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MATHEMATICAL MODELING AND EXACT PROBLEM SOLUTION OF ALLOCATION OF DOCTORS WORK SCHEDULE

***[1]Marcelo Lisboa Rocha, [2]Fernando Jorge Ebrahim Lima e [3]Silva and Geraldo Magella Obolari de Magalhães**

[1]Post-Graduate Program in Computational Modelling of Systems – UFT – Palmas, TO, Brazil
[2]Instituto Federal do Tocantins – Palmas, TO, Brazil
[3]Centro Universitário Luterano de Palmas, CEULP/ULBRA – Palmas, TO, Brazil

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***Corresponding author: Marcelo Lisboa Rocha**

ABSTRACT

This work aimed at the development of an advantageous mathematical model to meet the needs of the activity of creating schedules of work in the public health sector, helping both the elaboration of the work schedule itself and the management of professional staff by the compilation of managerial information that help in the decision making of the manager, greatly reducing the difficulty in administration, given the large number of variables that affect health services. As a contribution, in this work a computational model was developed and solved by an accurate method for the allocation and management of doctors work schedule in the public health area, serving as an aid in the development of software in the public health sector.

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INTRODUCTION

It is common knowledge that the public administration has difficulty in organizing its professional staff and due to the size of its human resources it should be concerned fundamentally in the management of this, optimizing it in order to make it efficient and safe, and for this purpose it is necessary to use a data processing system to facilitate this task. According to Balgrosky (2019) Health Information Systems (HIS) should perform the tasks of collecting, processing, storage and distribution of information interrelated, with the objective of guiding the decision-making process and assisting in the control of health organizations, supporting the improvement, planning and decision-making process of its multiple professionals. The society in search of its rights, seeks a positioning of the Public Power on the effective provision of health care at appropriate levels of quality and permanence, with this making legitimate the taking of public policy actions that generate efficiency in complying with this right. It is clear that a large number of organizations encounter difficulties in drawing up the work schedules of their professionals. Within the public sector we can see that this difficulty is more accentuated due to the large number of professionals involved, and therefore needs to accomplish this task in an agile, effective and efficient way, because the awkward use of human resources, also makes explicit the misuse of the scarce financial and budgetary resources of this sector. In this scenario, the use of Information Systems that use combinatorial optimization, provides the elaboration of working schedules in a more uncomplicated way, besides bringing greater process security, since it excludes much of the subjective factors in the elaboration of the same, generating not only the idea of accuracy in the deeds, but excluding hypotheses relating to the interpersonal relationship of management agents, creating thus the idea of impartiality in carrying out this task. According to Beddoe (2004), most of the mathematical formulations relating to staff problems in which shift work is performed are considered problems of NP-Hard complexity, because it takes a very long time for an approach to an acceptable resolution of the problem. Another interesting example is of Blake and Donald (2002), that proposed an integer programming model to allocate operating room time at Toronto's Mount Sinai Hospital, bringing both administrative savings and the ability to produce a quickly and equitable surgical schedule. In this context, it is justified to carry out this study, which aimed at developing a mathematical model advantageous to meet the needs of the activity of creating work's schedules in the public health sector, helping both in the elaboration of the work's schedule itself, the management of professional staff by compiling management information that helps in the decision-making of the manager, greatly reducing the difficulty in administration, in view of the large number of variables that affect the health services. As a contribution, in this work, a computational tool was developed to solve problems of allocation and management of health personnel, more specifically in determining the work schedule of doctors. This work can also serve as an aid in the development of software in the public health sector, as well as a source of research for academics interested in the subject, in view of the scarcity of studies on the subject in Brazil.

Theoretical Foundation: In this section are presented the main concepts related to the problem of allocation of work schedule, especially of medical work schedule.

