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Research Article

Optimization of Surgical Schedules at a Specialist Hospital: A Case Application

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Abstract

The operations management in health services has recently become extremely important since hospitals' main objective is to provide high-quality health services to patients while reducing their costs and improving their financial assets for their survival and growth. In this respect, operating rooms are of great interest to the hospitals since they are the hospital's largest cost and revenue center. However, despite their criticality in health services, they are generally bottleneck resources in hospitals. Therefore, increasing the efficiency of operating rooms results in improved patient satisfaction and reduction in the cost of surgical operations. At this stage, operating room scheduling is the key to accomplish these two conflicting goals at a reasonable level simultaneously. It includes the timing of each operation as well as the assignment of surgical resources to each operation such as operating room and surgical teams over a few days or a week. Operating room surgical schedules often present logistical difficulties in terms of assigning doctors to specific operating rooms. Due to a wide variety of factors such as room availability, working hours in a week, doctor preferences, and operating room capabilities, surgical scheduling can prove to be challenging. In many hospital administrators manually modify the assignments on a case-by-case basis, which makes it difficult and time-consuming when dealing with surgical schedules. In this paper, we try to implement a linear programming procedure, which transforms the operating room schedule into a working schedule that dynamically changes weekly; and can be programmed to incorporate different scenarios within the hospital-based on specific hospital parameters. With the application of a binary linear programming model on illustrative problems by using Excel Solver Add-in, we demonstrate the advantages of using such an approach in optimizing static and dynamic surgical assignments weekly in order to meet a specific goal.
Keywords: Operation Rooms Scheduling, Surgical Schedules, Operator Schedules, Doctor Assignments, Surgical Room Assignments

Bir İhtisas Hastanesinde Ameliyathane Programının Optimizasyonu: Bir Vaka Uygulaması

Öz

Hastaneler yüksek kaliteli sağlık hizmeti sağlarken varlıklarını sürdürebilmek ve büyüyebilmek için maliyet azaltmayı ve finansal varlıklarını artırmayı hedeflediğinden sağlık hizmetlerinde operasyon yönetimi son dönemde büyük önem kazanmıştır. Bu bağlamda, ameliyathaneler hastanelerdeki en önemli gelir ve maliyet merkezi olmaları itibariyle hastane yöneticilerinin ilgi odağı haline gelmiştir. Sağlık hizmetlerinde kritik bir öneme sahip olmalarına ragmen ameliyathaneler genellikle hastanelerde darboğazın oluştuğu kaynaklardır. Dolayısı ile, ameliyathane verimliliğini iyileştirmek, hasta memnuniyetini artırırken cerrahi operasyonların maliyetinde azalma ile sonuçlanacaktır. Bu noktada, ameliyathane çizelgeleme, bu iki çatışan hedefi belli bir düzeyde başarabilmenin anahtarı olarak öne çıkmaktadır. Ameliyathane çizelgeleme bir kaç gün veya bir haftalık bir periyotta gerçekleştirelecek ameliyatların zamanlarının belirlenmesini ve her bir ameliyat için gerekli olan ameliyathane ve ameliyat ekibi gibi kaynakların atanmasını kapsamaktadır. Ameliyathane çizelgeleme sürecinde doktorların belirli ameliyathanelere atanması esanasında genellikle bir takım lojistik zorluklar ortaya çıkar. Bu nedenle, ameliyathane çizelgeleme, ameliyathane kullanılabilirliği, çalışma saatleri, doctor tercihleri ve ameliyathanelerin teknolojik yeterliliği gibi çeşitli faktörler nedeniyle oldukça zorlayıcı bir iş haline dönüşebilir. Pek çok hastanede, idariciler ameliyathane atamalarını vakalar bazında manuel şekilde değerlendirerek değiştirmekte; bu da çizelgelemede zorluklara ve

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zaman kaybına yol açmaktadır. Bu çalışmada, spesifik hastane parametlerini göz önünde bulundurarak farklı senaryoları dahil edebileceğimiz bir esnekliğe sahip bir doğrusal programalama modeli geliştirerek haftalık değişen ameliyat gereksinimlerini dinamik bir ameliyathane çizelgesine dönüştüren bir yöntem uygulayacağız. Model detaylı bir şekilde anlatıldıktan sonra geliştirilen ikili doğrusal programlama yaklaşımının örnek problemler üzerinde Excel Çözücü eklentisi kullanılarak uygulanması ile ameliyat için gerekli olan kaynakların haftalık bazda atanması statik ve dinamik durumlar için optimize edilmiş; belirli bir hedef açısından ortaya çıkan avantajlar ortaya konmuştur.

