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Abstract

Purpose – The purpose of this paper is to use lean principles and simulation optimization on solving a combined hospital emergency department (ED) layout design and staff assignment problem.
Design/methodology/approach – This study is based on value stream mapping for the design and analysis of the ED. Subsequently, the authors investigate cellular manufacturing design, which addresses the decisions of continuous steps in a cell simultaneously and considers the optimal staff assignment. A simulation based on the case study is used for these methodologies. Simulation optimization is then used to optimize the staff assignments, minimize the waiting time and maximize the service level.
Findings – The linear layout outperformed in both waiting time and service level. The patients' average waiting time is reduced from 78 to 38 minutes. The service level increased from 54.86 to 88.55 percent. Moreover, the number of nurses was reduced from nine to six.
Research limitations/implications – First, the tests for model accuracy were performed using the actual arrival rate; however, seasonal variation should be reflected. Second, the staffing levels varied were not tracked. Third, the accuracy of individual patient treatment paths can be dynamic. Fourth, the 25 percent of delays in transferring a patient to an inpatient bed will be discussed in future studies.
Practical implications – A practical case is adopted for empirical illustrations.
Originality/value – The proposed methodology innovatively solved a practical application and the results are promising.

Keywords Emergency department, Layout design, Value stream mapping, Cellular manufacturing, Simulation optimization, Staff assignment
Paper type Research paper

1. Introduction

The annual number of emergency department (ED) visits in the USA increased by more than 23 percent from 1997 to 2007, twice the growth in population over the same period, whereas the overall capacity decreased by more than 5 percent (Niska *et al.*, 2010). Such increase along with reductions in the overall capacity leads to overcrowding. The USA has not been alone in facing this problem. Overcrowding in ED has also been reported in Canada, Australia, Great Britain and Taiwan (Derlet and Richards, 2000). Multiple effects of ED overcrowding has resulted in long waiting time for patients, dissatisfaction and poor outcomes (Schull *et al.*, 2003). There is a growing amount of literature that identifies this problem as a health-system failure, demonstrating that the negative impact of ED overcrowding is an important issue worldwide (Olshaker, 2009).

Overcrowding is a complex, multi-dimensional and difficult problem to define scientifically; therefore, the use of standard intervals for performance monitoring is

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important in this context (Asplin *et al.*, 2003). Some researchers have defined overcrowding in terms of delays in transferring a patient to an inpatient bed (Derlet and Richards, 2000); and some, in terms of precise waiting time or significant delay (Affleck *et al.*, 2013). In addition to waiting time, service level is an important measure of line performance. This research adopts α service level (type 1), which is an event-oriented performance measures for the probability that the demand of initial care arriving within a given time interval will be completely without delay. Waiting time in initial care is defined as the duration from the release of a patient from the triage to the administration of the first medical step to the patient. Specifically, this study defines service level as the probability that delay in the first-step care is less than or equal to the recommended waiting time under the emergency severity index (ESI) system, as illustrated in the following equation:

$$\text{Service level} = P\{\text{delay in the first}-\text{step care} \leqslant \text{recommended waiting time}\} \quad (1)$$

The five-level ESI system classifies patients and provides the recommended waiting time for assessment by a physician, as shown in Table I. The ESI is a five-level ED triage algorithm that provides clinically relevant stratification of patients into five groups from one (most urgent) to five (least urgent) on the basis of acuity and resource needs (Gilboy *et al.*, 2011). Research on performance of traditional triage revealed delay in initial care of most patients, evidencing the negative impact of ED overcrowding (Welch and Davidson, 2011).

Under the current system, the average waiting time is 78 minutes and the service level is 54.86 percent, both indicating unsatisfactory performance in providing prompt care at ED. Using Pareto analysis, this study found that a significant cause of overcrowding was the majority (75 percent) of outpatients being non-traumatic emergencies. To ensure timely attention given to ED patients, this study aimed to improve the waiting time and service level through improving the design layout of ED.