Work Schedule: In 1943 with the labor reform, there was the approval of the Consolidation of Labor Laws (CLT), regulating such relationships and legally establishing the modalities of working days. The schedules were included in the single paragraph of art. 67 of the CLT. Strategically organizing human resources is essential for the gain of productivity and reduction of labor costs. In addition to improving the employee's quality of life, because the worker's health and well-being have an impact on his productivity. According to a study carried out by Souza et al. (2011), carried out in a public teaching hospital of the Municipality of São Paulo, the elaboration of a schedule of work is a very complex activity, which involves a series of articulated actions such as the recognition of the staff, workload, medical licenses, shifts and productivity limitations of each employee, as well as a survey of data related to the specificities of each sector, which takes into account the capacity of service of the sector and the complexity of the assistance provided there. An important point highlighted by Fakih et. al. (2012), to be taken into consideration in the elaboration of work schedules, is absenteeism, because in addition to overloading the workers who are present, affects the production, operational cost and efficiency of the services provided. In a study carried out in the emergency room of a university hospital in the city of São Paulo, it was revealed that the causes of absenteeism may be related to lack of organization, and inadequate institutional policy, among others. As a solution, the authors propose changes in personnel management policy and work processes to increase satisfaction and commitment to the institution.

Costs of Public Health: In the definition of Drury (2017), cost is the sum of all values incorporated by the consumption or use of goods and services, in order to produce a new good or service. In view of Muenning (2007), the calculation of results through cost accounting for health institutions, assumes special relevance in the management of its resources, as well as for the realization of organizational planning, control and decision making. For Butler (1995), the health sector demands, whether for its complexity or its representativeness, the presentation of a solid cost management model that manages results, with the purpose of supporting consistent and results-oriented public policies. Brent (2003) adds that the lack of quality and basic managerial information are aspects that impair the formulation of behaviors aimed at the correction of vulnerabilities presented by the health system all over the world. This situation is aggravated by the lack of autonomy and commitment of hospital managers; the passivity and dilution of funding that is currently carried out in a way that is disjointed with the quality of the services provided; distortions between amounts paid per procedure and their actual costs; investments that do not take into account the schedule gain; among other reasons, it makes clear the need for information that support decisions and changes in public policies, with the purpose of generating the optimization of resources for the service of the population.

Related Works: Berrada et. al. (1996) implemented a multiobjective programming model to represent a problem of nurses scheduling, with the aim of increasing employee satisfaction with the schedule, which must comply with constraints classified as rigid or flexible, using the Tabu Search method. Bellanti et al. (2004) propose a local search approach providing partial solutions that are later completed through a greedy algorithm to avoid the generation of unfeasible neighbors, using strict constraints to solve the problem of the nursing schedules of the intensive care unit of a hospital in Turin, Italy. Borba (2010) proposed the application of a model of combinatory optimization to solve the problem of schedule of public health teams. The objective of the model proposed by Borba is to optimize the allocation of available human resources in view of the rigid and flexible constraints imposed by the problem. To solve the problem, Iterated Local Search (ILS) metaheuristics was used, associated with local search to obtain a satisfactory result, with low computational cost. A study of a problem analogous to the scheduling of workers was carried out by Hancerliogullari et. al. (2016), which uses heuristics and metaheuristics to solve the surgical scheduling problem. The concept of modes was used to differentiate the types of surgeries performed and the methodology adopted was the application of a greedy heuristic and Simulated Annealing metaheuristics for your solution.

Mathematical model proposed for the problem: This work aims to present a mathematical model and an exact solution by mathematical programming to solve the problem of allocation of medical' work scheduling. The State Department of Health of Tocantins (SESAU-TO) has a scheduling management system implemented in the PHP programming language and the data is stored in a SQL Server database. When observing the current routines of launching schedules, it is noticed that on average a team coordinator spends 14 hours after the activity of creating and launching schedules. In accordance with Ordinance 937/12 (TOCANTINS, 2012), doctors can execute four time patterns, these times being represented at work by the acronyms P1, P2, P3, P4 and Table in Table 1.

Table 1. Time Patterns

Acronym	Duration	Start	End
P1	12 hours	7 am	7 pm
P2	12 hours	7 pm	7 am +1d
P3	24 hours	7 am	7 am +1d
P4	24 hours	7 pm	7 pm +1d

The shifts are divided into three: morning, afternoon and night, with their respective durations, as shown in Table 2.

