector. Analysing the situation shows that the procedure assignment should be directed to the professional with the best possible scores (for sector 1 is 8, sector 2 is 7 and sector 3 is 9), seeking to maximize the total score and allocate the most appropriate employees in each sector.

Table 1. Illustration of a Nurse Allocation Problem

Sector	Nurse 1	Nurse 2	Nurse 3	Nurse 4
Sector 1	2	6	5	8
Sector 2	7	4	6	5
Sector 3	5	3	9	0

Source: Authors (2024).

The example shows a fictitious situation, but in a real environment, the dimension of the problem (number of employees and sectors) is significantly larger. Additionally, other possible variables and constraints consistently increase the difficulty of solving the problem (Xiang et al., 2015; Silva & Silva, 2023).

In the problem under study, one of the sets of restrictions present in problems of this nature is related to meeting the demand by sectors. The number of professionals allocated to each sector should be equal to or greater than the existing demand. Another set of constraints concerns the minimum allocation score, which prevents a professional from being assigned to work in a sector with a score lower than the minimum desired. These restrictions prevent the professional from operating in a sector that has a very low personal preference and/or lacks the skills and competencies to provide quality services in this sector.

The mathematical and computational complexity of the problem is significantly high, especially in large hospital environments (Gür & Eren, 2018; Özder et al., 2020). Therefore, it is essential to develop and use optimization and artificial intelligence approaches to plan hospital nurse assembly teams. These methods allow the treatment of problems with a large volume of variables and restrictions, seeking solutions that maximize the satisfaction of nursing professionals and the quality of services the healthcare organization provides.

In this sense, the study in question aimed to develop a heuristic optimization approach, based on local search mechanisms, to perform the planning and assignment of nurse professionals in hospital sectors to maximize both the preferences of the professionals and the quality of the services provided based on their skills and competencies.

METHODS

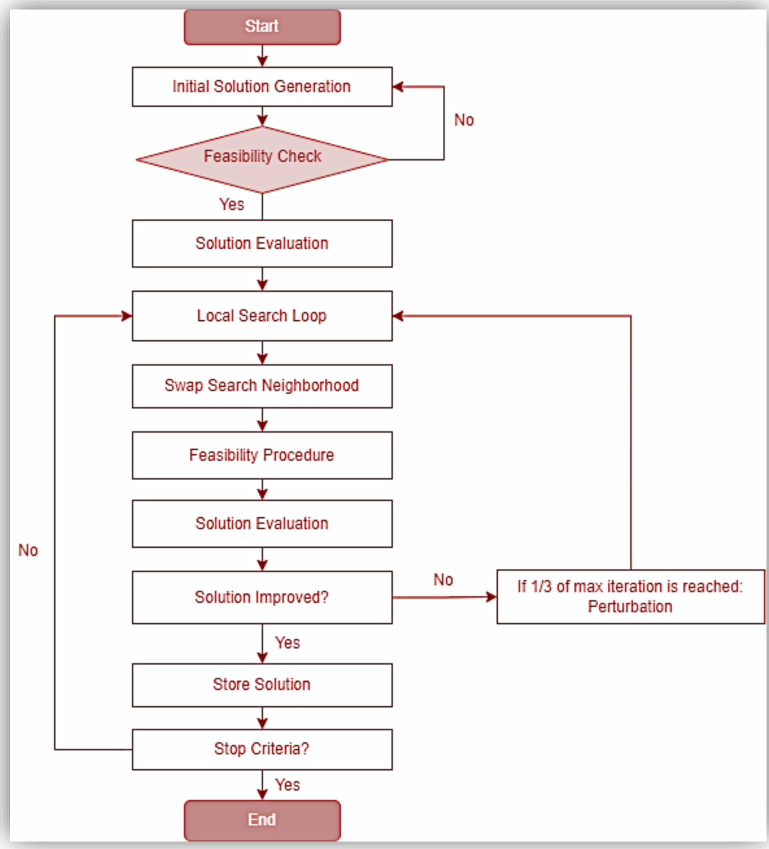
This study aimed to develop a local search optimization heuristic to solve problems of allocation and assignment of nurses in hospital networks. Optimization strategies were implemented to allow a better use of existing resources, maximizing the performance preferences of professionals, as well as the skills and competencies in their specialties.

For this, a local search-based optimization heuristic approach with solution perturbation mechanisms and search neighbourhoods was proposed. In the first moment, the method proceeds with the generation of an initial solution. A greedy procedure is applied, seeking to reach diversified solutions in the search space, respecting the problem constraints. After the generation, the qualities of the solutions are evaluated.

The iterative process of local search is initiated, defining as the main stopping criterion the amount of 10 thousand iterations, where a 'swap' search neighbourhood is used, which, according to preliminary studies, demonstrated greater efficiency being used isolated in the proposed problem, instead of in conjunction with other search neighbourhoods. The mechanism allows us to perform an efficient search, preserving a significant part of the previous solution.