Patients arrive at the ED either by ambulance or as walk-ins. Thus arrivals vary with the time of the day. To represent the times of arrivals, t_1, t_2, … of patients 1, 2, … starting from time t_0, the entire planning horizon is divided into multiple periods according to differences in demand. In each period, the possible demands are known with certain probabilities as the stochastic demand. The arrival rates and severity of each patient's condition are unpredictable in ensuring emergency patients receive care on time. To ensure that ED patients receive timely care, most countries including Taiwan use triage scoring to prioritize their ED patients according to their clinical urgency, and this method has exhibited good reliability (Beveridge *et al.*, 1999).

By observing the workflow at the ED under the ESI system, a physician would see multiple patients and write orders sequentially in a batch (Graban, 2009). A batch describes a process in which one step is completed for multiple items before the next step is started. Batch processing can lead to low-acuity patient care being held for many hours. The average cycle time in a queue (CT_q) will increase owing to the variability of batching, as illustrated by the VUT Equation (2), which

Table I. Recommended waiting time

Triage and severity scale	1	2	3	4	5
Recommended waiting time (minute)	1	10	30	60	120

describes the relationship between waiting time, variability (*V*), utilization (*U*) and process time (*T*) for a single process (Hopp and Spearman, 2008). The motivation of this study was to identify the batching interaction and to convert from a batch process to a one-piece flow to reduce the queue time in the patient assessment process:

$$CT_q = VUT = \left(\frac{C_a^2 + C_e^2}{2}\right)\left(\frac{u}{1-u}\right)t_e \quad (2)$$

In this study, the value stream mapping (VSM), a lean management tool, is employed for the design and analysis of an ED. With VSM, the non-value-added time is identified. Then, the batch process is converted into a one-piece flow using cellular manufacturing (CM). Finally, simulation optimization is performed to optimize staff assignment, minimize waiting time and maximize service level. The proposed methodology is applied to a case for empirical illustration.

The remainder of the paper is structured as follows. Section 2 provides a review of the relevant literature. Section 3 describes the case study considered. Section 4 discusses the proposed methodology. Empirical illustrations are reported in Section 5. Finally, the conclusions drawn and remarks concerning future research are offered in Section 6.

2. Literature review

Overcrowding in an ED is an operational problem (Sinreich and Marmor, 2005). To solve such problem, VSM, a lean management tools, is an extremely useful tool for analyzing the flow of material, information and the associated CT across multiple processes. Value stream is defined as the actions (both valued-added and non-value-added actions) necessary to deliver a product or service to a customer (Rother and Shook, 2003). Problems with multistage processes can be solved using VSM to identify waste in the process. VSM provides a visual roadmap of solutions (Lu *et al.*, 2011; Yang and Lu, 2011).

Lean principles have been successfully applied to ED problems (Dickson *et al.*, 2009; Holden, 2011). While the existing literature evidences the potential of lean principles, it does not discuss operational problems. Some studies have concluded that CM should be employed to convert batch processes into one-piece flows with shorter setup times, lower resource utilization and shorter travel distances (Harhalakis *et al.*, 1994; Agarwal and Sarkis, 1998; Albino and Garavelli, 1998). The application of cell formation provides a solution to efficiently managing patients in the ED (Malakooti *et al.*, 2004), but their model and solution algorithms cannot handle the cellular layout. This study adapts the ideal design of CM which addresses decisions of cell formation and layout simultaneously to obtain the best possible results (Logendran, 1991). Instead of identifying the cell formation of the step-patient incidence matrix, researchers focus on the arrangement of continuous steps into a cell (Baker *et al.*, 2009). This study proposes using a similar method with the only difference of having optimal staff assignment being considered under dynamic and stochastic demands.

A layout design specifies the layout of cells on a shop floor (Arkat *et al.*, 2012). In the Toyota Production System, a *U*-shaped layout is the more effective in that it provides a convenient foundation for one-piece flow, easier communication among teams in the cell, and requires a generally smaller floor space (Monden, 2011). However, a layout of linear design may be more efficient at ED (Boyle *et al.*, 2012). In this study, the performance of a *U*-shaped and a linear layout design are compared.