Table 2. Work Shifts

Shift	Duration	Start	End
Morning	6 hours	7 am	13 pm
Afternoon	6 hours	13 pm	7 pm
Night	12 hours	19 pm	7 am +1d

Each sector requires a minimum number of doctors serving each shift to ensure proper functioning. In the tests performed in this work, multiple values of 12 were chosen because they have the shortest duration among the allowed shifts patterns. Depending on the employment relationship, there is a pre-established workload for each server. In the survey carried out, 3 different monthly workloads for SESAU-TO's servant doctors were identified, 90 hours, 180 hours and 270 hours. However, as in Ordinance 937/12 (TOCANTINS, 2012), the following amounts of monthly hours are considered for the effective exercise of the work respectively: 72 hours, 144 hours and 216 hours. The model respects the number of hours disciplined by this ordinance. The period of leave of each employee must be reduced proportionally to the required monthly workload, taking into account the number of days in the reference month, and shifts should not be made for days off. Leave is the period in which the employee is prevented from attending work. Some reasons for leave are: sick leave, vacation, maternity leave, etc. The model conceived in this work will take as parameter the monthly workload of each server with the due discounts due to leave. Must also respect the rest period between working hours. The institution analyzed in this work, follows what CLT recommends in its article 66, which imposes on the worker 11 hours of rest between working hours. In this case, doctors can do up to 24 hours of uninterrupted work. However, after this period, they must rest for at least 11 hours. In the proposed model, the preferences of dates and times suggested by workers must also be flexibly considered.

The flowchart in Fig. 1 shows how are the steps for preparing medical schedules with mathematical modeling.

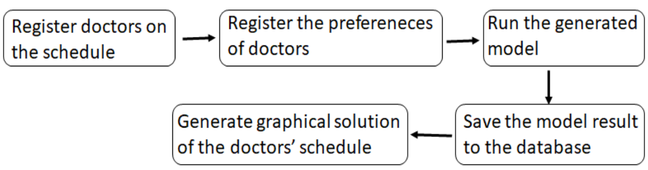

Figure 1. Flowchart showing the steps for preparing time scheduling

Mathematical Model: In this section, the mathematical model proposed for the scheduling of medical professionals is presented. The proposed model aims to optimize human capital for the optimal solution, taking into account the strict restrictions required by the institution and to accommodate, whenever possible, the preferences of dates and times of employees. The Binary Integer Linear Programming (BILP) technique was used to formulate the mathematical model.

Objective Function: The objective function for the proposed problem seeks to minimize the number of hours worked by doctors to meet the demand of the sector to which the model is being applied and to meet the maximum flexible restrictions related to the preferences of days and times: see Eq. (1).

Input Parameters and Decision Variables: For the construction of the mathematical model, the following input parameters and problem decision variable must be considered:

- d: represents the day of the month on which the shift will be performed.
- i: represents the identification of the measurement that will perform the shift.
- p: represents the time patterns to be followed:
  (p1)=shift from 7 am to 7 pm (morning and afternoon) lasting 12 hours.
  (p2)=shift from 7 pm to 7 am (night time) lasting 12 hours.
  (p3)=shift from 7 am to 7 am (morning, afternoon and evening) lasting 24 hours.
  (p4)=shift from 7 pm to 7 pm (night, morning and afternoon) lasting 24 hours.
- CH_i: represents the number of hours to be performed by medical professional i during the month.
- M_{ipd}: binary variable representing whether Physician i will follow (1) or not (0) the time pattern p on the day of the month d.
- CP: represents the number of hours to be fulfilled by the medical professional on shift with standard p.
- CH_m, CH_v e CH_n: epresent the minimum number of hours required for the morning (m), afternoon (v) and night (n) shift respectively.

Description of Restrictions: The proposed problem has a series of restrictions imposed by law, the institution's operational model or the preferences of professionals. The following hard constraints were taken into account:

i) The schedule shock restriction aims to prevent the same doctor from having shifts posted at the same time overlapping each other in whole or in part:
   - On d day there can be only one or no occurrence of the time patterns p1, p3 and p4 for the same doctor i: see Eq. (2)
   - On d day there may be only one or no occurrence of the time patterns p2, p3 and p4 for the same doctor i: see Eq. (3)
   - On d day there can be only one or no occurrence of the time patterns p3 and p4 for the same doctor i: see Eq. (4)
   - When on day d there is a time pattern p4, the next day d + 1 there cannot be a time pattern p3 for the same doctor i. Because the p4 pattern ends at 7 pm the next day and the p3 pattern the next day starts at 7 am, which would cause these shifts to overlap: see Eq. (5)
   - When on day d there is a time pattern p4, the next day d + 1 there cannot be a time pattern p1 for the same doctor i. Because the p4 pattern ends at 7 pm the next day and the p1 pattern the next day starts at 7 am, which would cause these shifts to overlap: see Eq. (6)

ii) After performing one or more consecutive shifts totaling 24 hours of uninterrupted duty, you must have an interval of at least 11 hours of rest until the next shift:
   - The time patterns p1 on day d, p2 on day d and p1 on day d + 1 for the same doctor i, cannot occur because they would violate the rest restriction between working

hours. In this case, only two of these three cases can succeed in sequence: see Eq. (7)