A perturbation procedure is performed after several iterations without improvement to escape the local optimums. The mechanism allows the method to explore other regions of the search space, helping obtain better results with computational efficiency. Figure 1 illustrates in more detail the main steps and flows of the heuristic approach developed.

Figure 1. Proposed heuristic flowchart



Source: Authors (2024).

The method begins by generating the initial solution to the problem, followed by a feasibility checking mechanism, which checks if the solutions conform to the constraints of the problem. This procedure is essential in executing the method and allows the local search loop is started with feasible solutions.

Through the flowchart presented in Figure 1, it is possible to observe that during the iterative loop of local search, several steps are executed in sequence, mainly: Swap Search Neighbourhood to generate new solutions; Feasibility Procedure; Solution Evaluation to identify the best solution; Perturbation Mechanism to analyse new search spaces. In the following topics, their functions and parameters are presented, aiming to understand with more detail the proposed approach. Below is Table 2, with the names used in the algorithms in the following topics.

Table 2. Algorithm data

Symbol	Description
Ɗ	Matrix of sectoral demands
S	Initial solution matrix
Ş	Optimized solution
ş	Sectors
Ƒ	Employees
c	Sector allocation counting matrix
p	Perturbance counter
ɪ	Maximum iteration
E	Specialties
Ȩ	Best specialties

Source: Authors (2024).

INITIAL SOLUTION

The initial solution represents the first stage of the problem-solving process. A greedy heuristic is used to generate the proposed method. It produces pseudo-random solutions while respecting the problem constraints by swapping the positions of the solution (which represents the allocation of nurses in the sectors).

The greedy heuristic performs exchanges throughout the solution, exchanging a number of positions that are also defined randomly. The aim is to generate initial solutions that cover as comprehensively as possible the search space, allowing the following iterated search process to be more effective in finding efficient solutions or the optimal solution itself.

In the research, data is collected in the matrix of preferences and specialties (E), which contains the scores of health professionals for each sector, the matrix of demands by sector (Ɗ), and matrix/solution vector (*S*), initially empty. Iteratively, it generates random initial solutions to be allocated in the *S* (Algorithm 1). As a Feasibility Mechanism (Algorithm 4), if the initial solution does not satisfy sector demands or minimum score constraints, new solutions are generated until satisfies the constraints and thus can be allocated in the *S*.

Algorithm 1. Initial Solution Generation Pseudocode

Procedure Initial Solution

Entry: Ɗ, ş, Ƒ, c, S

Output: S'

For *i* = 1, ..., $Ƒ_i$ do

Generate a ş (Randomly)

Allocate $Ƒ_i$ in ş and store in S

End for

For *i* = 1, ..., $Ƒ_i$ do

For *i* = 1, ..., $ş_i$ do

Count the allocation by sector

Store the sector allocation in c

End for

End for

If c < Ɗ do

Feasibility Mechanism

End if

Update the S' solution

End - Inicial Solution

Source: Authors (2024).

SWAP LOCAL SEARCH NEIGHBOURHOOD

After the initial solutions are generated, the iterative local search process is executed. An efficient local search neighbourhood allows the generation of more efficient solutions since it searches for new neighbouring solutions, preserving a part of the solution to improve the previous solution. The new solutions are obtained through moves in the current solution structure. That is, neighbours of the current solutions are selected, enabling the method to intelligently and efficiently scan the search space.

A local search neighbourhood 'swap' was adopted in the proposed heuristic approach. The search mechanism proved efficient in the presented problem and is performed by selecting two random positions from a MS solution, which will be swapped later, as seen in Figure 2.

Figure 2. Swap procedure representation

1	2	3	4	5
		⇩		
1	4	3	2	5

Source: Authors (2024).

In order to preserve a considerable part of the most current solution, the swap is performed on up to one-third of the number of nurses randomly selected. It is replaced when the new solution is better than the current one. Otherwise, it is ignored. In addition, it is analysed if the problem constraints are being satisfied in the newly generated solutions, executing feasibility mechanisms if necessary. Algorithm 2 describes the iterative process of the local search adopted.

Algorithm 2. Swap pseudocode

```
Procedure Local Search Approach - Swap Neighborhood
Entry: Ɗ, ş, Ƒ, c, ɪ, S, Ş, E, Ę
Output: Ş
For i = 1, ..., 0.33*Ƒ_i do
  Generate a random employee Ƒ_n
  Generate a random sector ş_1
  Generate a random sector ş_2
  If ş_1 = ş_2 do
    While ş_1 = ş_2 do
      Generate a random sector ş_2
    End while
  End if
  Perform the heuristic procedure and change the employee Ƒ_i from ş_1 to ş_2
  Store the result in the solution S
  For i = 1, ..., Ƒ_i do
    For i = 1, ..., ş_i do
      Count the allocation by sector
      Store the sector allocation in c
      Count the value of the E in S
    End for
  End for
  If c < Ɗ do
    Feasibility Mechanism
  End if
  If E > Ę do
    Ş = S
  End if
End for
Update the Ş' solution
End - Local Search Approach - Swap Neighbourhood
```

Source: Authors (2024).

