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Using Queuing Theory and Simulation to Improve Oral Health Program

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Abstract: Queuing Theory is an important branch of Applied Mathematics which involves the mathematical modelling and analysis of systems where entities, such as customers in a line, arrive at a service facility, wait for service, and then depart after being served. Applied Mathematics provides the tools needed to model and analyze queuing systems. In 2021, the 74th World Health Assembly approved the historic resolution for Oral Health, which, recognizes the need to develop a project and proceed with the launch of a "Global Strategy for Oral Health". In this sense, and for the necessary adaptations to occur in the Portuguese National Health System (PNHS), an in-depth study is necessary specially at the level of human resources, essential for the program to be effectively implemented and the objectives proposals duly achieved. Minimizing patient waiting times is a crucial consideration in healthcare sector management. This work aims to improve and build a discrete event simulation model for modeling patient flow queuing system in an NHS dentist's office, with the purpose of exploring options for designing an effective queuing system. The model of a public dental office is simulated with the help of Arena Software, based on data collected by the Portuguese Dental Association to optimize dental service management. Therefore, through this simulation, the efficiency of this public dental administration can be increased, thus being able to offer oral health care to the entire Portuguese population. The findings of the simulation indicated that little adjustments to the current system could have a significant impact on the use of resources.

Keywords: Arena simulation software, Healthcare logistics, Simulation, Queuing theory, Applied mathematics

Introduction

Queuing Theory is a mathematical approach used to analyze the behavior of queues, which are lines of waiting customers, patients, or other entities requiring service. The fundamental elements of a queuing system include the arrival process (how entities arrive at the queue), the service process (how entities are served), and the queue discipline (the order in which entities are served) (Newton & Medhi, 1992).

In healthcare, Queuing Theory provides essential tools for modeling and analyzing patient flow through various medical facilities, such as hospitals, clinics, and dental offices. Efficient management of these flows is critical to minimizing patient waiting times, optimizing resource utilization, and enhancing the overall quality of care (Green, 2006). Healthcare systems are inherently complex, involving multiple stages of service, varying arrival rates, and diverse patient needs, making Queuing Theory an ideal approach for addressing these challenges (Wallace et al., 2013). Dental offices, use Queuing Theory to streamline patient flow from arrival to departure. By simulating different scenarios, dental offices can identify bottlenecks, optimize appointment schedules, and ensure that resources are allocated efficiently to minimize patient waiting times (Fomundam & Herrmann, 2007).

The Benefits of Queuing Theory in Healthcare are many, such as: by understanding and modeling patient arrival and service processes, healthcare facilities can implement strategies to reduce waiting times, leading to improved patient satisfaction and outcomes (Duguay & Chetouane, 2007; Hall, 2006); queuing models help in determining the optimal number of staff, equipment, and other resources needed at different times, ensuring that resources are used efficiently without overburdening the system(Harper & Shahani, 2002); efficient queuing systems contribute to higher service quality by reducing delays and ensuring that patients receive timely and appropriate care (Kolker, 2008; Rasheed et al., 2012); queuing theory provides a quantitative basis for decision-making, allowing healthcare administrators to make informed choices about resource allocation, staffing, and process improvements (Worthington, 2008; Worthington, 1987).

In 2021, the 74th World Health Assembly (World Health Organization, 2021a)approved a historic resolution for Oral Health, recognizing the critical need to develop a "Global Strategy for Oral Health." This global initiative underscores the importance of oral health and necessitates strategic adaptations in national health systems, including Portugal's National Health System.

The objective of this study is to simulate a queuing model of a public dental office using Arena Software. This simulation aims to enhance the efficiency of the public dental service by evaluating different scenarios and conducting a sensitivity analysis to improve system performance. Ultimately, this research seeks to minimize patient waiting times and ensure the effective delivery of oral health care to the Portuguese population.

Background and Literature Review

Queuing Theory Applications

Queuing Theory is a branch of operations research and applied mathematics that studies the behavior of queues, which are systems where entities wait for service. The fundamental components of a queuing system include the arrival process, the service process, and the queue discipline (Newton & Medhi, 1992). According to Donald Gross (Gross et al., 2011),the key principles of queueing theory are as follows:

- **Arrival Process** - Describes how entities arrive at the service point. It can be deterministic or stochastic. A common stochastic model is the Poisson process, where arrivals are random and independent over time.
- **Service Process** - Explains how entities are served once they reach the service point. This can also be deterministic or stochastic. The exponential distribution is often used to model the time between services.
- **Queue Discipline** - Refers to the rules that determine the order in which entities are served. Common disciplines include First-In-First-Out (FIFO), Last-In-First-Out (LIFO), and priority-based systems.
- **Number of Servers** - The number of parallel service points available. Systems can have a single server or multiple servers.
- **System Capacity** - The maximum number of entities that can be in the system (both waiting and being served) at any time.
- **Population Size** - The size of the population from which entities arrive. This can be finite or infinite.

