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Genetic Algorithm-Based Optimization for Nurse Scheduling Problem

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ABSTRACT

The nursing workforce problem is essentially a scheduling problem. Scheduling problems involve the efficient planning and sequencing of specific resources, aiming to find the best time schedule that meets all constraints. Genetic Algorithm can be utilized to solve scheduling problems effectively. In this study, taking into account the success of the Genetic Algorithm in scheduling problems, a software has been developed in the Python environment to ensure the optimal assignment of nurses in clinics. The Genetic Algorithm-based software operates on a population basis, seeking to find the best schedule that satisfies various tasks and constraints. During the study, the planning of nursing staff considered the possibility of different clinics within the hospital, each dealing with patients requiring different care durations. It was assumed that a nurse works according to legal restrictions. Furthermore, a 4-week period was taken into consideration during the scheduling process, and the program was executed for a total of 28 days (a total working time of 160 hours). As a result, a software solution was presented that can successfully achieve an optimal nurse assignment, enabling the complete fulfillment of patients' care requirements in a given clinic.

Keywords: Genetic algorithm, nurse scheduling, optimization

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Hemşire Çizelgeleme Problemi için Genetik Algoritma Tabanlı Optimizasyon

ÖZ

Hemşire iş gücü planlama problemi temelde bir çizelgeleme problemdir. Çizelgeleme problemleri, belirli kaynakların verimli bir şekilde planlanması ve sıralanmasıyla ilgili olup, tüm kısıtlamaları karşılayan en iyi zaman çizelgesini bulmayı amaçlar. Genetik Algoritma, çizelgeleme problemlerini etkili bir şekilde çözmek için kullanılabilir. Bu çalışmada, Genetik Algoritmanın çizelgeleme problemlerindeki başarısı dikkate alınarak, hemşirelerin kliniklerde optimal bir şekilde atanmasını sağlamak amacıyla Python ortamında bir yazılım geliştirilmiştir. Genetik Algoritma tabanlı yazılım, bir nüfus temelinde çalışarak, çeşitli görevleri ve kısıtlamaları karşılayan en iyi çizelgeyi bulmaya çalışmaktadır. Çalışma sırasında, hemşire planlaması yapılırken, hastanede farklı klinikler göz önünde bulundurulmuş ve her bir serviste farklı bakım süresi gerektiren hastaların bulunduğu varsayılmıştır. Bir hemşirenin yasal kısıtlamalara göre çalıştığı varsayılmıştır. Ayrıca, çizelgeleme sürecinde 4 haftalık bir dönem dikkate alınmış ve program toplamda 28 gün (toplam çalışma süresi 160 saat) için çalıştırılmıştır. Sonuç olarak, bir klinikte hizmet alan hastaların bakım gereksinimlerini tamamen karşılayan optimal bir hemşire ataması yapabilen bir yazılım çözümü sunulmuştur.

Anahtar Kelimeler: Genetik algoritma, hemşire çizelgeleme, optimizasyon

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1. Introduction

Hospitals, healthcare institutions, and clinics must have an adequate nursing workforce to provide quality patient care and medical services. Nurses play a fundamental role in the healthcare sector and assume a critical role in the care, treatment, and recovery processes of patients. However, ensuring the correct number and qualified nurses are assigned can be a time-consuming and complex task for administrators. This is a highly challenging problem to calculate due to various factors influencing the nursing workload [1]. These factors include the number of patients, support services provided, patient care requirements, and legal limitations. Additionally, seasonal effects or extraordinary situations like natural disasters or pandemics can significantly impact these factors [2].

The traditional methods used for nurse workforce planning are generally methods performed manually or based on simple calculations. Among these methods, the use of Excel spreadsheets, Paper-based Planning, Experience and Needs-Based Planning, Semi-Automatic Planning Tools, and Shift Management Software can be counted. On the other hand, in recent years, heuristic algorithms have been widely used to address complex scheduling problems where classical and manual methods struggle to find precise and quick solutions [3][4]. One effective optimization technique based on natural evolution processes is the Genetic Algorithm (GA) method. GAs have been widely used in various fields due to their ability to optimize multidimensional nonlinear problems [5]. GAs have been proposed as an effective method for scheduling nurses under different constraints, such as shift and day-off preferences, and have been shown to efficiently reduce infeasible solutions due to practical scheduling constraints [3]. Additionally, GAs have been used to generate high-quality nurse schedules within an acceptable computation time, indicating their applicability to real-world problems with numerous constraints [6].