Maximizing specialties helps that a nurse is not assigned to a job that is averse to their professional preference, leading them to work unsatisfactorily (possibly compromising his performance and the service quality).

Perturbation Procedure

Perturbation procedures are techniques adopted in heuristic approaches that seek to significantly alter a set of solutions during the method. The perturbation mechanism aims to allow solutions to escape locals optimal, which prevents them from progressing and finding more efficient solutions just by using search neighbourhoods.

Thus, the perturbation applied to the solutions helps the solving method explore different regions of the search space, increasing the chances of finding the optimal solution or a high-quality solution that performs very close to the optimal solution.

The perturbation occurs in the proposed method when the algorithm performs 20% of the maximum number of iterations without improving the current solutions (or in some iteration with a small probability).

For its realization, the swap search mechanism was used in order to swap the sectors of specific professionals randomly. For each nurse, one or two pairs of sectors are randomly selected (following a previously defined probability distribution). Then, the values at the positions of the sectors in the solution matrix are swapped to modify the assignment (Algorithm 3).

Algorithm 3. Pseudocode of Perturbation Mechanism.

Procedure Perturbation
Entry: p, Ɗ, c, ş, Ƒ, S
Output: S'
Assess the need for Perturbation
    If p = 2000 do
        For *i* = 1, ..., $Ƒ_i$ do
            Generate a random sector $ş_1$
            Generate a random sector $ş_2$
            If $ş_1$ = $ş_2$ do
                While $ş_1$ = $ş_2$ do
                    Generate a random sector $ş_2$
                End while
            End if
            Perform the heuristic procedure and change the employee $Ƒ_i$ from $ş_1$ to $ş_2$
            Store the result in S
        End for
        For *i* = 1, ..., $Ƒ_i$ do
            For *i* = 1, ..., $ş_i$ do
                Count the allocation by sector
                Store the sector allocation in c
            End for
        End for
        If c < Ɗ do
            Feasibility Mechanism
        End if
        p = 0
    End if
Update the S' solution
End - Perturbation

Source: Authors (2024).

FEASIBILITY MECHANIMS

The feasibility mechanism addresses the factors considered for accepting the developed approach according to practical situations commonly found in hospital networks. The proposed heuristic can represent and provide an optimization strategy with better use of the available human resources.

As explained in the problem description, there is a strong constraint: all sectors must have their demands satisfied. That is, the number of nurses allocated to each sector must be equal to or greater than its minimum demand. This constraint is handled through a mechanism, as presented in Algorithm 4.

Algorithm 4. Demand Verification Pseudocode

```
Procedure Feasibility Mechanism
Entry: Ɗ, ș, Ƒ, c, S
Output: c > Ɗ
If c < Ɗ do
  While c < Ɗ do
    For i = 1, ..., Ƒi do
      Generate a random sector ș
      Allocate the Ƒi in ș and store in S
    End for
    For i = 1, ..., Ƒi do
      For i = 1, ..., și do
        Count the allocation by sector
        Store the sector allocation in c
      End for
    End for
  End while
End if
End - Feasibility Mechanism
```

Source: Authors (2024).

RESULTS AND DISCUSSION

For the computational tests of the proposed method, non-real data based on three hospitals (i.e. there was no direct involvement of people or identifiable data in the research) were proposed and used, which will be designated as instances A, B, and C. For all instances, the scores represent an average of their personal preference values to act in each sector, as well as for their declared ability/competence related to each sector. The size of the instances, indicated by the number of nurses and sectors, are presented in Table 3.

Table 3. Number of nurses and sectors in each instance

Instance	Nurses	Sectors
A	40	6
B	30	4
C	50	8

Source: Authors (2024).

For each of the instances considered in the study, Table 4 presents the respective minimum demands of nurse professionals that must be assembled in each of the sectors.

Table 4. Nurses demand per sector in each instance

Instances	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6	Sector 7	Sector 8
A	5	5	6	11	3	8	-	-
B	5	8	8	7	-	-	-	-
C	3	11	5	4	8	5	4	7

Source: Authors (2024).

Ten experimental tests were conducted for each instance to evaluate the mathematical and computational efficiency of the proposed heuristics. The tests used the principle of repeatability, i.e., the performance of successive measurements taken under the same conditions. Thus, the experimental tests on the instances were carried out on a computer equipped with an Intel(R) Core (TM) i7-8565U CPU running at 1.80 GHz—1.90 GHz, 8GB of RAM, and the Windows 11 operating system.

