Chapter 23
Using Simulation to Analyze Patient Flows in a Hospital Emergency Department in Hong Kong

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Abstract This paper presents a case-study of applying simulation to analyze patient flows in a hospital emergency department in Hong Kong. The purpose of our work is to analyze the impact of the enhancements made to the system after the relocation of the emergency department. We developed a simulation model (using ARENA) to capture all the key relevant processes of the department. Using the simulation model, we evaluated the impact of possible changes to the system by running different scenarios. This provides a tool for the operations manager in the emergency department to "foresee" the impact on the daily operations when making possible changes (such as, adjusting staffing levels or shift times), and consequently make much better decisions.

23.1 Introduction

The Prince of Wales Hospital (PWH) is one of the largest public general hospitals in Hong Kong and the teaching hospital for the Medical Faculty of the Chinese University of Hong Kong. It provides 1,360 hospital beds, employs around 4,000

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people and operates as the regional hospital of the New Territories East (serving more than 1.5 million people). In order to provide a good quality of service, PWH has to best-utilize its resources because of the large number of patients served and its limited budget due to tight government financial support. One of the departments facing this challenge head-on is the Emergency Department (ED) which provides 24-h Accident and Emergency (A&E) services. In preparation for the growing (and aging) population in Hong Kong, the ED was relocated in October 2010 to accommodate the increasing patients' demands. Since then, the hospital management has been trying to enhance the daily operations in the new department.

The ED handles 420 cases a day on average. In the daytime, the department is internally divided into two independent divisions: the *Walking* division and the *Non-walking* division respectively treating mobile patients (who can walk) and patients on a trolley or a wheel chair (thus non-walking). After 23:00, the Walking division is closed and the walking patients are diverted to the Non-walking division until 07:00 (i.e., walking patients and non-walking patients are merged to have the same treatment procedure.).

Critical patients arriving by ambulance are rushed to the resuscitation rooms and treated immediately. Otherwise, after registration, patients are assessed by a triage nurse and classified by category (level of urgency) so as to assign priorities for receiving treatments. There are five categories of patients: 1(critical), 2(emergency), 3(urgent), 4(standard) and 5(non-urgent). In our work and the rest of this paper, we put category 5 patients into category 4 as they have the same flow and priority in real practice and there are only small proportion of category 5 patients. *Critically-ill patients* (categories 1 and 2 patients), *less urgent walking patients* (categories 3 and 4 walking patients) and *less urgent non-walking patients* (categories 3 and 4 non-walking patients) follow different procedures of receiving treatments. Critically-ill patients have the highest priority and category 3 patients have a higher priority over category 4 patients. Within the same category, patients are seen on a first-come, first-served (FCFS) basis.

To provide 24-h A&E services, the ED employs different shifts (8 h a shift including a meal break of an hour and a short break of 20 min) of doctors to cover the patients' demands over a whole day. Basically, there are three shifts: morning (08:00–16:00), evening (16:00 to midnight) and mid-night shifts (00:00–08:00). In addition, an off-duty doctor is on-call.

As the ED has to handle a large number of patients a day, it must operate at a very high level of efficiency and quality. Ineffective operations can lead to serious consequences such as delay of treatments or even death of critical patients. To guarantee good quality of services, the ED aims to achieve the following service targets, as recommended by the Hospital Authority of Hong Kong.

1. Critical and emergency patients have to be given immediate care after they are admitted to the ED.
2. 90% of urgent patients (category 3 patients) have to be seen by a doctor within 30 min after registration.
3. Most patients are expected to be seen within 2.5 h after registration.

As mentioned, there are a large number of patient visits but the manpower is insufficient, the ED has the very difficult task of trying to offer a good quality service (minimizing patients' waiting times whilst not compromising the required attention for each patient), and making sure that valuable resources (e.g., doctors' and nurses' time and treatment equipment) are well-utilized. Our project team was asked by the ED to analyze and improve patient flows so as to enhance the quality of services provided. We adopt a simulation approach to provide the operations manager in the ED with a set of measurements (e.g., patients' waiting times and doctors' utilization) to assess the department performance and evaluate the impacts on the daily operations with different policies. Our previous investigations were reported in [15].