Originating from the study of telephone call arrivals, Queuing Theory has grown to encompass a wide range of applications, including:

- **Telecommunications** - Managing data packet transmission, call routing, and network bandwidth allocation (Alfa, 2010; Daigle, 2005);
- **Manufacturing**: Optimizing production lines, inventory management, and maintenance scheduling (Bansal & Moses, 2022; Salawu et al., 2020; Xu et al., 2023);
- **Healthcare** - Reducing patient waiting times, optimizing staff levels, and scheduling surgeries or consultations (Kalwar et al., 2021; Mahmudov & Mahmudova, 2022; Nawusu et al., 2020; Santos et al., 2022; Weerakoon et al., 2019);
- **Transportation and Logistics** - Managing traffic flow, scheduling flights, optimizing freight handling, and minimizing delays (Alharbi et al., 2022; Aziziankohan et al., 2017; Jia et al., 2022; Reyes et al., 2023; Zheng et al., 2023);

- **Customer Service** - Staffing call centers, managing checkout lines, and improving customer satisfaction (Brahma, 2013; Feuer & Fallah-Fini, 2020; Gong et al., 2018; Nosek & Wilson, 2001; Preeti & Gupta, 2024; Sakr et al., 2023; Subrayan et al., 2023);
- **Computing and IT** - Allocating computational resources, load balancing in servers, and optimizing cloud services (Fedorova et al., 2023; Han et al., 2023; Kushchazli et al., 2024; Quattrocchi et al., 2024; Sufyan & Banerjee, 2023; Vilaplana et al., 2014; R. Xu et al., 2020).

The main purpose of queuing theory is to improve the efficiency of systems that involve waiting lines, ensuring that resources are utilized effectively while minimizing wait times and costs. By understanding and modeling the behavior of queues, businesses and organizations can make informed decisions about capacity planning, resource allocation, and system design.

Applications in Healthcare

As said before, queuing theory is widely applied in healthcare to improve the efficiency of patient flow, optimize resource utilization, and enhance the quality of care. Some of the key applications in different health fields are:

- **Emergency Departments (EDs) -** Queuing models help manage patient flow in EDs, which often face unpredictable arrival patterns and varying levels of urgency. By optimizing staffing levels and resource allocation, queuing models can reduce patient waiting times and improve care delivery (Alavi-Moghaddam et al., 2012; Cochran & Bharti, 2006; Hajrizi & Berisha, 2019; Samaha et al., 2003). Samaha et al. (2003) used discrete event simulation to analyze and reduce the length of stay in an emergency department. By modeling different scenarios, the study identified optimal staffing levels and process improvements that significantly reduced patient waiting times. Similarly, Cochran and Bharti (2006) applied queuing models to balance bed utilization in obstetrics hospitals, enhancing overall patient flow and resource management.
- **Outpatient Clinics** - Queuing Theory aids in designing appointment systems and managing patient flow in outpatient clinics. Effective scheduling can reduce wait times and enhance patient satisfaction (Cayirli & Veral, 2003; Mtonga et al., 2022; White & Pike, 1964). White and Pike (1964) studied appointment systems in outpatient clinics, focusing on the impact of patient unpunctuality on waiting times. Their work laid the foundation for subsequent studies on outpatient scheduling. Cayirli and Veral (2003) provided a comprehensive review of outpatient scheduling in healthcare, highlighting various queuing models and their applications in reducing patient wait times and improving clinic efficiency.
- **Surgical Units** - In surgical units, queuing models optimize the scheduling of surgeries and the utilization of operating rooms. This helps in minimizing downtime and improving throughput (Ferdinandes et al., 2017; Schulz & Fliedner, 2023; Wang et al., 2020).
- **Pharmacy Services** - Queuing models manage prescription fulfillment processes in pharmacies, ensuring timely service and reducing patient wait times (Adams et al., 2021; Jacobson et al., 2006; Sari et al., 2022; Setiawan & Restiana, 2024).
- **Dental Offices -** Queuing Theory helps dental offices streamline patient flow and optimize appointment schedules, enhancing service delivery and patient satisfaction (Fomundam & Herrmann, 2007; Kakooei, 2022).