- The time patterns p2 on day *d*, p1 on day *d* + 1 and p2 on day *d* + 1 for the same doctor *i*, cannot occur because they would violate the rest restriction between working hours. In this case, only two of these three cases can succeed in sequence: see Eq. (8)
- The patterns p3 on day *d* and p3 on day *d* + 1, cannot occur because they violate the rest restriction between working hours: see Eq. (9)
- The patterns p4 on day *d* and p4 on day *d* + 1, cannot occur because they violate the rest restriction between working hours: see Eq. (10)
- The patterns p4 on day *d* and p2 on day *d* + 1, cannot occur because they violate the rest restriction between working hours: see Eq. (11)
- The patterns p2 on day *d* and p3 on day *d* + 1, cannot occur because they violate the rest restriction between working hours: see Eq. (12)
- The patterns p1 on day *d* and p4 on day *d* + 1, cannot occur because they violate the rest restriction between working hours: see Eq. (13)

iii) The number of hours escalated for the doctor cannot be less than the number of hours contracted for the same (where *y* is the number of days of the month in question): see Eq. (14)

iv) Flexible constraint (soft-constrains) referring to doctors' time preferences will be met as long as they do not affect the strict restrictions imposed by the problem: see Eq. (15)

Where,

- *k* is the group of doctors that has a certain preference.
- *P* is the penalty factor. The penalty was used to disadvantage days and / or shifts when the worker does not wish to work. The value for each penalty is *P* = 100.

v) Constraint to prevent shifts being launched on days when the doctor is on vacation (vacation, medical leave, leave, etc.): see Eq. (16). Where, *t* is the group of doctors who are away and *c* is the set of days the doctor is away.

vi) Morning shift: see Eq. (17) Afternoon shift: see Eq. (18) Night shift: vide Eq. (19) Constraint that guarantees the minimum number of doctors in attendance per shift in each sector. Morning shift: see Eq. (17) Evening shift: see Eq. (18) Night shift: see Eq. (19)

Following we have the complete mathematical model using BILP, as explained in sections 3.1.1 to 3.1.3.

$$MINIMIZE\ Hours = \sum_i \sum_p \sum_d C_P M_{ipd} + Penalization \quad (1)$$

Subject to:

$$M_{ip_1d} + M_{ip_3d} + M_{ip_4d} \leq 1 \quad (2)$$

$$M_{ip_2d} + M_{ip_3d} + M_{ip_4d} \leq 1 \quad (3)$$

$$M_{ip_3d} + M_{ip_4d} \leq 1 \quad (4)$$

$$M_{ip_4d} + M_{ip_3d+1} \leq 1 \quad (5)$$

$$M_{ip_4d} + M_{ip_1d+1} \leq 1 \quad (6)$$

$$M_{ip_1d} + M_{ip_2d} + M_{ip_1d+1} \leq 2 \quad (7)$$

$$M_{ip_2d} + M_{ip_1d+1} + M_{ip_2d+1} \leq 2 \quad (8)$$

$$M_{ip_3d} + M_{ip_3d+1} \leq 1 \quad (9)$$

$$M_{ip_4d} + M_{ip_4d+1} \leq 1 \quad (10)$$

$$M_{ip_4d} + M_{ip_2d+1} \leq 1 \quad (11)$$

$$M_{ip_2d} + M_{ip_3d+1} \leq 1 \quad (12)$$

$$M_{ip_1d} + M_{ip_4d+1} \leq 1 \quad (13)$$

$$\sum_{d=1}^{y} \left(M_{ip_1d + M_{ip_2d} + M_{ip_3d} + M_{ip_4d}} \right) \geq CH_i \quad (14)$$