To model the behavior of a complex system, discrete-event simulation can be used. Through simulation, a system's behavior can be observed, and the potential improvement achieved after applying the changes can be evaluated (Sinreich and Marmor, 2005; Ujvari and Hilmola, 2006; Lu *et al.*, 2012).

VSM and CM are two most common lean methodologies (Feld, 2000), and they have been in the spotlight in the field of operation management since the work of Womack *et al.* (1990). The use of VSM, CM and simulation promises successful problem solving (Abdulmalek and Rajgopal, 2007; Pattanaik and Sharma, 2009). VSM provides a visual roadmap of solutions while CM can convert the batch process into a one-piece flow with shorter setup times (Ruiz-de-Arbulo-Lopez *et al.*, 2013). However, optimal staff assignments must still be determined to achieve the best solution for a given problem.

3. Case description using current-state VSM

The case study is of a medical center in southern Taiwan that provides a 24-hour service for traumatic, non-traumatic and pediatric emergencies. It has 1,600 beds and treats 79,500 patients annually. Medical staff attending non-traumatic emergencies includes 15 emergency physicians and nine nurses. Each staff member works eight hours per day. A visit to the ED typically involves a complex series of decisions, activities and interactions with hospital staff. Although it is impossible to classify exactly the flow processes for all ED patients, a general five-step flow process, which occurs in a linear sequence and requires different medical staff, can be determined.

3.1 Current-state VSM

VSM has three components. The information system boxes required to operate each process are located at the top of the map. The map features many icons. Each step is mapped from the left, vertically aligned rectangle, with the title placed at the top of each box. The CT within the box is typically the value-added time. The other non-value-added time is represented by a triangular icon. The middle of the map depicts patient or information flow. The bottom part of the map contains a timeline. Once the flow of a current process is understood, data that measure time can be added to the map. The timeline lists the waiting time at the top, and the CT for an individual step at the bottom. The lead time can be described as the amount of time that a patient waits between receiving and submitting a completed step. The map shows the steps patients experience and the waits in between. VSM serves as a visual aid and eliminates wasted actions between the current-state mapping and future-state mapping by combining resources, as shown in Figure 1.

As indicated by the current-state VSM, the triage is normally the initial stage the patient experiences and consists of a brief assessment, including clinical measurements, pulse rate, temperature, respiration rate and blood pressure, that indicate the patient's essential body functions. In most departments, this role is fulfilled by a nurse, who typically conducts a face-to-face interview when the patient arrives. Most patient care will be assessed at triage and then passed to another area with their recommended assessment time determined by their clinical need. Generally, patients with a less severe condition must wait until all of the more serious emergencies are treated first. The first medical step is usually a physical examination to obtain a patient's medical history and determine the chief complaint. This role is fulfilled