The existing literature demonstrates the successful application of queuing models across various medical and dental settings, resulting in reduced waiting times, enhanced service quality, and better overall healthcare outcomes. As healthcare systems continue to face challenges such as increasing demand and limited resources, the application of Queuing Theory will remain crucial in achieving efficient and effective healthcare delivery.

Global Perspective on Oral Health

Oral health is a crucial component of overall health and well-being. It encompasses the health of the teeth, gums, and the entire oral-facial system that allows us to smile, speak, and chew. Poor oral health can lead to significant pain and suffering, impacting an individual's quality of life. It is linked to a range of systemic conditions, including cardiovascular disease, diabetes, respiratory infections, and adverse pregnancy outcomes (Glick et al., 2016; Macdonald, 2000; Petersen & Kwan, 2011).

Globally, oral diseases are among the most common non-communicable diseases (NCDs) and affect people throughout their lifetime, causing pain, discomfort, disfigurement, and even death. The Global Burden of Disease Study 2017 estimated that oral diseases affect half of the world's population (3.5 billion people), with dental caries (tooth decay) in permanent teeth being the most prevalent condition (Kassebaum et al., 2015). Periodontal (gum) disease, which may result in tooth loss, was the 11th most prevalent disease globally (Chang & Chang, 2019; Naqvi et al., 2022).

Oral diseases disproportionately affect the poor and socially disadvantaged in all countries, reflecting significant inequalities. Access to oral health services is limited in many low- and middle-income countries, and even in high-income countries, underserved populations often experience high levels of oral disease (Petersen & Kwan, 2011).

Recognizing the importance of oral health, the 74th World Health Assembly in 2021 approved a historic resolution for oral health, calling for the development of a "Global Strategy for Oral Health." This strategy emphasizes the need for integrating oral health into primary healthcare, improving oral health literacy, and addressing the social determinants of oral health (World Health Organization, 2021b).

Importance of Oral Health in Portugal

In Portugal, oral health has gained increased attention over the past decades. However, despite improvements, there are still significant challenges. The Portuguese population has historically faced high levels of oral diseases, including dental caries and periodontal disease. The prevalence of these conditions remains a public health concern, especially among children and older adults (Portuguese Dental Association, 2021).

The importance of oral health in Portugal is underscored by its impact on individuals' overall health, productivity, and quality of life. Poor oral health can lead to pain, infection, and tooth loss, affecting nutrition, speech, and self-esteem. Additionally, it is associated with chronic conditions such as diabetes and cardiovascular diseases, which are prevalent in the Portuguese population (Carvalho et al., 2016; Costa et al., 2024).

In alignment with global initiatives, Portugal has taken steps to enhance its national oral health strategy. The Portuguese government has launched several programs aimed at improving oral health services, particularly for vulnerable populations. One such initiative is the National Program for the Promotion of Oral Health (PNPSO), which focuses on preventive care, access to dental services, and education (Direção-Geral da Saúde, 2020).

Simulation in Healthcare System

In simulation, the system of interest is replaced with a physical or computational model, resulting in model-based experimentation. Doing field experiments and using this approach are conceptually quite similar. In numerous instances, the technique has shown to be helpful in helping management gain a deeper grasp of their present operations and create better models to address issues. In order to minimize wait times, this method comprises assessing and testing various designs as well as verifying, elucidating, and endorsing simulation results and research recommendations (Alam et al., 2018).

One of the best simulation tools for creating models based on observations and offering different possibilities is Arena Software. Several studies have demonstrated improvements in patient flow, resource utilization, and overall efficiency of health services. These, provide a comprehensive understanding of how Arena Software can be effectively used to enhance dental healthcare delivery (Günal & Pidd, 2010; Kakooei, 2022; Kamali et al., 2022; Mohd Fadilah et al., 2023).