Anahtar Kelimeler: Ameliyathane çizelgelenmesi, cerrahi çizelgeler, operatör çizelgeleme, doktor atama, cerrahi oda atama.

1. Introduction

Hospitals must operate in a way that allows them to provide effective medical services to their patients while utilizing the human resources and valuable facility, such as the available operating rooms, in the most efficient way. Several objectives must be addressed when the hospital administration makes scheduling assignments for its operator physicians. Scheduling procedures in hospitals often present logistical difficulties due to a wide range of variables such as doctor availability, doctor preferences, operating hours, and functionality of rooms. With many moving elements and many factors to consider, creating an optimal surgical schedule is not an easy task. Having an optimal, or close to an optimal, surgical schedule can improve the efficiency in the hospital by reducing patient waiting time, and increasing the utilization of the operating rooms.

The surgical scheduling problem has been studied by several healthcare pieces of research based on different views. The objectives of operating room scheduling, the constraints, and the solution methods significantly vary. For instance, Yang et al. (2015) designed time segments based on the preferences of surgeons. They indicated that a satisfactory level of surgeons was enhanced with efficient use of time resources. Khaniyev et al. (2020) considered the next-day scheduling problem of a hospital operating room. The aim was to minimize the weighted sum of expected patient waiting times, room idle time, and overtime. They proposed simple-to-use and close-to-optimal scheduling heuristics which reached up to a 1.22% average performance gap and worst average optimality gap of 2.77%. The studies, which are determined from the most recent literature to address surgical scheduling are summarized in the following Table 1.

Table 1. Researches on surgical scheduling of healthcare institutions

Authors	**Aims and Findings**
Zhang et al. (2020)	In order to minimize the patient-related costs as well as the hospital-related costs, a two-stage stochastic programming model with recourse to address the surgical scheduling problem in an operating theater. The surgical intensive care unit capacity constraint is considered to deal with uncertainties in surgery operations and postoperative length of stays. A column-generation-based heuristic (CGBH) approach decreased the gap between the resulting near-optimal solutions and the exact ones below 1%.
Silva and Souza (2020)	It is addressed scheduling with common resources for emergency and elective situations. Approximate dynamic programming with an integer programming model was proposed to monitor surgical scheduling for a short period. The expected cost is decreased with a confirmed statistical analysis.
Gecici and Guler (2019)	In this study, a nurse scheduling problem of cardiovascular surgery service of a hospital in Istanbul is considered. The proposed mixed-integer programming and decision support system enabled managers to plan fair and balanced schedules practically.
Cappanera et al. (2018)	They proposed a mixed integer multi-objective model which enables determining the number and typology of surgeries to be scheduled in each operating room. Goal programming was used to examine the weight space that can lead to more efficient use of resources.
Abedini et al. (2017)	In order to minimize blockings between two consecutive stages, a blocking minimization model is proposed for the MSS based on deterministic data. Thet found out that the model decreases the number of blocking with a 94% improvement level.
Huang et al. (2012)	In this research, the surgical scheduling problem is considered as the hybrid flow-shop scheduling problem. Beds and operating rooms were indicated as parallel machines.

	A mathematical model for a surgical scheduling problem was presented and solved by LINGO. A case study with its optimal solution was also indicated to verify the model.
Oostrum et al. (2010)	They analyzed the advantages and disadvantages ways of master surgical scheduling(MSS) and compared it with centralized and decentralized planning approaches. They indicated several implementation subjects of MSS and assessed its suitability in hospitals considering different organizational cultures.
Cardoen et al. (2009)	A multi-objective combinatorial optimization problem was considered to conduct the decision process of the operating room scheduler. The computational performance of the algorithmic approaches was compared with the data collected from UZ Leuven Campus Gasthuisberg (Belgium) with 224 instances.
Trilling et al. (2006)	In this study, the authors focused on the anesthesiology nurse scheduling problem (ANSP) of a French public hospital in which anesthesiology nurses are the most shared human capital in the service units. Two different methodologies were proposed to solve the ANSP based on integer and constraint programming while the objective was t**o** maximize the fairness level of the schedule.