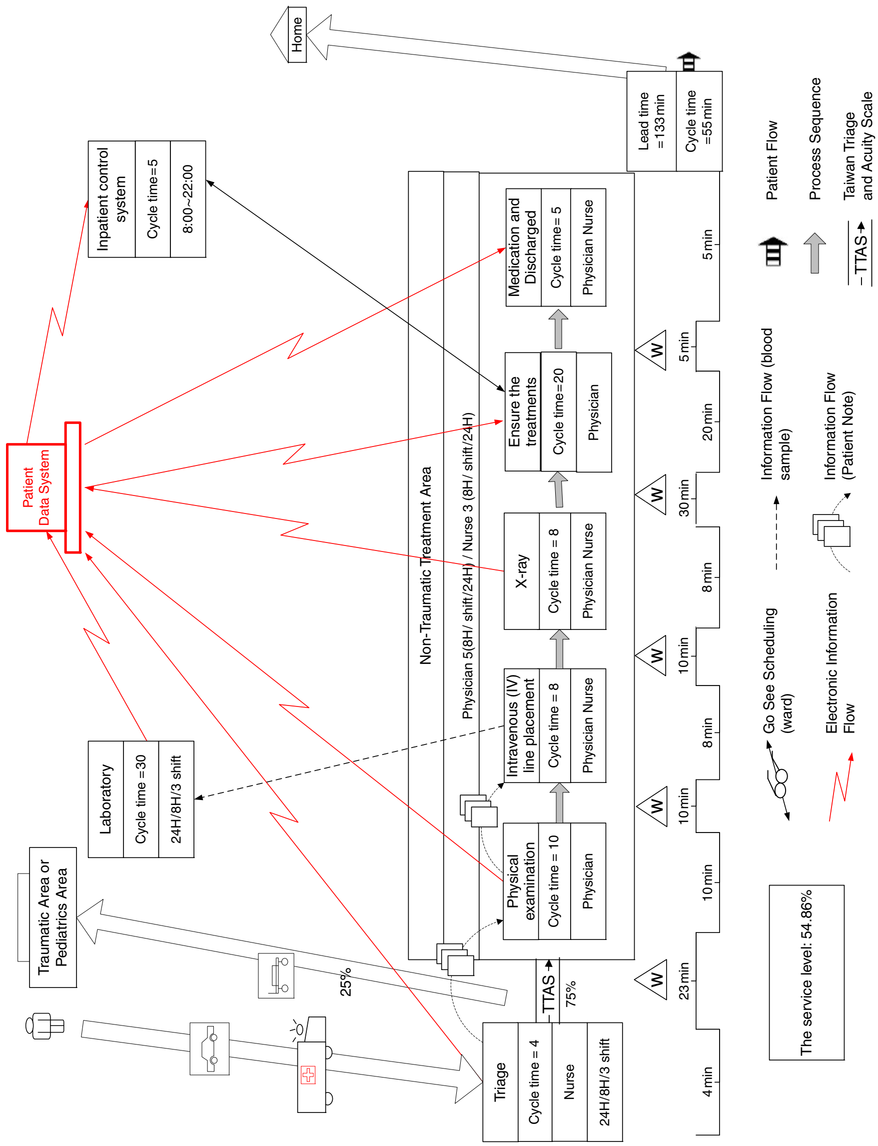

Figure 1.
Current-state value stream mapping

by a physician. After a physical examination, a variety of actions can be performed such as the placement of an intravenous (IV) line in a second step and gathering of X-rays in a third step, which can conducted by a physician and a nurse. The first step to the third step can be treated as a continuous flow. Once diagnostic test results are available electronically, the physician performs the fourth step of formulating a decision regarding the treatment. After the fifth step of medication and discharge, the patient can leave the ED.

As indicated by the current-state VSM, the triage is normally the initial step the patient experiences and consists of a brief assessment on the patient's essential body functions with pulse rate, temperature, respiration rate and blood pressure measured. In most cases, the assessment is performed by a nurse, who typically conducts a face-to-face interview upon patient arrival. According to the patient's clinical need assessed at triage, he/she will be transferred to other areas in the ED for further medical care. Generally, patients with less severe conditions must wait until all of the more serious emergencies are treated first. The first medical step is usually a physical examination to obtain a patient's medical history and determine the chief complaint. This examination is usually conducted by a physician. Further steps including placement of an IV line and taking X-rays can be performed by a physician and a nurse. The first step to the third step can be treated as a continuous flow. Once diagnostic test results are available electronically, the physician performs the fourth step of formulating a decision regarding the treatment. After the fifth step of prescribing medication and authorizing discharge, the patient can leave the ED.

In the current VSM, the lead time is 133 minutes, with a long waiting time of 78 minutes. In other words, the non-value-added time represents 59 percent of the lead time. The variability of the sequential batch process increases the lead time to be long, particularly the waiting time at the beginning of the process. On the other hand, the physical examination and treatment only 23 and 30 minutes, respectively. Based on Little's law, CT increases with increasing work-in-process (WIP). In a later section, an additional *VUT* algorithm is employed to further analyze these delays within steps.

4. Proposed methodology of CM design

Details regarding the development of the CM design used in this study have been reported by Rother and Harris (2003). The following section provides a detailed step-by-step description of implementation and empirical illustrations of the design.