Methodology

Simulation Arena software was used in this study's simulation modeling approach. The data collection process, including dental consultation times in the National Health Service (NHS) were collected from the Order of Dentists, which developed a reference document with the aim of promoting the normative and guiding bases for organizing the consultation, both by dentists and health management planners (Ordem dos Médicos Dentistas, 2021). The model needs information about the number of patients, their arrival time at the dental office as well as the start and finish times of each procedure, including registration, medical care, dental consultations, prescription fillings, and payment. This study also aims to demonstrate that it is possible to create dental medical offices in the Portuguese National Health System (PNHS) as well as create the careers of dentists and dental assistants, in a planned manner and above all supported by the Primary Health Care (PHC), taking into account the scarcity of resources in the dental health area, so that Portugal can meet the objectives recommended in the Global Action Plan for Oral Health (2023-2030) by the WHO (World Health Organization, 2023). As a way to maximize the profitability of PNHS dental practices, only one dental office is available in a PNHS health unit, it is proposed to use three dentists for every two dental practices, located in different health units, but close to each other; two of the three dentists work full-time, in different offices; and the third dentist fills the gaps between the two offices, alternately between the two offices close to each other, making up a total of 12 hours of continuous daily operation of the dental medical offices in the PNHS health units. Appointments are taken at the dental medical offices from 8:00 am to 8:00 pm, Monday through Friday, excluding holidays. Dentists are always assisted by an assistant, who works equally in terms of hours and rotation, so that they can make the most of available resources and considering the need for permanent care in the PNHS and can cover the greatest number of possible users. There is no Emergency dentist in these PNHS dental offices. Figure 1 shows the flowchart of patients at the local health unit from PNHS, with patient care by the dentist in the specialties: Consultation, Dentistry, Surgery, Endodontics, Periodontics and Prosthetics.

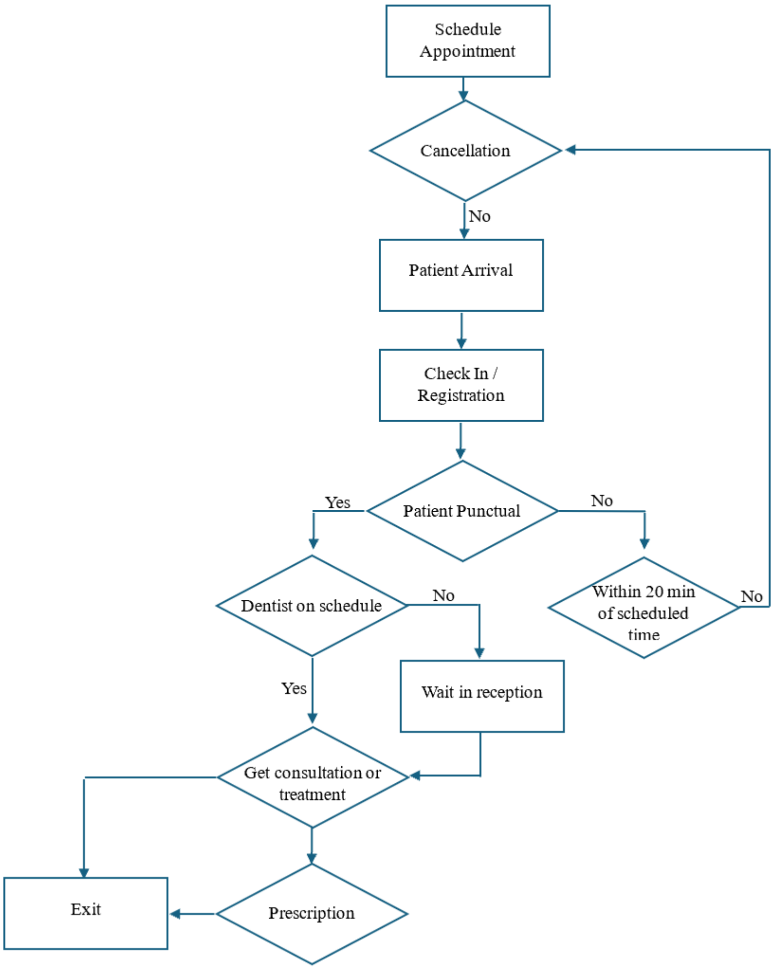

Figure 1. Illustration of the dental office Flowchart in a PNHS health unit

Data regarding dental specialties were taken from the 7th Ed. Oral Health Barometer (Ordem dos Médicos Dentistas (OMD), 2022), which the OMD carries out and publishes annually and only treatments that are included in the National Oral Health Promotion Plan (NOHPP) and according to the goals set out in the Working Group Report – SNS | Oral Health 2.0 (Sistema Nacional da Saúde (SNS), 2023). Among the treatments and respective specialties, Orthodontics was not taken into consideration, as it is not covered by the NOHPP and is not included in the Working Group Report – SNS | Oral Health 2.0. In table 1, there are the percentages of appointments by specialty.