This paper is organized as follows. In Sect. 23.2, we give a literature review on related work. In Sect. 23.3, we compare the original and the current layouts of the ED. In Sects. 23.4 and 23.5, we describe our simulation model and present the results of the tests with different scenarios. Section 23.6 summarizes our work.

23.2 Literature Review

The applications of operations management techniques in the health-care industry are vast. We refer the reader to [18] for a recent survey. Here we focus on the applications to operations enhancement, in particular patient flows in emergency rooms.

In recent years, researchers have successfully built queueing models for analyzing and improving patient flows, and proposing decision strategies and policies in EDs. Green et al. [9] used a Lag stationary independent period by period queueing analysis to allocate staff to reduce the number of patients who leave without being seen. Cochran and Roche [5] presented a spreadsheet implementation of a queuing network model with split patient flows (accounting for patient categories of different acuity and arrival patterns and volume), to help reduce patient "walk-aways" and improve service provision of the ED. Huang et al. [12] considered the control of patient flow, in which physicians have to choose between seeing patients right after triage (facing deadline constraints on their time-till-first-service) and those who are in process but possibly need to return to physicians several times during their ED sojourn (resulting in feedbacks to the queueing system). They also proposed and analyzed scheduling policies with two types of costs: queueing costs incurred per individual doctor visit and congestion costs accumulate over all visits during patient sojourn-times. Saghafian et al. [20, 21] proposed patient streaming (based on their likelihood of being admitted to the hospital) and complexity-based triage (an up-front estimate of patient complexity) for improving operations in EDs. In both papers, they used a combination of analytic and simulation models to show the effectivenesses of the policies. While there has been much work on deriving analytical models for helping operations enhancements in EDs, we adopt a simulation approach for improving patient flows in the ED of PWH as it is easier to examine many "what-if" scenarios with the complex system of the ED (such as time and category-dependent arrival rates of patients, different service-time distributions and time-varying staffing levels). And more importantly, a simulation approach is much convenient for real implementations as practitioners, who are not necessarily equipped with advanced mathematical and programming knowledge, can easily understand and make changes in the system within a user-friendly graphical interface to "foresee" the outcomes, which are basic statistical performance measures such as maximum and average waiting time of patients and utilization of staff.

The applications of simulation in the area of health-care management have been studied for more than half of a century, e.g. [7]; and the academic literature on simulation in health-care is immense. We refer the reader to [10, 14] for an overview. In EDs, reported successful cases of applying simulation models were mainly to improve the efficiencies of daily operations. A major proportion of work with the use of simulation is staff scheduling. The approaches are mainly to evaluate process performance with different staff shift schedules, e.g. [8, 19]. Some papers integrated optimization techniques with simulation. Ahmed and Alkhamis [1] presented a simulation optimization approach to determine the optimal number of doctors, lab technicians and nurses required to maximize patient throughput and to reduce patient time in the system subject to a set of constraints imposed on budgets, patient waiting time and number of servers. Centeno et al. [4] integrated simulation (for establishing the staffing requirements for each period) and integer linear programming to help ED managers optimize staff schedules so as to maximize utilization within given budgets. Yeh and Lin [22] utilized simulation and a genetic algorithm to obtain a near-optimal nurse schedule based on minimizing the patients' queue time. There has also been work on examining queueing priorities by running simulation experiments. Connelly and Bair [6] developed a simulation model for system-level investigation of ED operations and to compare a fast-track triage approach with an acuity ratio triage approach. Other related applications include policy/decision making. Hoot et al. [11] used simulation of patient flow to predict near-future ED operational measures and to forecast with several measures of ED crowding. Lane et al. [16] used simulation to analyze the functioning of the ED system and the policies with different bed capacity and demand pattern scenarios. Baseler et al. [2] developed a simulation model to estimate the function of patients' time in system and the maximum level of patients' demand that the system can absorb.

Although, according to [3], the number of articles related to health-care simulation or modelling is currently expanding at the rate of about 30 articles a day, Jahangirian et al. [13] found out that only 8% of the related papers actually applied simulation to a real problem where real data was used. This proportion is substantially smaller than the corresponding percentages in the areas of commerce (49.1%) and defense (39.4%) [13]. This highlights the fact that real implementations of simulation models in practice in the health-care sector are still rare and we still need to put more effort on promoting the use of simulation for advancing health-care management. In this paper, we present a real case of analyzing and improving patient flows in an ED in Hong Kong with the use of simulation.