4.1 Limitation of current layout

The first step in implementing CM requires certain workstations to be relocated to special operational environments. That would involve identifying first the limitations of the current floor layout. To begin with, the current floor layout is measured and divided into five distinct care areas for outpatients with non-traumatic emergencies. After a patient passes through the initial stage of triage, he/she is given the recommended time for assessment by physician according to the severity level of his/her condition and is then moved to a bed. Patients with similar levels of emergency severity are placed in the same area. Figure 2 presents the current layout design. According to the dimensions of the building shown, the current layout would cause staff members to spend a large portion of their duty time walking between different areas.

To provide a more in-depth interpretation of the batching process, the following parameters must be defined (Hopp and Spearman, 2008): k is the sequential batch size;

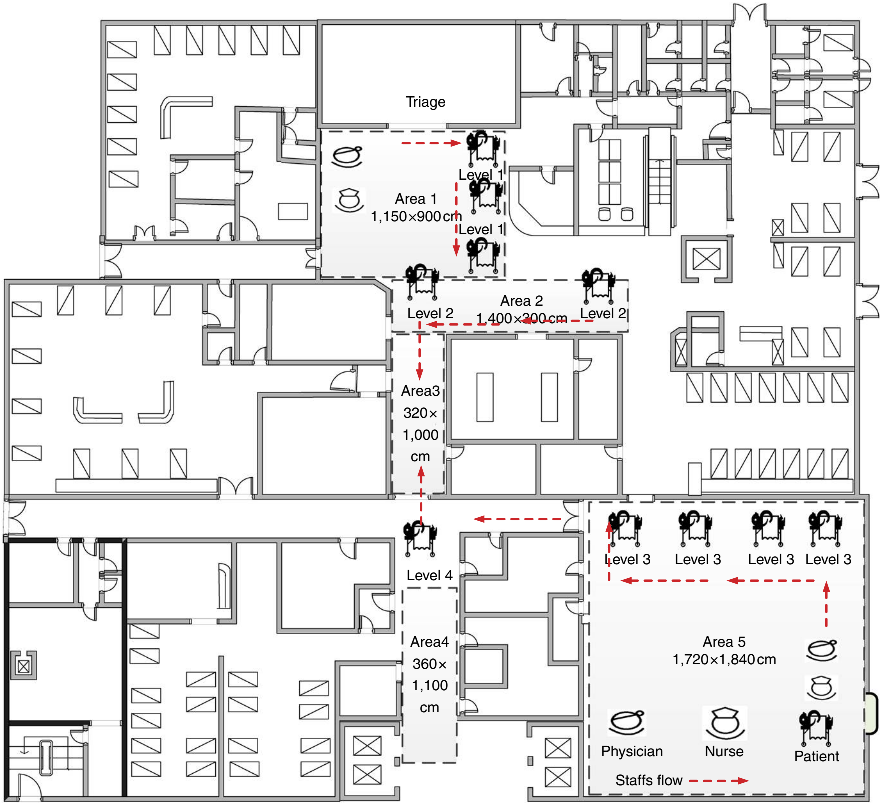

Figure 2.
Current layout design

t the time to process a single part; r_a the arrival rate (patients per hour); s the time to process a single part; σ_o the standard deviation of natural processing time; c_o the coefficient of variability of natural processing time; N_s the average number of cases between setup; and C_e^2 the effective SCV for processing time of a batch, including both process time and setup time:

$$t_e = kt + s, \tag{3}$$

$$u = \frac{r_a t_e}{km}, \tag{4}$$

$$\sigma_e^2 = \sigma_o^2 + \frac{\sigma_s^2}{N_s} + \frac{N_s - 1}{N_s^2} t_s^2, \tag{5}$$