The highest and lowest results obtained for the objective function (maximization of total score) were evaluated from the execution results for each instance. Additionally, the computational execution times were collected. In addition to calculating the maximum and minimum values, we computed the average scores and computational times. The results obtained from the tests conducted in all scenarios are shown in Table 5.

Table 5. Computational experiments for each tested instance

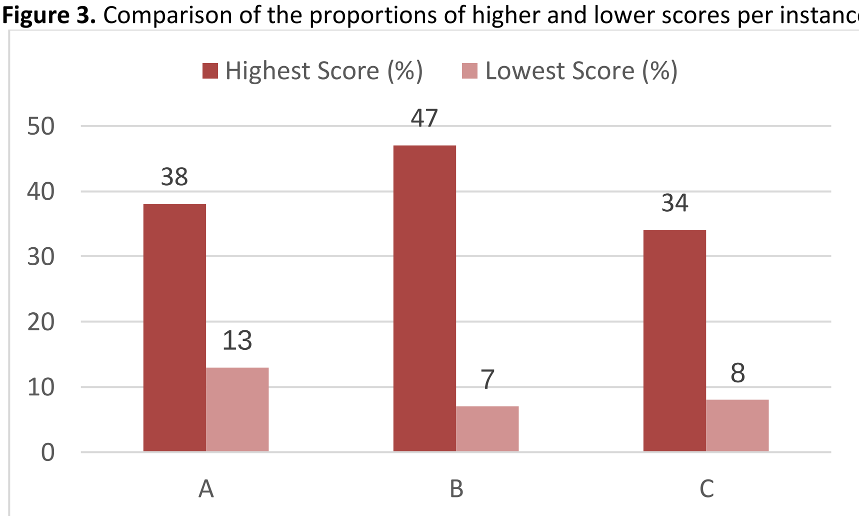
Instance	Result Min	Result Max	Result Avg	Time Min	Time Max	Time Avg
A	264	273	268,5	00:20:02	00:39:00	00:29:31
B	200	208	204	00:00:11	00:00:38	00:00:25
C	298	313	305,5	04:11:21	07:10:34	05:40:58

*The time is shown in hours: minutes: seconds.

Source: Authors (2024).

A study was produced of where each professional would be allocated, evaluating sectors with the highest and lowest scores per nurse, seeking to deepen the analysis of the best results obtained. Thus, Figure 3 shows the percentages referring to the allocation of nurses who stayed in the sector with the highest and lowest scores.

Figure 3. Comparison of the proportions of higher and lower scores per instance



Source: The authors (2024).

The data allows us to observe the high efficiency of the proposed algorithm, which allows an efficient allocation of professionals in their appropriate assignments, respecting all the problem constraints. Besides this, less than 13% were allocated in the lowest scoring sectors, reaching about 7% in the best scoring instance.

The results demonstrate the effective contribution that the proposed method can make to nursing staff assignment decisions in practice. The maximization of preferences and skills in the allocation process can contribute significantly to the performance of healthcare organizations since it promotes the satisfaction of the nurses while seeking an allocation according to the skills and experience of professionals in each sector, favouring improvement in the quality of services provided.

CONCLUDING REMARKS

This study aimed to develop a heuristic optimization approach for the allocation and assignment of nurse professionals in hospital environments. This problem represents one of the significant challenges of resource management in healthcare optimization due to its mathematical and computational complexity and the impacts of its planning on the performance of healthcare organizations.

The purpose is to define the optimal assignment of nurses in specific hospital sectors, aiming to maximize a global score. The score is based on the personal preference of professionals, as well as on their skills and experience in the respective sectors.

For this, a heuristic approach based on local search was developed, which uses a search neighbourhood mechanism named swap. Feasibility mechanisms were implemented to better fit the solutions generated with the existing operational constraints. These mechanisms guarantee that the sets of constraints regarding the demand for professionals per sector, as well as the minimum scores per sector, are duly respected.

The method was applied in three instances, created from data based on three different hospitals. After analysing the computational results obtained, it was possible to verify the efficiency of the proposed method, both in terms of the quality of the solution obtained and in computational cost, since the time required to reach the solutions is considered viable for practical application in hospital planning.

The results showed that it was possible to achieve solid contributions to the literature on the subject with the study. Also, it was possible to achieve practical contributions to hospital management since maximizing preferences and skills in the allocation process can significantly contribute to the performance of healthcare organizations. A maximized score promotes staff satisfaction and appropriate allocation according to skills by sector, promoting better quality care.

As a suggestion for future research, we propose considering the allocation of work shifts, commonly called the nurse rostering problem. This approach can enable systemic management of the problems and facilitate more efficient and appropriate decision-making in organizations.

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