23.3 Comparisons Between the Original and Current Settings

In October 2010, the ED of PWH was relocated to a new building with a new layout. Several changes were also made in the new system to accommodate the growing patients' demands. In this section, we analyze two major changes in the operations and compare the efficiencies of the original and current systems. To make fair comparisons, we present the data of the month of December 2009 (when operating in the old location) and December 2010 (after relocation). There were 12,945 patient visits in December 2009, and 13,287 visits in 2010, which translate to around 418 and 429 cases per day respectively. (The reason why we did not choose the first month after the relocation to make comparisons is that a "warm-up" period was needed since initially most of the staff needed time to get used to the new layout, system and settings.) Below, we describe two key changes in layout and operations and their impacts.

23.3.1 A Closer Sub-waiting Area for Consultation in the Walking Division

After the relocation of the ED, the waiting area for doctor's consultation in the Walking division was moved from the main waiting area to a new sub-waiting area, which is closer to the consultation rooms than before. This aims to shorten the walking time of patients. More importantly, this enables the nurses to more easily notify the patients that they will soon be seen by a doctor, so that they would not leave the waiting area (e.g. for a meal) while waiting. Consequently, this reduces the inactivity times of doctors waiting for "missing" patients, and hence reduces the waiting times of subsequent patients seen.

We compare the net times from triage to consultation for category 4 patients, who are mostly walking patients, before and after the relocation.

Comparing the data of 2009 and 2010, although there was an increase of 2.64% in the total number of patient visits, the average net time from triage to consultation for category 4 patients decreased from 112.91 to 107.77 min (a 4.55% decrease). This shows that walking patients benefit from the change of the layout of the waiting area in the Walking division. From Fig. 23.1, we observe the patterns of the net times from triage to consultation in the 2 months are similar but the one in December 2009 has a heavier tail. The percentage of category 4 patients who had net time from triage to consultation more than 3 h decreased from 21.57 to 16.01% (a 25.78% decrease). This indicates the increase in walking time of patients could amplify the waiting times of patients.

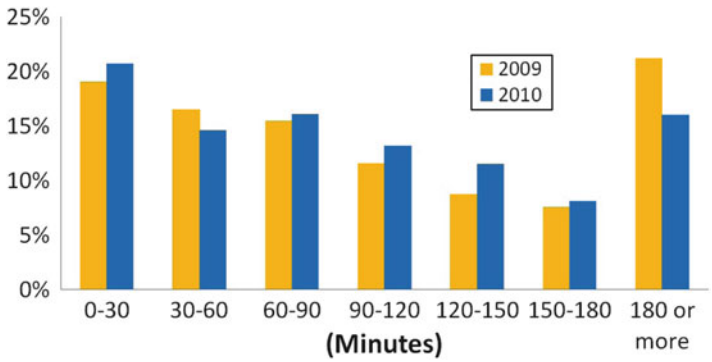

Fig. 23.1 Net time from triage to consultation for category 4 patients

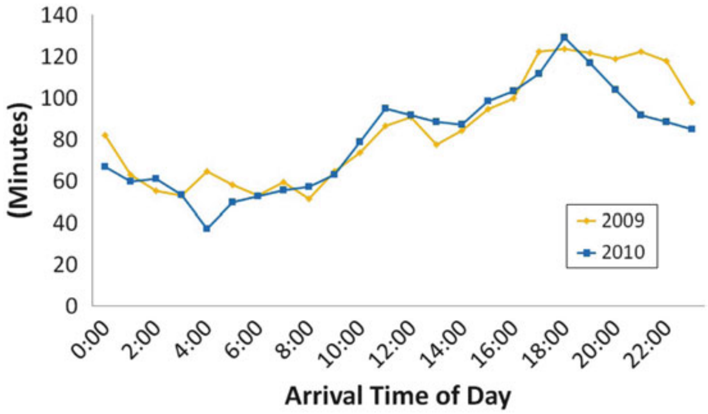

Fig. 23.2 Average net time from triage to consultation for less urgent patients by arrival time of day

23.3.2 Consolidation of the Walking and Non-walking Divisions in Nighttime

Before the relocation, the Walking and Non-walking divisions operated independently, each with its own staff and resources. After the relocation, the ED started to implement the policy that during nighttime (from 23:00 to 07:00) the Walking division is closed and the walking patients would join the system of the Non-walking division. It aims to better-utilize the reduced workforce (about half of the workforce of daytime) due to the low arrival rates of patients in nighttime.