The literature supports the effectiveness of GAs in addressing the nurse scheduling problem, particularly in handling various constraints, optimizing multi-objective functions, and addressing real-world scheduling instances. Leksakul and Phetsawat [6], utilized a GA with two-point crossover and random mutation to obtain optimal nurse schedules, demonstrating the effectiveness of GAs in addressing staffing and overtime challenges. In another study, Maenhout and Vanhoucke [7] presented a hybrid GA for the nurse scheduling problem, highlighting the potential of GAs in this domain. Moreover, Wibowo and Lianawati [8] introduces a multi-objective GA for optimizing nurse scheduling, emphasizing the significance of GAs in overcoming scheduling challenges in healthcare institutions [3].

In this research, considering the efficacy of Genetic Algorithms in addressing scheduling issues, a Python-based software has been created to optimize nurse assignments in clinics. The software, relying on Genetic Algorithms, operates on a population scale, aiming to discover the most suitable schedule meeting diverse tasks and constraints. The scheduling process spans a 4-week period, executed for a total of 28 days (equivalent to 160 working hours).

The paper is structured as follows: Section 2 introduces the nurse scheduling problem, and Section 3 provides an explanation of the genetic algorithm. Section 4 presents the application and its results. The concluding remarks are presented in Section 5.

2. Nurse Scheduling

Nurse workforce planning involves ensuring an adequate number of qualified nurses to provide quality nursing care for both patients and healthy individuals. The decline in the quality of care and service performance in hospitals is often a result of insufficient nursing staff. The planning process aims to address this issue by providing the necessary number of nurses with the required qualifications [9].

When looking at nursing workforce planning approaches in inpatient care institutions, there are factors that affect the nurse workload. These include the number of patients, support services undertaken by nurses, and the care requirements of patients. The patient count is influenced by seasonal changes, natural disasters, or pandemic situations. Additionally, the 24-hour care requirement for each patient admitted to a unit varies. For this purpose, patients are classified based on their care needs. Table 1 provides different patient types and their characteristics according to the Cheltenham patient classification scale [10]. This scale plays a critical role in optimizing nurse staffing, workload management, and patient outcomes in healthcare services.

Table 1. Patient's classification

Type	Patient condition
Patient 1	Capable of self-care and independence
Patient 2	Demands moderate nursing care, semi-independent
Patient 3	Requires comprehensive nursing care, bedridden but not incapacitated
Patient 4	Necessitates intensive nursing care, bedridden and incapacitated

On the other hand, the patient classification system categorizes patients based on care needs, illness severity, and care amount, considering individual characteristics. Its goal is to assign scores to similar-needs groups, defining required nursing care quality. This system classifies patients with diverse care needs and calculates 24-hour care requirements for optimal nurse staffing, ensuring patients' needs are met. In Table 2, sample patient care durations are provided for patients admitted to services in a hospital. According to Table 2, the number of beds in the cardiovascular surgery service is 28. Observation data for three different time intervals are given for this service. These observations represent 8-hour intervals within a 24-hour period. In the first observation, the number of type 1 patients is 15, type 2 patients is 11, and type 3 patients is 2. There are no type 4 patients in this service. The required care need for these patients is calculated as 51.50 for the first and second observations and 39.50 for the third observation. The average care need is 15.02 for the first and second observations and 11.52 for the third observation. In this study, the second and third observations are combined, and a night shift with a working time of 16 hours is planned.

Table 2. Sample patient care durations

Service name	beds	shift	Type1	Type2	Type3	Type4	Care needs	Avg. care needs
Obstetrics	20	1	14	6	0	0	29.00	8.45
Obstetrics	20	2	16	3	1	0	28.00	8.16
Obstetrics	20	3	15	4	0	0	25.00	7.29
cardiovascular surgery	28	1	15	11	2	0	51.50	15.02
cardiovascular surgery	28	2	14	6	5	0	51.50	15.02
cardiovascular surgery	28	3	12	11	0	0	39.50	11.52
Neurology	27	1	20	0	5	2	62.50	18.22
Neurology	27	2	20	2	3	1	48.50	14.14
Neurology	27	3	21	1	3	1	47.00	13.70

3. Genetic Algorithm

Genetic algorithms are a computational method based on the principles of biological evolution for solving optimization problems. These algorithms explore the solution space by mimicking evolutionary processes such as natural selection, genetic crossover, and mutation, aiming to find the best solution. The origin of genetic algorithms dates back to the 1970s when John Holland and his colleagues initiated the development of artificial evolutionary systems [11].