$$Penalization = P * \sum_k \sum_p \sum_d M_{kpd}, \quad k \leq i \quad (15)$$

$$\sum_t \sum_p \sum_c M_{tpc} = 0, \quad t \subseteq i \quad e \quad c \subseteq d \quad (16)$$

$$\sum_{id} 6 * M_{ip_1d} + 6 * M_{ip_3d} + 6 * M_{ip_4d} \geq CH_m \quad (17)$$

$$\sum_{id} 6 * M_{ip_1d} + 6 * M_{ip_3d} + 6 * M_{ip_4d} \geq CH_v \quad (18)$$

$$\sum_{id} 12 * M_{ip_2d} + 12 * M_{ip_3d} + 12 * M_{ip_4d} \geq CH_n \quad (19)$$

Computational Experiments: In this section, the parameters and results of the experiments performed using the mathematical model for the scheduling problem presented in section 3 are shown here. In the experiments carried out in this section, real information from professionals, hospital sectors and institution restrictions was used. The identification information of the professionals was changed to preserve them. All tests performed were performed on a computer with an Intel Core i5 3.2 GHz processor, 8GB RAM and Windows 10 Pro 64-bit operating system. The generated schedules are dynamic, being able to be altered and the modeling performed again since the model execution is fast. The software developed to find the optimal solution was implemented in the C ++ language and making use of the GLPK API (GNU Linear Programming Kit) version 4.65 which is a library of routines widely used in solving large scale linear programming problems (GLPK, 2020). Among the techniques available in the GLPK API, the exact Branch-and-Cut method was used to solve the problem. Work schedules can be changed up to ten days before the start of the reference month. After this period, the schedules are closed and published and cannot change in their regular shifts except for shifts and inclusion of extraordinary shifts due to unforeseen events during the reference month. For the execution of the comparative test, a real work schedule was used, containing 15 pediatric professionals. For each shift there was a requirement for two professionals in attendance. The number of professionals converted into hours required for each shift is obtained by multiplying the duration of the shift by the minimum number of professionals. The workload for each one of the doctors is described in Table 3.

Table 3. Workload in hours in a specific month of 15 pediatric professionals (doctors)

Professional	Workload	Days Apart	Workload Available
doctor01	144	0	144
doctor02	144	0	144
doctor03	72	3	60
doctor04	72	0	72
doctor05	144	0	144
doctor06	144	31	0
doctor07	72	1	68
doctor08	72	0	72
doctor09	72	0	72
doctor10	144	0	144
doctor11	72	0	72
doctor12	72	0	72
doctor13	72	0	72
doctor14	72	0	72
doctor15	144	0	144

For the comparative test demonstrated in this section, a real work schedule was used, prepared in a specific month by SESAU-TO, to serve as a model comparable with a doctor work schedule generated by mathematical programming, which followed the same parameters as the original work schedule. The original work schedule had 15 employees, with a total workforce of 1512 hours, and as an important factor, it can be noted that the doctor06 was apart the entire month, which reduces the total workload by 144 and the doctor03 was apart for 3 days, which decreases another 12 hours, leaving 1356 hours of workforce. It was also possible to note that on the original work schedule 1272 hours of ordinary shifts and 252 hours of extraordinary shifts were launched, resulting in a total of 1524 hours of work launched on the work schedule, with a daily average of 48 hours of workforce. On the day with the highest number of professionals when added together there were 72 hours of workforce, and on the day with the least number of professionals there were 48 hours.The proposed model was solved on a machine with the configuration reported at the beginning of this section and the average time to find the optimal solution was 2 seconds. Thus, on the schedule generated by the solver (using the proposed model), 1488 hours of work were launched, as well as the total number of hours of available workforce of 1356 hours. The 132 hours that exceeded this value were adopted as overtime. Due to the insufficient workload to complete the work schedules, the Government of the State of Tocantins in Annex II of Law No. 2,716 / 13 (Tocantins, 2013), instituted values for extraordinary shifts of doctors in order to guarantee the full functioning health units according to Table 4.