Figure 23.2 depicts the average net time from triage to consultation for less urgent patients by arrival time of day in 2009 and 2010. From 07:00 to 20:00, the net times were similar in the 2 months. From 20:00 to 07:00, a significant improvement was observed. An interesting finding is that patients arriving after 20:00 but before 23:00

also benefited from the consolidation of the divisions. We believe it is due to the fact that some of these patients might need to wait for consultation for more than 3 h so that they might start consultation after 23:00 and hence benefited from the change.

23.4 Simulation Model

We developed a more detailed model of the new ED to analyze patient flows. As reported by other researchers, it is very difficult to build analytical models for the ED as there are many complicating factors in reality (such as time and category-dependent arrival rates of patients, multiple shift-times of doctors and re-entrant flows to the many "service stations"of the system). For this reason, we adopt a simulation approach which facilitates examination of many "what-if" scenarios, and provide valuable indications as to where the major bottlenecks of the system might be. It also provides a way to explore possible changes without jeopardizing patient care. Figure 23.3 depicts the screen-view of our simulation model, built using the software ARENA.

Our simulation model captures: all relevant treatment processes (triage, consultation, lab tests, etc.), the complexities of intertwining and re-entrant patient-flows, complicated arrival rates that vary by time and patient category and adjustable staff deployment (shift, breaks, doctors on reserve). The necessary input parameters/data are arrival rates, probability distributions of service times, available resources and schedules of doctors and nurses. To model the non-stationary time-varying arrival

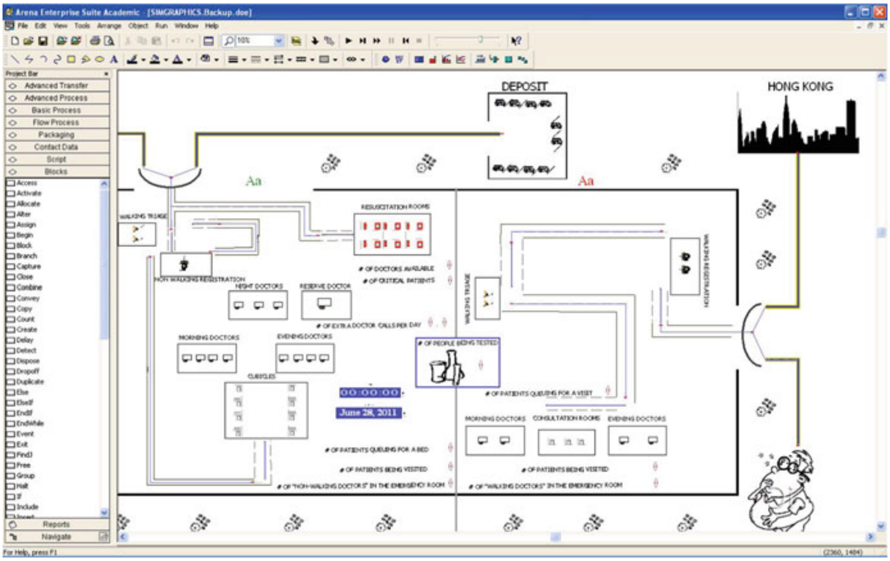

Fig. 23.3 The screen-view of our simulation model in ARENA

Table 23.1 Actual and simulated net times between services for less urgent patients

	Actual (min)	Simulated (min)	% error
Registration to triage	7.06	7.02	−0.57
Triage to consultation	85.27	81.76	−4.12

rates of patients, for each patient, his/her arrival time is the arrival time of the previous patient from the same category plus an interarrival time, which follows an exponential distribution with arrival rate in the time period of the previous arrival. We also tackled a challenge that the service-time distributions were not directly obtainable from the historical data. To resolve the problem, we assume that each service activity follows a Weibull distribution and develop two meta-heuristics, Descent Method and Simulated Annealing, to search for a good estimate of the parameters of the distributions, by considering the available time points in the data provided. For detailed descriptions of the challenge and parameter estimation procedure, we refer the reader to [15]. The outputs of the model are the key performance measures such as patients' waiting times, queue lengths, utilizations of doctors, which help us study and understand the performance of the ED.