The fundamental principle of genetic algorithms is based on how natural selection and genetic processes work in the biological world to increase diversity and adaptability. The operation of the algorithm consists of the following steps.

- **Step 1**. Creating the Initial Population: The first step is to create a population consisting of randomly selected individuals. This population representing potential solutions
- **Step 2**. Fitness Evaluation: Each individual has a fitness value indicating how well it provides a solution for a specific problem or task.
- **Step 3**. Selection: The probability of selecting more fit individuals is determined based on their fitness values. This symbolizes the transmission of better solutions to future generations.
- **Step 4**. Crossover: Genetic material exchange occurs among the selected individuals. This increases diversity and generates new potential solutions.
- **Step 5**. Mutation: With a certain probability, the genetic material of individuals is randomly altered. This allows for the emergence of new features or solution proposals.
- **Step 6**. Creating a New Population: A new population is formed from individuals obtained through selection, crossover, and mutation steps.
- **Step 7**. Stopping Criterion: The algorithm terminates when a specific stopping criterion is met. Otherwise, the steps are repeated.

4. GA-based Nurse Scheduling

In the study, the functionality of the nurse scheduling application developed based on GA was assessed using the data presented in Table 2. As an example, the Obstetrics service chosen has 20 beds, with 14 patients categorized as type 1 and 6 as type 2. There are no type 3 or type 4 patients. Three observation shifts are assigned for these patients throughout the day. The average care hours for patients are 8.45 for the morning shift, 8.16 for the afternoon shift, and 7.29 for the evening shift. A total of 8 nurses are allocated to this service. However, it's crucial to note that an entire 8-hour work shift of a nurse may not be exclusively spent in this service. Nurses are observed to dedicate approximately 18% of their average working hours to service-related tasks and 24% to personal tasks.

In the study, while conducting nurse scheduling, it is assumed that a nurse works according to the legal constraints specified below, taking into account the Obstetrics service:

- The number of nurses in the service is 8.
- Nurses work in two shifts: day and evening. The day shift lasts for 8 hours, and the evening shift lasts for 16 hours. For these periods, the time spent on patient care is 4.64 hours during the day (after subtracting 18% for service-related tasks and 24% for personal tasks) and 9.28 hours during the night.
- A nurse working the 16-hour night shift will be considered on leave the next day.
- A nurse's weekly (7 days) working hours will not exceed 40 hours.
- A nurse's monthly (28 days) working hours will not exceed 160 hours.
- A nurse working the day shift cannot work the night shift simultaneously.
- It is assumed that no nurse has any impediment (illness, having completed 30 years of service, pregnancy, exemption from duty) for the night shift.

In the study, when determining the fitness function, penalty value (*pv*) were calculated for situations where patient care times exceed or fall below the specified durations and for situations where nurses' weekly or monthly working hours exceed or fall below certain limits.

If nurse care time < patient care time:
pv1 = patient care time - nurse care time
If nurse care time > patient care time:
pv2 = nurse care time - patient care time
If nurse working time > weekly/monthly working time:
pv3 = nurse working time - weekly/monthly working time
If nurse working time < weekly/monthly working time:
pv4 = weekly/monthly working time - nurse working time

Considering 8 nurses and their weekly/monthly working times, the optimization goal in the optimization process is to minimize the *pv* value.

$$Total\ pv = pv1 + pv2 + pv3 + pv4$$

To minimize the *pv* value in the study, the GA method was chosen. In the Genetic Algorithm, the process begins with creating the initial population. The Initial Population is the set where all individuals come together. The goal here is to obtain higher-quality individuals in each iteration. The fitness value of these individuals is calculated, and then basic operations are iteratively applied. These operations are selection, crossover, and mutation. In selection operations, a random selection method is applied so that the best individuals in the current population will have a higher chance. Randomness is essential in genetic algorithms, but in the selection process, it is a selection where the chances of better individuals are higher. Crossover aims to obtain 2 child individuals from 2 descendent individuals. Random genes are changed within chromosomes. The mutation process is applied rarely but randomly. It can be applied to avoid getting stuck at maximum or minimum points of the optimization problem. The parameters used in the GA are provided in Table 3 below. The parameter values used in genetic algorithms are values obtained manually through trial and error, ensuring the successful operation of the optimization process. In the study, the application was developed using the Python programming language.