$$C_e^2 = \frac{\sigma_e^2}{t_e^2}, \tag{6}$$

$$WIBT_{\text{non-split}} = (k-1)t, \quad (7)$$

$$WIBT_{\text{split}} = \frac{k-1}{2}t, \quad (8)$$

$$CT_{\text{non-split}} = CT_q + s + WIBT_{\text{non-split}} + t, \quad (9)$$

$$CT_{\text{split}} = CT_q + s + WIBT_{\text{split}} + t. \quad (10)$$

Take Area 1, for example. In this area, the average arrival rate, r_a, is 5.5 patients per hour, and the average process rate of the first step, r_e, is six patients per hour. A patient's arrival rate at the ED varies according to a non-stationary Poisson process; hence, the inter-arrival time is assumed to be exponential ($c_a^2 = 1$). In the first step of conducting a the physical examination to obtain the patient's medical history and determine the chief complaint, the process time t, is 0.17 hour, the setup time s is 0.17 hour and the standard deviation σ is 0.03 hour. The effective processing time of a batch, t_e, is determined by the time required to process k ($k = 4$) patients in the batch plus the setup time using Equation (3). This calculation yields $t_e = 0.85$ hour; thus according to Equation (4), the time required to complete the first stage is 0.39 hour. The average time in the queue $CT_q = 0.28$ hour is obtained using by the VUT Equation (2), where u and C_e^2 are given by Equations (5) and (6).

The average CT in the first step consists of the queue time plus the setup time, the wait-in-batch time (WIBT), and the process time. The WIBT depends on whether the lots are split downstream. If they are not, then all patients wait for the other $k-1$ patients in the batch and is determined by Equation (7). If the lots are split, then the first patient spends no time waiting. The second patient waits behind the first patient and hence spends t waiting time in the batch. Therefore, the WIBT with split lots is determined by Equation (8). The total CT with non-split and split lots, can be calculated by using Equations (9) and (10), where $CT_{\text{non-split}} = 1.41$ hours (84.6 minutes) and $CT_{\text{split}} = 0.875$ hour (52.5 minutes). According to the calculation results, the average CT can be reduced if the process batch becomes a one-piece flow. Thus, one of the objectives of this study is converting a batch into a one-piece flow to reduce queuing time in the process.

4.2 Configuration of CM design and space requirement

The configuration of the CM design and space requirement involves converting the area into a cellular layout by rearranging the process elements such that the processing steps are executed immediately adjacent to each other. In this study, steps are placed close together for only a minimal quantity of WIP under a *U*-shaped design and a linear design for performance comparison.

To enable a smooth conversion, it is typically necessary to evaluate the workstations for adaptability and then develop a conversion plan. For this case, the length of the workstation for the staff accommodates at least one bed, which measures 190 cm × 56 cm. Hence, the space required by a *U*-shaped unit is 578 cm × 510 cm as shown in Figure 3, while that required by a linear unit is 950 cm × 194 cm as shown in Figure 4. The CM

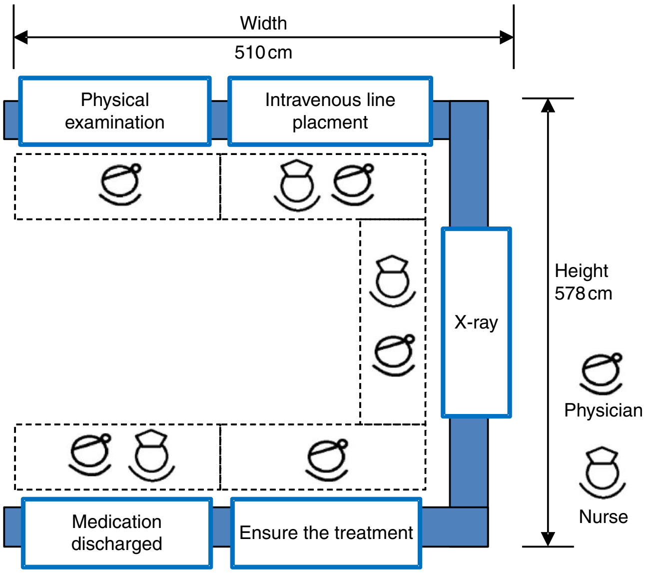

Figure 3. Dimensions of *U*-shaped unit

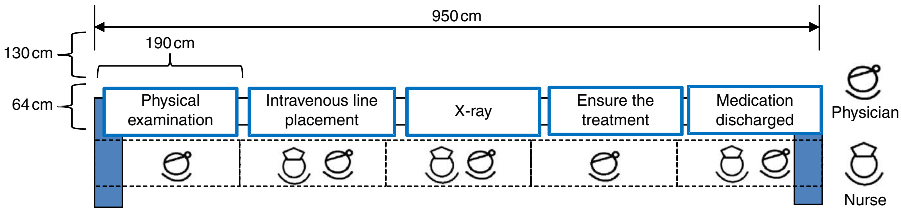

Figure 4. Dimensions of linear unit

design can save the time spent by the staff in walking between different areas, which would mean more time for better patient care.