To validate our simulation model, we presented the model and the simulated key performance indicators such as queue lengths and waiting times of patients to a consultant in the ED. He believed the model was sufficient to capture all the key activities in the ED and those values agreed with his estimations. The simulation model was also validated by comparing several key statistics as generated by the model to actual observations. As an illustration, Table 23.1 shows the comparison between the actual and simulated net times between services for less urgent patients. More details of the validation of the simulation model are discussed in [15].

23.5 Simulation Results

By running simulations, we have a way to obtain performance measures for the ED under different scenarios and, thus, to evaluate possible policies and changes in the system. We used the current arrival rates and the actual staff schedule as the input parameters for our base case. We did a series of simulation runs to evaluate different possible scenarios. In this section, we present some key findings.

23.5.1 10% Growth in Patient Arrivals

The population in Hong Kong keeps increasing (with an annual growth of around 1% according to the statistics of 2012 [17]), mainly due to an influx of immigrants. Moreover, more and more non-immigrant visitors from Mainland China also come

Table 23.2 Average waiting times of the patients based on the current arrivals and the simulated scenario (10% growth in patient arrivals)

	Current situation (min)	10% growth (min)	% change
Triage(walking)	10.20	12.66	+24.11
Triage(non-walking)	2.64	3.26	+23.48
Consultation(category 3 walking)	31.11	31.55	+1.41
Consultation(category 4 walking)	236.91	274.81	+15.99
Consultation(category 3 non-walking)	10.71	15.39	+43.69
Consultation(category 4 non-walking)	92.34	149.12	+61.49

to Hong Kong for a better quality of medical treatments. Thus, the demand for medical services in Hong Kong is expected to have a significant growth in the coming future. This is of particular concern for the EDs, which are often viewed as inexpensive clinics by the non-critical patients who visit them.

To study how the growth of patient visits impact on the daily operations in the ED, we increased the arrival rates of all patient categories by 10% (which is equivalent to the percentage increase in 3–4 years using the estimated annual increase of 2.64%) and keep all the capacities and resources at the current levels. We ran simulations and recorded the waiting times of patients. (In this section, waiting time for consultation is defined as the total waiting time for the first consultation and the "follow-up" consultation after extra tests, if needed, for the same patient visit.)

From Table 23.2, we observe that a 10% growth of patient arrivals leads to a big increase in the waiting times of patients for triage and for consultation. The waiting times of patients increase mostly more than 20%. As expected, a larger increase in waiting times is observed for categories 4 patients since a lower priority is given to them. The 10% growth in patient arrivals leads to an increase in doctors' utilization, from 88.44 to 94.3%. Some doctors are overloaded with utilization more than 100% (i.e. working time is extended). Moreover, it is important to point out that, based on the above results, the targets of services set by the ED probably cannot be met after 10% growth of patients arrivals.

23.5.2 Adding an Extra Doctor

In order to reduce waiting times of patients, we evaluate the performance of the ED if an extra doctor is hired, based on the current situation. This activity is useful to determine the optimal trade-off between the cost of additional workforce and the services provided.

Before adding an extra doctor to the simulation model, we calculated the utilization of every doctor in order to assess which doctors are overloaded. We observe a significant overuse of the doctors working the afternoon shift in the Walking division and those for the mid-night shift. Therefore, we simulated the two scenarios when an extra doctor is added to each of the shift.

Table 23.3 Average waiting times of the patients for consultation based on the current situation and the simulated scenario (an extra doctor added to the afternoon shift in the Walking division)

	Current situation (min)	Doctor added (min)	% change
Consultation(category 3 walking)	31.11	28.02	−9.93
Consultation(category 4 walking)	236.91	188.50	−20.43

Table 23.4 Average waiting times of the patients for consultation based on the current situation and the simulated scenario (an extra doctor added to the mid-night shift)

	Current situation	Doctor added	% change
Consultation(category 3 walking)	31.11	29.79	−4.24
Consultation(category 4 walking)	236.91	236.06	−0.36
Consultation(category 3 non-walking)	10.71	8.47	−20.92
Consultation(category 4 non-walking)	92.34	49.80	−46.07

Table 23.3 lists the average waiting times of walking patients if we add an extra doctor to the afternoon shift in the Walking division. Not surprisingly, on average, the relative time reduction for category 3 patients waiting for consultation is smaller than category 4 patients' as category 3 patients have a higher priority. A significant reduction in average waiting time of categories 4 patients for consultation is observed.