Table 3. Parameters of the genetic algorithm

Parameters	**value**
Crossover rate	0.95
Mutation rate	0.05 / 0.1
population	30 / 100
Elitism strategy	Roulette wheel
iteration	100.000 / 1.000.000
Crossover strategy	Single point (week scheduling) Two point (month scheduling)

The chromosome structure generated for a 7-day period is provided in Figure 1. A gene has been defined for each nurse (in this example, planning has been made for 8 nurses), representing each day of the week. The possible values for these genes are 0 for non-working days, 8 for day shifts, and 16 for night shifts. Thus, the initial solution randomly generated for solving the problem is determined according to this chromosome structure, taking constraints into account. The size of the chromosome vector varies depending on the number of days and nurses designed for the problem.

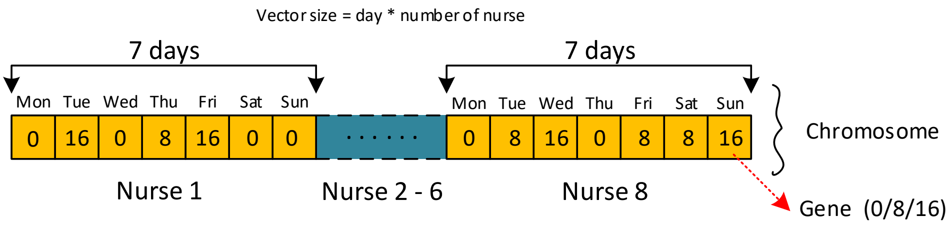

Figure 1. Chromosome structure for 7 days

4.1. Results

The program's functionality was tested based on the information from the Obstetrics Service. The three different shift systems in the Obstetrics Service were reduced to two. The 24-hour time frame was expressed as 8 hours of daytime and 16 hours of nighttime work. Accordingly, the program was calculated weekly, with each nurse working 40 hours every weekend. For the daytime shift, a total of 8.45 hours were allocated for patient care, and for the nighttime shift, 15.75 hours were allocated, as indicated in Table 2. Figure 2 depicts the results of the weekly nurse assignment based on a population size of 30, mutation rate of 0.085, iter = 100.000, and single-point crossover values. In the figure, rows represent nurses, columns represent days, and the last column (7) indicates the weekly working hours obtained as a result of the optimization process. Additionally, the cells show 8 hours for morning shifts, 16 hours for night shifts, and 0 for days off.

	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Total Working
N1	8	8	16	0	8	0	0	40
N2	0	8	0	16	0	16	0	40
N3	16	0	16	0	0	8	0	40
N4	0	0	0	8	16	0	16	40
N5	0	0	8	8	16	0	8	40
N6	0	0	8	16	0	16	0	40
N7	8	16	0	0	0	0	16	40
N8	16	0	0	0	8	8	8	40

Figure 2. Nurse scheduling for 7 days

According to Figure 2, Nurse 1 (N1) has been assigned 8 hours of work on Monday, 8 hours on Tuesday, 16 hours on Wednesday, and 8 hours on Friday. This nurse has been designated as being on leave on Thursday, Saturday, and Sunday. Additionally, according to Figure 2, for example, on Monday, only 4 nurses have been assigned. Two of these nurses are assigned to the morning shift, and the other two are assigned to the night shift. Accordingly, the daytime care duration for 2 nurses is 2 * 4.64 = 9.28 hours. During this time, the required patient care duration is met by 8.45 hours. In addition, the total care duration assigned to the two nurses for the night shift is 2 * 9.28 = 18.56 hours. During this time, the patient care duration meets the 15.75-hour requirement.

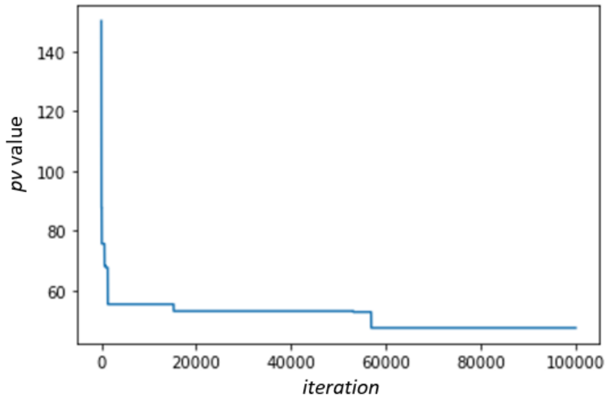

Figure 3. *pv* value minimization for 7 days

In Figure 3, the pv minimization process, graphically demonstrating the attainment of the best value, is shown. As can be seen from the graph, pv is minimized to at least 42.18 after 58,000 iterations. Here, pv does not reach zero due to the fact that nurse care durations may not be exact multiples of patient care durations, and there may be 1-2 hours of excess time relative to the patient care duration.