4.3 Number of cells required

This study pursues a one-piece flow to balance the workload and obtain the required number of cells, while avoiding overproduction. The number of cells required is determined in the following steps (Tapping *et al.*, 2009). First, the CT, which is the amount of time required to complete the entire process, must be determined by adding all the time required by different steps associated with the particular value stream. Then, the takt time, which is a function of time that determines how fast a process must run to meet customer demand, is calculated using Equation (11). Finally, CT is divided by takt time, as shown by Equation (12), to determine the number of cells required for the system. For the current VSM, the total CT calculated for the five steps is 51 minutes. However, from the fourth step onward, the treatment to be administered would depend on laboratory test results. Hence, in this study, the CT of a particular value stream is determined by adding the time from first step to the third step, which is 26 minutes. The available daily work time is 1,440 minutes (24 hours × 60 minutes), and the average number of patients is 96. Hence, the takt time of the case study is 15 minutes

(1,440 minutes/96 patients), and the number of cells required is 1.73 (26 minutes/15 minutes). That is to say, the case study needs two cells to meet the process requirements:

$$Takt\ time = \frac{Available\ daily\ work\ time}{Total\ daily\ work\ time\ required} \tag{11}$$

$$Number\ of\ cells\ required = \frac{Cycle\ time\ of\ particular\ value\ stream}{Takt\ time}. \tag{12}$$

4.4 Number of staff members required per cell

As described above, the five steps are executed by two types of staff, the nurse and the physician. After being assigned to their respective cell, staff members are not allowed to change cells. Under this constraint, due consideration should be given to flexibility of staff, which is defined by the number of steps a staff member can perform (Treleven, 1989). In the present case study, a physician is responsible for the first and fourth steps, whereas the second, third and fifth steps require the cooperation of both the physician and the nurse. The goal of this investigation is to determine the optimal step-staff assignment. Another factor for consideration during staff assignment is the tradeoff decision between the wait-to-patient time and workload sharing. Given the fourth-step care is affected by laboratory test results, to prevent the third-step patients from blocking an incoming patient, these patients need to be transported to another area to wait until the test results are available. In the scenario of non-split cells, staff members ready for execution of fourth-step care have to wait for third-step patients to be transported back from another area. However, for the scenario of split cells, the constraint that staff members are not allowed to change cells makes workload sharing impossible as shown in Figure 5.

4.5 Dispatching rules

After determining the staff assignment to the CM system, the dispatching rule must be determined. Different dispatching rules have been proposed by researchers, and the simplest rule is first-in, first-out (FIFO) (Blackstone *et al.*, 1982).

4.6 Simulation modeling

Simulation is a proven tool in solving stochastic problems and allows for the examination of likely behavior under selected conditions (Lu *et al.*, 2012). Rockwell Arena® 13.51 was employed to build a simulation model that represents the ED system. The simulation allowed us to explore how variability affects waiting time and

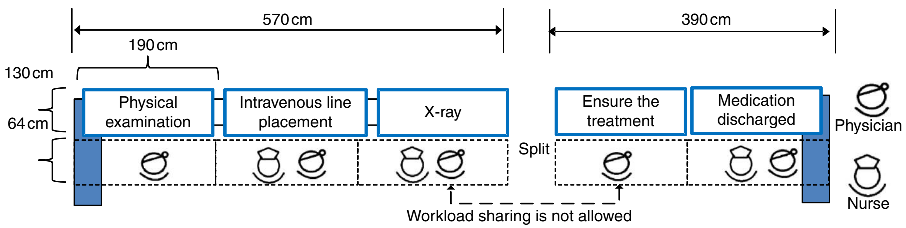

Figure 5. Dimensions of split linear unit

service level. The computer-based module logic design establishes an experimental platform that allows the user to perform different simulation experiments without actually changing the system structure as represented in the model frame. The tool has to include several modules to meet all the requirements. To launch a simulation, the inputs to the model are patients' arrival rates collected from the medical history data. One-month historical data are obtained from the computer system of the case hospital. The day is divided into 12 segments as shown in Table II. The arrival rate in each segment can be considered stochastic.