In this paper, we have analyzed a surgical scheduling procedure in a specialist hospital, where the schedules are currently done manually based on experience. We have formulated the problem following a new approach in order to obtain an optimal schedule to achieve certain goals set by the hospital administration. Our model is different from the previously developed model concerning the objective function, which was to balance the workload between the surgical teams while producing a workable optimum schedule. In addition to using operations research tools to optimize the weekly schedules, a procedure has also been incorporated to adjust the dynamically changing schedules every week to fit different scenarios due to surgery delays within the hospital.

2. Methodology

The surgery department, where this study was conducted had a total of 31 beds. The hospital provides progressive healthcare programs and services to around 700,000-800,000 people for the specific area it serves. The surgery department is divided into 4 units; A, B, C, and D, where each unit has a total of 10 physicians and around 80 nurses in total. The following hierarchy is used for the doctors: ***A Consultant*** is a senior doctor who practices in one of the medical specialties. A consultant does not spend the entire 24-hour duty but remains on call when needed. ***Specialists*** are doctors who have completed advanced education and clinical training in a specific area of medicine (their specialty area). Specialists do not spend the entire 24-hour duty but remain on call when needed. ***Senior Registrars*** are medical practitioners undertaking, or had completed, several years of higher-level training in a hospital specialty or public health but had not yet gained a consultant position. While on sentry duty, the senior registrar has the highest position. ***A Registrar*** is a doctor who is receiving advanced training in a specialist field of medicine. A registrar comes right below the senior registrar. ***Assistant Registrar*** follows the registrar on the hierarchy position and are doctors always on duty helping the other registrars. ***A Trainee*** also known as junior doctors is those in postgraduate training, starting at graduation with a Bachelor of Medicine. The physicians are grouped into several teams and a team or group of physicians perform the surgery operations that need to be scheduled based on certain requirements and constraints. The hospital considered in this study maintains a 24-hour emergency center with hospital-based ambulance services.

There are about 80 nurses in the surgery department, which work in rotating three shifts as 7:00 AM-2:00 PM; 2:00 PM–10:00 PM; and 10:00 PM-7:00 AM. There are two types of nurses: ***Circulating nurses*** manage the overall nursing care in the operating room and help in maintaining a safe and comfortable environment. ***Scrub nurses*** select and pass instruments and supplies used for the operation. While the hospital has a total of eight operation rooms, only four of them are assigned to the surgery Department. Two rooms are divided between the units on sentry that day, one room is only assigned for Urology and Plastic related surgeries and the fourth room is for the cases that come from the emergency department. Such cases have priority over the scheduled surgeries.

Scheduling the operation rooms to be used by different physician teams at different time slots of the day and the week may be a challenging problem. The problem is referred to as optimizing an operating room schedule. Since the problem is so widespread, many operations research studies have been conducted with varying objective function formulations. Based on the requirements in the hospital, we have defined a new objective function to be optimized to minimize the difference between the targeted and the allocated hours assigned to each physician team per week. A binary linear program is used to optimize the assigned number of daily time slots in each operating room to each physician team during the week. Historical data were obtained from the hospital and the model was applied to the data. The data collected from the hospital did not include any cost data since the hospital was a state-owned hospital and the cost was not the main concern in the operating room scheduling problem.

2.1. Scheduling Model

The operating room scheduling problem is formulated as a mathematical model, for which the following components had to be included in order to define the model variables, the constraints, as well as the objective function.

1. Four surgical teams, which are denoted as i=1, 2, 3, 4.
2. Four days of the week denoted as j=1, 2, 3, 4.

3. Two operating room types are denoted as k=1, 2.
4. Three daily time slots for long surgeries denoted as l==1, 2, 3.
5. Six daily time slots for short surgeries also denoted as l==1, 2, 3, 4, 5, 6

The combination of these components of the problem results in a total of 48 decision variables for the long surgeries and 96 decision variables for the short surgeries. Therefore, the model included a total of 144 decision variables.