Table 1. Percentages for type of consultation by specialty

Type of Appointment by Specialty	**Percentage (%)**	**Specialty**
Regular visits / Check-Up	26,3%	Consultation
Perform Restorations	14%	Dentistry
Tooth Extraction	9,2%	Surgery
Pain	8,1%	Endodontics
Teeth Cleaning / Gum Problem	27,2%	Periodontics
Placing Prosthetics/Implants	15,2%	Prosthetics

To improve the appointment scheduling process and optimize scarce resources in the PNHS dental practice, the current system was modeled based on data provided by the Dental Association and many years of professional experience. Model performance was evaluated, and output results were compared with those of the current system.

A dental office in a PNHS health unit simulation model was created using Arena simulation software version 16.2, to predict changes in patient waiting time and queue waiting length resulting from variations in the system. Figure 2 shows a screenshot of the existing simulation model in Arena. Seven Discrete Processing modules, Create, Process, Delay, Assign, Route, Station, and Dispose, one Decisions module, Decide, and one Input Output module, Record, with the analysis from the input analyzer, were included in the model.

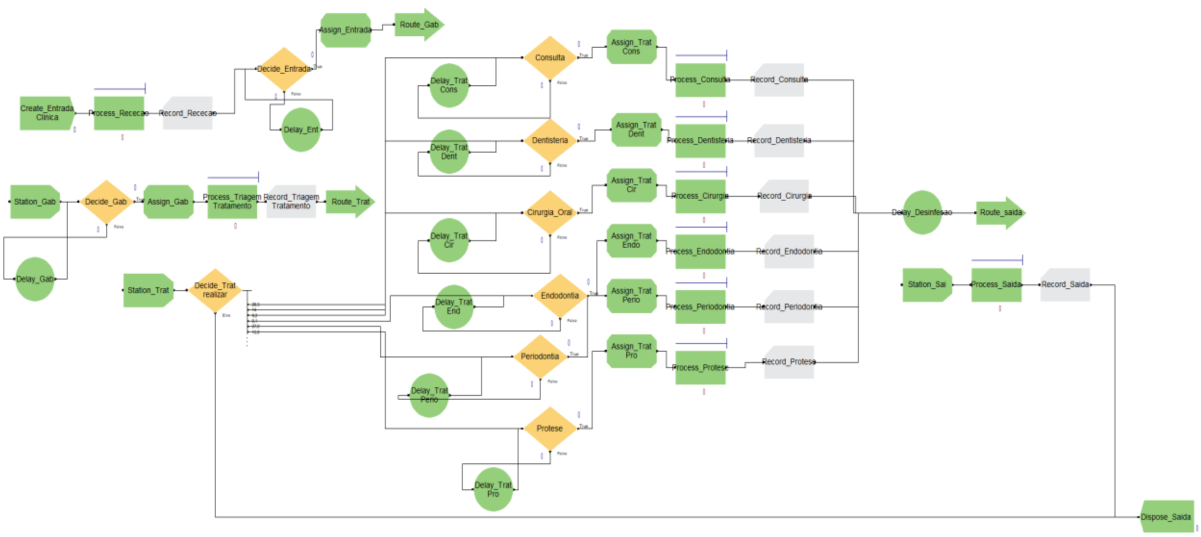

Figure 2. Screenshot of the Arena simulation model of the dental office in a PNHS health unit

The simulation model was executed for ten replications, with each replication simulating a full week of five business days, ensuring the robustness of the results. The dental office operates for 720 minutes (12 hours) each day. Two scheduling scenarios were tested to optimize the appointment scheduling times: Scenario 1 with 30-minute slots and Scenario 2 with 40-minute slots. To evaluate the effectiveness of the processing procedures used in dental offices, a few outputs were tracked. These outputs will be utilized to improve the model. The results are presented in the next section.

Results and Discussion

A simulation model for modeling patient flow queuing system in an Portuguese National Health System dentist's office, with the purpose of exploring options for designing an effective queuing system of a public dental office is simulated by using Arena Software and run it to get the simulation results. The primary metrics tracked were the average processing time for each process and the average number of patients treated for each process.

In Scenario 1, the dental office used 30-minute scheduling slots. The results, as shown in Table 2, indicate the average number of patients treated and the average time spent for each type of appointment by specialty.