In the study, the nurse workforce planning was considered over a 4-week period, and the program was run for 28 days, with a total working time of 160 hours. The results of the study are presented in Figure 4 for 2 weeks (first and last) sections.

	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue
N1	8	0	8	16	0	0	16	0	16
N2	0	8	16	0	16	16	0	0	8
N3	0	16	0	0	0	16	0	0	0
N4	8	16	0	8	8	0	0	8	0
N5	16	0	16	0	16	0	8	16	0
N6	8	8	0	0	8	0	16	0	8
N7	16	0	0	8	0	8	0	16	0
N8	0	8	8	16	0	8	8	8	0

	Sat	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Total Working
N1	0	8	8	0	8	16	0	8	160
N2	0	8	16	0	0	8	16	0	160
N3	0	0	8	8	8	0	0	16	160
N4	0	16	0	0	16	0	8	0	160
N5	8	0	0	16	0	0	0	16	160
N6	16	0	0	8	0	16	0	8	160
N7	0	16	0	16	0	8	8	0	160
N8	16	0	16	0	16	0	16	0	160

Figure 4. Screenshot showing first and last week in 30-day nurse planning

In Figure 4, the results of the monthly nurse assignment are shown based on a population size of 100, mutation rate of 0.1, iter = 1.000.000, and double-point crossover values. As a result of the program, each nurse has been appropriately placed to work 160 hours per month. However, in some cases (e.g., the 8th column), the assignment of the number of nurses required to meet patient needs could not be achieved. In this case, a single nurse assignment for the night shift was made, and the nurse workforce was reduced to 9.28 hours, falling below the required 15.75 hours of patient care. The main factor contributing to this situation is the constraint on the number of nurses and the monthly working hours.

The pv minimization process for the optimization process given in Figure 4 is presented in Figure 5. As can be seen from the graph, pv is minimized to at least 259.11 after 43.451 iterations.

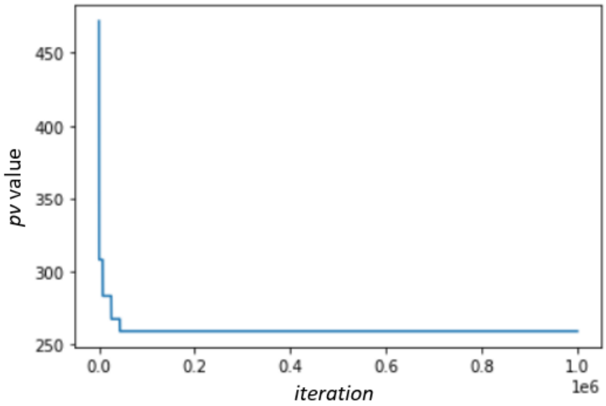

Figure 5. pv value minimization for 28 days

The expected success in the study is to determine the minimum number of nurses that can meet the minimum nurse requirements in a service, including constraints, through the optimization process using genetic algorithms, and to plan them on a schedule. From this perspective, it is observed that the optimization process works successfully.

5. Conclusion

The application of Genetic Algorithms (GAs) to nurse scheduling in healthcare settings has proven to be a robust and effective approach. The GA methodology, inspired by biological evolution principles, provides a versatile framework for optimizing nurse schedules while considering various constraints. The study employed a fitness function with penalty values to assess schedule compliance with legal regulations, working hour constraints, and patient care requirements, aiming to minimize penalties for a balanced and efficient nurse schedule. The study's results, depicted in Figures 2, 3, 4, and 5, highlight the successful implementation of the GA-based nurse scheduling application. The algorithm effectively generated schedules that adhered to legal constraints, met patient care demands, and optimized working hours for nursing staff.

In summary, the application of Genetic Algorithms in nurse scheduling demonstrates adaptability and effectiveness in addressing the intricate requirements of healthcare workforce planning. The developed GA-based application serves as a valuable tool for healthcare administrators to optimize nurse schedules, contributing to improved operational efficiency, regulatory compliance, and enhanced patient care. Future research can focus on refining the algorithm, considering additional constraints, and exploring its applicability in diverse healthcare settings.

Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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