The Decision Variables: The variables are defined as follows:

X_{ijkl} = integer variable representing the assignment of surgical team type i = {1,2,3, 4}, in day j = {1,2,3,4}, in the operating room k = {1,2,} during the time slot l = {1,2,3} or {1,2,3,4,5,6} depending if it is short or a long surgery slot.

X_{ijkl}= {0,1} [Binary Variable]

Where,

X_{ijkl}= 1 If the team i is assigned on day j to room k in the time slot l.

X_{ijkl}= 0 If the specific assignment is not made,

The index i specifies a particular surgical group or team. Each doctor who works in the operating rooms is associated with a particular surgical group, and for our purposes, all doctors in a particular surgical group are interchangeable. We used the following indices:

Index i	Team
1	A
2	B
3	C
4	D

Index j	Day
1	Monday
2	Wednesday
3	Thursday
4	Friday

The index j simply corresponds to the day of the week. We used the following indices, assuming that Tuesdays are scheduled for doctors to go on Major Rounds visiting patients. Surgeries are scheduled only during the remaining four days

The index **k** specifies the operating room type, which allows us to differentiate between the surgical lengths. We used the following indices:

Index k	Room Type
1	Long Surgeries
2	Short Surgeries

The index **i** specifies the time slots in each room. Three slots are fit into operating room 1 (long surgeries) and six slots fit into operating room 2 (short surgeries). Figure 1 illustrates the daily slots for short and long surgeries.

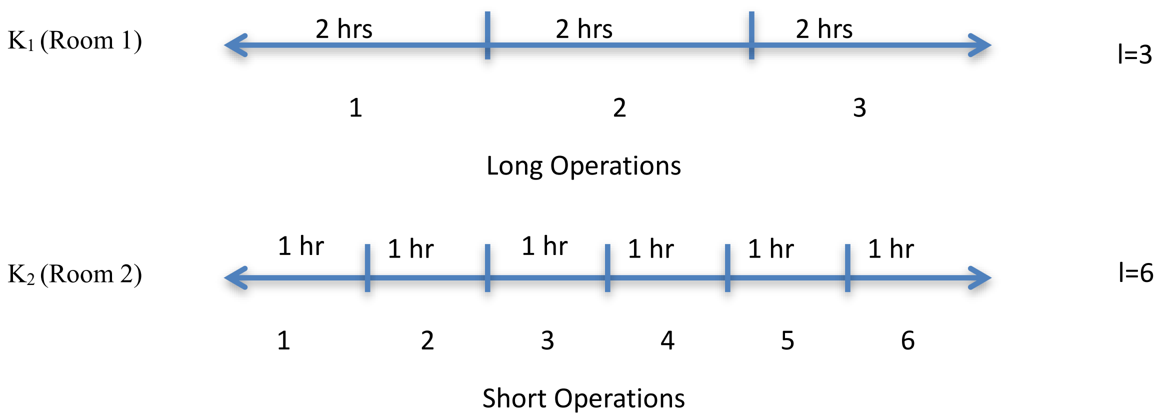

Figure 1. Time slots of the operating rooms

The Objective Function: As it was mentioned above, the main objective in surgical scheduling was is to minimize the difference between the targeted and allocated hours for all surgical groups per week. This goal has been specified by the hospital administration in order to reduce the deviation in the difference between the working hours of the surgeons. The objective function of the linear programming formulation is given as follows:

Minimize $Z = \sum_{i=1}^{4} Y_i$

Where $Y_i = \left|\text{Target Hours} - \sum_{j=1}^{4}\sum_{k=1}^{2}\sum_{l=1}^{m}\sum_{i=1}^{4} X_{ijkl} d_{kl}\right|$

Where,

- Target Hours = 12 hours/week for each surgical team (estimated from historical data)
- d_{kl} is the number of operating hours in the k^{th} type of operating room during the l^{th} time slot
- $Y_i - 12 + X_{ijkl}d_{kl} \geq 0$ and $Y_i - 12 + X_{ijkl}d_{kl} \leq 0$
- $\sum_{j=1}^{4}\sum_{k=1}^{2}\sum_{l=1}^{m} X_{ijkl}d_{kl}$ = Total time allocated/week

During the formulation of this objective, we decided to set the objective function simply be the difference between the targeted hours and the actual allocated hours across each of the surgical groups. It was decided that the objective function should provide a level of fairness across the surgical groups by minimizing the difference between the targeted and the allocated hours rather than the simple difference.