Table 2. Average number of patients treated and average time for each process from Scenario 1

Type of Appointment by Specialty (Scenario 1)	**Average Number Patients**	**Average Time (min)**
Consultation	29	20,0544
Dentistry	15	44,6888
Surgery	10	31,7800
Endodontics	9	55,2606
Periodontics	30	30,0854
Prosthetics	16	30,1025

In Scenario 2, the dental office used 40-minute scheduling slots. The results, as shown in Table 3, indicate the average number of patients treated and the average time spent for each type of appointment by specialty.

Table 3. Average number of patients treated and average time for each process from Scenario 2

Type of Appointment by Specialty (Scenario 2)	**Average Number Patients**	**Average Time (min)**
Consultation	24	20,1947
Dentistry	13	45,0330
Surgery	8	31,6178
Endodontics	7	55,5634
Periodontics	24	30,1713
Prosthetics	13	30,0708

The results from the simulation highlight several important aspects of scheduling effectiveness in the dental office setting:

- **Consultation Appointments**:
  - In Scenario 1, with 30-minute slots, the dental office was able to treat an average of 29 patients per week, with an average processing time of approximately 20 minutes.
  - In Scenario 2, with 40-minute slots, the number of patients treated decreased to 24, while the average processing time remained similar.
- **Dentistry Appointments**:
  - The average number of patients treated in Scenario 1 was 15, with an average processing time of about 45 minutes.
  - In Scenario 2, the number of patients treated decreased to 13, while the average processing time slightly increased.
- **Surgery Appointments**:
  - Scenario 1 allowed for an average of 10 surgeries per week with an average processing time of approximately 32 minutes.
  - In Scenario 2, both the number of surgeries and the average processing time slightly decreased.
- **Endodontics Appointments**:
  - In Scenario 1, an average of 9 patients were treated, with the longest average processing time of 55 minutes.
  - Scenario 2 saw a decrease to 7 patients, with a slight increase in processing time.
- **Periodontics Appointments**:
  - Scenario 1 facilitated the treatment of 30 patients per week, with an average processing time of 30 minutes.
  - Scenario 2 saw a reduction to 24 patients, with a marginal increase in processing time.
- **Prosthetics Appointments**:

- Scenario 1 managed to treat an average of 16 patients per week, with an average processing time of approximately 30 minutes.
- Scenario 2 treated fewer patients (13), but the processing time remained virtually unchanged.

Implications for Dental Office Operations

The analysis suggests that shorter scheduling slots (Scenario 1) generally allow for a higher number of patients to be treated across most specialties, although with marginal increases in processing time for some types of appointments. On the other hand, longer slots (Scenario 2) reduce the number of patients treated but do not significantly impact the average processing time for most appointment types.

Optimizing scheduling times is crucial for balancing the number of patients treated with the quality of care provided. The results indicate that a 30-minute slot scheduling system might be more effective in maximizing patient amount without substantial increases in processing times, making it a potentially better choice for the dental office's queuing system. Future improvements to the model could include additional factors such as patient satisfaction, variability in appointment types, and more detailed tracking of resource utilization to further refine the scheduling system.

Conclusion and Recommendations

This study aimed to optimize the scheduling system of a public dental office within the Portuguese National Health System by simulating patient flow using Arena Software. Two scenarios were analyzed: one with 30-minute scheduling slots (Scenario 1) and another with 40-minute scheduling slots (Scenario 2). The primary metrics evaluated were the average processing time for each process and the average number of patients treated per week. The findings revealed that Scenario 1, utilizing 30-minute slots, generally allowed for a higher number of patients to be treated across various specialties compared to Scenario 2 with 40-minute slots. Specifically, Scenario 1 facilitated a greater patient throughput in consultations, dentistry, surgery, endodontics, periodontics, and prosthetics. Despite the increased patient numbers, the average processing times remained comparable between the two scenarios, indicating that shorter slots did not significantly compromise the time required for each appointment type. This research underscores the importance of optimizing scheduling times to enhance the efficiency of dental office operations. The 30-minute slot scheduling system demonstrated a potential to maximize patient throughput without notably increasing the processing times, suggesting it as a more effective option for the public dental office's queuing system. Implementing such a system could lead to improved patient access to dental care services and better utilization of resources.

Future research could build on these findings by incorporating additional variables such as patient satisfaction, variability in appointment durations, and resource allocation to further refine the model and enhance the effectiveness of the dental office scheduling system.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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