Table 4. Annex II to Law No. 2716, of 16 May 2013. Values in Brazilian Currency

Professional	Extra Shift of 6h	Extra Shift of 12h	Extra Shift of 24h
Doctor in intensive care unit	R$ 600,00	R$ 1.200,00	R$ 2.400,00
Doctor in emergency room	R$ 550,00	R$ 1.100,00	R$ 2.200,00
Doctor in attendance	R$ 500,00	R$ 1.000,00	R$ 2.000,00
Doctor in alert	R$ 324,00	R$ 648,00	R$ 1.296,00

When the expense with overtime was calculated, the original schedule generated 252 hours of overtime shifts, which in total values taking into account the financial disbursement necessary to pay them, as established in Law 2,716 (Table 4) was R$25.200,00, and the 132 hours of extraordinary shifts generated by mathematical programming would create an expense of R$13.200,00, thus generating savings of R$12.000,00, representing a decrease in expenditure of 47.6%. In the construction of this work, two master's dissertations were used as reference, Borba (2010) and Hancerliogullari et. al. (2016), which deal with problems analogous to this work.
The difference of this work for the reference works is that the two previous works use heuristics to find feasible solutions to the doctors working scheduling problem, while in this work the exact Branch-and-Cut method is used to find the solution to the problem. The modeling differences in comparison to the work of Borba (2010) is that in this work, rest time restrictions were used, preventing shifts from being released on days when the professional is away and taking into account the number of days away to launch the proportional workload. The main distinction used in the work of Hancerliogullari et. al. (2016) is the presence of soft-constraints, which are used in this work, while the reference work includes only rigid/hard constraints.

Conclusion

Due to the complexity and representativeness of the Brazilian Health Management, considering the size of the necessary investments, both in relation to budgetary resources, and in the use of the workforce to maintain the constitutional right of health for an estimated 207.6 million people. people across the national territory, the best use of techniques and technologies to optimize the scarce financial resources and specialized work, is vital for the preservation of SUS. Neste contexto, modelagem matemática para solução de problemas de natureza complexa é necessária tanto para questões operacionais, quanto para o auxílio na tomada de decisões e análise de resultados. O modelo elaborado neste trabalho tem como objetivo facilitar o escalonamento de profissionais médicos, por meio de BILP, com a finalidade de proporcionar exatidão na elaboração de escalas de trabalho e principalmente garantir o melhor uso dos recursos disponíveis. Conforme demonstrado na análise de resultados, a abordagem empregada permite a melhor distribuição da força de trabalho, comprovando a economicidade gerada pelo modelo matemático desenvolvido. In this context, mathematical modeling for solving complex problems is necessary both for operational issues, as well as for aid in decision making and analysis of results. The model developed in this work aims to facilitate the scheduling of doctors through BILP, in order to provide accuracy in the elaboration of work schedules and mainly to ensure the best use of available resources. As demonstrated in the analysis of results, the approach employed allows for a better distribution of the workforce, proving the economy generated by the mathematical model developed. In the comparative test carried out between the schedule of real work and the schedule generated by mathematical programming, it was found a decrease of 120 hours of extraordinary shifts, which represents a 47.6% reduction, which in financial terms generated savings of R$12.000,00 in a single month, a schedule that had only 15 doctors. It is believed that by processing all the schedules of all doctors, this financial gain is even greater. In view of these results, we can point out that, when imagining such innovation being practiced on a larger work schedule, it would potentially represent a great reduction in expenses with personnel from SESAU-TO and similar organizations, resources that could be used in more timely and necessary expenses. Another factor to be considered is greater objectivity, impartiality and security in the composition of work schedules, as factors of interpersonal relationships are not considered in the mathematical model, excluding hypotheses of undue favoring professionals. Likewise, it is emphasized that the work schedules being generated autonomously, allows that the time previously dedicated by the coordinators for the elaboration of the work schedule in a conventional way, can be better used in other activities related to the management and monitoring of the teams, thus being able to increase the gain in productivity and quality of services provided. The mathematical model developed shows the possibility of depending on convenience and opportunity, taking into account, as non-rigid restrictions (soft-constraints), factors of a personal order of the professional/server. However, the overriding rule is the preservation of the organization's full functioning. Regarding the objectives of this work, all were satisfactorily met, both in the diagnosis of the problem and in the presentation of results, and the main objective of the same was strictly accomplished, because in addition to developing the mathematical model, its efficiency and effectiveness were proven. It is important to mention that the study carried out focused on only a small portion of the SESAU-TO servers and the tests were carried out on a small sample, so that, in the future, it may be the subject of more in-depth studies regarding the implementation of the final product of this work.

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