The Constraints: The following constraints have been defined for the problem based on the physical operations and functions carried out in the hospital.

1. The deviation between the teams should be less than or equal to 4 hours.

   $|Y_i - Y_j| \leq 4$

   Where, $Y_i - Y_j \leq 4$ and $Y_j - Y_i \leq 4$

2. Assigning team i on the j^{th} day to the k^{th} room into time slot l must be less than or equal to 6 hours/day, which was a requirement.

   $\sum_{k=1}^{2}\sum_{l=1}^{m} d_{kl}X_{ijkl} \leq 6 \quad \forall$ **i, j**

3. Assigning team i on the j^{th} day to the k^{th} room into time slot l must be greater than or equal to 1 hour/day.

   $\sum_{k=1}^{2}\sum_{l=1}^{m} d_{kl}X_{ijkl} \geq 1 \quad \forall$ **i, j**

4. It should be ensured that each slot on each day in each room should be assigned only once.

   $\sum_{i=1}^{4} x_{ijkl} \leq 1\ \forall$**j,k,l**

5. The number of surgeries in each time slot should not exceed the specified numbers.

   $\sum_{l=1}^{3}\sum_{i=1}^{4} x_{ij1l} = 3\ \forall$**j**

   $\sum_{l=1}^{6}\sum_{i=1}^{4} x_{ij2l} = 6\ \forall$**j**

3. Results and Discussion

The integer linear program formulated for the scheduling problem above has been solved using the standard Excel Solver Add-In. The solution is illustrated for the hospital case problem and the optimum surgical schedule obtained for this case has been presented in Table 2. The results are shown concerning the teams denoted by letters and colors, days of the week, surgery rooms, and time slots of the day, where the assignment is made.

Table 2. The optimal schedule in a form of a timetable.

Room Type	**Room 1**			**Room 2**					
Time Slots	1	2	3	1	2	3	4	5	6
Days									
Monday	A	B	C	D	C	B	C	B	B
Wednesday	D	B	C	A	A	A	A	A	A
Thursday	D	B	C	D	D	D	D	D	A
Friday	D	D	C	B	A	A	A	A	A

As it is seen in the schedule, by the end of the week, teams A and D would have worked for a total of 14 hours/week each and, teams B and C both would have worked for a total of 10 hours/week for each team. This means that teams A and D work 2 hours more than the targeted 12 hours (14 hrs–12 hrs=2 hrs) and teams B and C work 2 hours less than the targeted 12 hours (12 hrs–10 hrs=2). This is the minimum deviation that could be achieved for the scheduling case considered.

Handling Dynamic Schedules:

As mentioned above, the schedules change weekly and the solver also needs to be run weekly to obtain new schedules. If surgery was canceled on a specific day of the week, it will be postponed and scheduled for the upcoming week. This can mean that the team whose surgery got canceled the week before, a certain time slot will have to be fixed for that operation on the following week. Also, if there was a very long surgery that might occupy the operating room for the whole day by a certain team, the following surgeries will have to be postponed to the following week as well. This will also result in a fixed schedule for this specific day during the following week. The linear program has to be run with the fixed slot as a constraint to maintain minimum deviation from the target hours for each team in that week. Thus, in each schedule, consideration must be given to specific changes such as delays and cancellation of surgeries. Surgeries can be canceled for several reasons and the most common ones are due to the cases coming from the emergency department. To deal with such issues, we consider the canceled surgery when running a schedule for the upcoming week by setting the variable corresponding to that certain day, room, slot, and team equaling to one before the program is run. This will give us an optimum schedule while taking into consideration those certain surgeries that were previously canceled. The following are three case examples, each showing certain fixed slots due to surgeries delayed from the previous week. In each case, certain variables are set to one representing the shifts of surgeries from the previous week.

Example 1:

Let team B occupy operating room type 2, time slot 3 on Monday. $X_{2123}=1$

Let team C occupy operating room type 2, time slot 2 on Wednesday. $X_{3222}=1$

Let team C occupy operating room type 2, time slot 6 on Thursday. $X_{4426}=1$

Let team A occupy operating room type 2, time slot 3 on Friday. $X_{1323}=1$

This will give us the scheduling results presented in Table 3 from the solver for the upcoming week.