Alternatively, if we add an extra doctor to the mid-night shift, we observe a significant reduction in the average waiting times for the patients in the Non-walking division (see Table 23.4). Surprisingly, although the walking patients are directed to the Non-walking division for consultation in nighttime, we cannot make any significant reduction in the waiting times for walking patients after adding an extra doctor to the mid-night shift. We believe the surprising result is due to the fact that the consultation is still not fast enough to clear the patients of the lowest priority, who are category 4 walking patients. Another possible reason is that patients usually experience longer waiting times during afternoon but not nighttime, which is shown in Fig. 23.2. It seems that adding an extra doctor to the mid-night shift cannot benefit the walking patients. Finally, we note that having an extra doctor can contribute to a decrease in doctors' utilization from 88.44 to 81.64%.

23.5.3 Shift Planning

Although adding more resources to the ED is the best way to improve the patient flows, the financial issue is one of the major concerns of the hospital management. Given limited budgets, one way to improve the patient flows is to best-utilize the current resources. Therefore, we would like evaluate how the schedules of the doctors, who are the most valuable resources in the ED, might be changed to improve the efficiency of the ED. By measuring the utilizations of doctors in

Table 23.5 Average waiting times of the patients for consultation based on the current situation and the simulated scenario (reallocation of doctor)

	Current situation (min)	Reallocation (min)	% change
Consultation (category 3 walking)	31.11	27.85	−10.48
Consultation (category 4 walking)	236.91	185.37	−21.76
Consultation (category 3 non-walking)	10.71	20.19	+88.52
Consultation (category 4 non-walking)	92.34	102.03	+10.49

the current scenario, we can find out the doctors with the heaviest and lightest workloads. They are the doctors in the Walking division and Non-walking division, respectively, in the afternoon. An interesting scenario would be to assign the doctor who has the lightest workload to the shift of heaviest workload. (i.e. In the afternoon shift, extract a doctor in the Non-walking division and assign him/her to the Walking division). The results are shown in Table 23.5.

As expected, the walking patients benefited from this reallocation. A significant time reduction in the average waiting times for consultation is observed for walking patients. However, the average waiting times for consultation for non-walking patients increase as a doctor is removed from the Non-walking division. The reallocation of doctor, of course, benefits the majority, but at the same time, hurts the more urgent minority. To decide whether we should employ this schedule, we have to determine the optimal trade-off. Simulation is a tool for decision makers to "predict" how good or how bad a change impacts on the system in order to make the right balance. We would like to point out that, although there is a large percentage increase in the waiting time for consultation for category 3 non-walking patients after this reallocation, the absolute increase (9.48 min) is still small enough to be within range of the target waiting time set by the Hospital Authority for patients of this category. Moreover, this increase is comparably much smaller than the absolute reduction for the category 4 walking patients (51.45 min). As the majority of patients are category 4 walking patients, a reduction in total average waiting time is expected after the reallocation. Nonetheless, this balance between benefits to the majority and urgency of service to those in need is a difficult decision for the hospital management.

Although we just presented some of the issues examined, the simulation model could be used by the operations manager in the ED to evaluate many other possible changes in the system, such as layout, capacities and resources.

23.6 Conclusions

This paper presents a case-study of analyzing patient flows in a hospital emergency department in Hong Kong. We analyzed the enhancements of the system changes after the relocation of the ED in October 2010. We also developed a simulation tool for the ED to evaluate the impacts on patient flows with different scenarios. The simulation tool can also throw some light on key issues of decision making for the operations manager.

Finally, it is important to remark that, in general, it is very difficult (or nearly impossible) to build a simulation model for an ED to capture all the activities and events in the system, particularly when key parameters cannot be estimated directly. However, the inclusion of the major activities and events, as captured by our simulation model, was already sufficient to let operations managers in EDs "foresee" the impacts on the daily operations due to possible changes, and consequently enable them to make much better decisions.

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