Table 3. The optimal schedule for example 1 in the form of a timetable.

Room Type	**Room 1**			**Room 2**					
Time Slots / Days	1	2	3	1	2	3	4	5	6
Monday	D	A	A	C	A	B	A	A	A
Wednesday	A	A	C	A	C	D	B	B	C
Thursday	B	B	B	C	D	A	D	B	D
Friday	C	D	D	A	C	C	C	B	D

Therefore, by the end of the week, teams A has worked for a total of 15 hours/week each and, teams B, C, and D have worked for a total of 11 hours/week for each team. This means that teams A work 3 hours more than targeted (15 hrs–12 hrs = 3 hrs) and teams B, C, and D work 1 hour less than targeted hours (12hrs–11hrs=1)

Example 2:

Let team B occupy operating room type 1, time slot 1 on Monday. $X_{2111}=1$

Let team D occupy operating room type 1, time slot 2 on Wednesday. $X_{4312}=1$

Let team B occupy operating room type 1, time slot 3 on Thursday. $X_{2413}=1$

Let team C occupy operating room type 2, time slot 5 on Friday. $X_{3325}=1$

The optimal schedule for this case is given in table 4 below.

Table 4. The optimal schedule for example 2 in the form of a timetable.

Room Type	**Room 1**			**Room 2**					
Time Slots / Days	1	2	3	1	2	3	4	5	6
Monday	B	C	B	B	D	A	B	A	A
Wednesday	D	D	B	A	C	A	A	A	A
Thursday	C	D	C	B	A	D	D	C	D
Friday	C	B	B	D	D	D	A	A	D

Therefore, by the end of the week teams, A has worked for a total of 11 hours/week each and, team B has worked for a total of 13 hours/week each, team C has worked for a total of 10 hours/week each and, team D has worked for a total of 14 hours/week each.

This means that team A work 1 hour less than targeted (12hrs – 11 hrs = 1), team B work 1 hour more than targeted (12hrs – 13 hrs = -1), team C work 2 hours less than targeted (12hrs – 10 hrs = 2) and, team D work 2 hours more than targeted (12hrs – 14 hrs = -2),

Example 3:
Let team A occupy operating room type 1 on Monday for a long surgery that takes 6 hours (the whole day). Fixing this room for team will give us the schedule results shown in Table 5 from the solver for the upcoming week.

Table 5. The optimal schedule for example 3 in the form of a timetable.

Room Type	**Room 1**			**Room 2**					
Time Slots / Days	1	2	3	1	2	3	4	5	6
Monday	A	A	A	A	A	D	A	B	C
Wednesday	C	C	B	B	A	A	D	C	B
Thursday	D	B	D	B	D	C	A	A	A
Friday	D	B	D	A	B	C	C	C	C

This shows that, by the end of the week, team A has worked for a total of 15 hours/week each and, teams B, C, and D have worked for a total of 11 hours/week for each team. This means that teams A works 3 hours more than the targeted time (15 hrs–12 hrs=3 hrs) and teams B, C, and D work 1 hour less than the targeted time (12hrs–11hrs=1 hr). This is the optimum or minimum deviation from the target hours that could balance the working load between the surgeon teams.

4. Conclusion

The main objective of this study was to develop a model that could be used to generate surgical schedules in a specialist hospital in a relatively simple and direct procedure so that workload between the surgical teams is distributed as evenly as possible. To achieve this goal, a simple linear integer programming model was formulated with an objective function, which was constructed to minimize the deviation between the working hours of the surgeons weekly. The model included several constraints and resulted in workable schedules that could be also dynamically changed as surgeries were shifted to the following week due to delays or longer than planned surgeries. Based on our case results, we feel confident that the model works well and can be utilized as a tool for more efficient scheduling in a hospital setting. The model is relatively easy to construct and to run on Excel Solver Add-In, which makes it suitable for hospital administration to solve their simple scheduling problems by a computer in an optimal way rather than trying to do manual schedules, which are not optimum and consume time. Based on our discussion with the hospital staff, this model and the solution would benefit the management in scheduling and assigning different surgical teams to different time slots in various days to minimize the deviation from the target hours and eliminate to overlaps.

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