Furthermore, with reference to current operational practices, several specific assumptions and constraints are used in constructing the simulation model. These characteristics are the follows:

(1) Determined by the triage of the ESI system, the percentages, by patient type of non-traumatic patients with outpatient emergencies, trauma patients and emergency pediatric patients with inpatient emergencies, according to the data, are 75.29, 14.67 and 10.04 percent, respectively.

(2) The ED operates 24 hours a day, seven days a week. A day comprises three shifts of eight hours each. Staff breaks are combined with lunch/dinner to give each staff a 25-minutes break.

(3) Staff members are responsible for handling different cells, and the walking speed between procedures is assumed to be 88 cm/second.

(4) Under non-split cell condition, when laboratory test results become available, the fourth medical step must resume for the waiting patients and are to be transported back to the appropriate cell for treatment. The speed of transportation is assumed to be 62 cm/second.

(5) Patients are removed from process queues according to the FIFO rule, assuming no procedure breakdowns or rework.

(6) The process times of the five steps are stochastic and vary with level of acuity. Process time is longer for more severe patients who generally require more ED care. The percentages of patients experiencing severity levels ranging from level 1 to level 5 are 4.15, 23.02, 61.89, 10.75 and 0.19 percent, respectively. This study uses the estimates for min, mode and max in a triangular distribution for the stochastic process time, as shown in Table III.

4.7 Simulation runs

The study horizon is 30 days, which is considered adequate to address the performance of the case problem. In addressing this problem, first, the proposed simulation is built

Table II. Arrival rates per hour throughout the day

Time (hour)	Rate (patients/hour)	Time (hour)	Rate (patients/hour)
0:00-2:00	3.61	12:00-14:00	8.3
2:00-4:00	4.25	14:00-16:00	6.44
4:00-6:00	3.68	16:00-18:00	8.27
6:00-8:00	3.38	18:00-20:00	8.03
8:00-10:00	3.92	20:00-22:00	5.94
10:00-12:00	8.25	22:00-24:00	6.53

and followed by the numerical analyses. The simulation is classified as being either terminating or in steady state. Terminating signifies that the system has starting and stopping conditions (Kelton *et al.*, 2010). The case involves a 24-hour service provided under dynamic and stochastic demands. With variable ("non-stationary") arrival rates, a steady-state simulation is used as the scenario. Because there are no clearly defined start and end times, the initial stage of the simulation may result in a significant disagreement between the estimated value and the real value. The process must be run for a sufficiently long time to avoid this bias. The frequency at which the observed interval contains the throughput is determined by the confidence level, which is computed using the initial setting for replication and indicates the probability that the confidence range captures the true population.

Most systems start with empty entities and idle resources, which can bias the output in a steady-state simulation. This study determines warm-up times using an Arena® 13.5 Output Analyzer as a visual aid. By observing when the WIP curve becomes stabilized, this shows the relationship between the resulting WIP levels from the ten replications along the simulation time. A reasonable warm-up period of 30 hours is determined, as shown in Figure 6. The data collected during the warm-up period can bias the output analysis results and are discarded for further analysis.

Once the simulation model is constructed, the goal is to tighten the precision to cover the population mean; the smaller the confidence interval, the larger the number of simulation replications required. The length of one replication was set as one month. Each replication starts with both an empty and an idle system. The coefficient of variation (CV), which is defined as the ratio of the sample standard deviation to the sample mean, is used as an indicator of the magnitude of the variance. The value of the CV stabilizes when the number of replications reaches 23, as shown in Figure 7 (Yang *et al.*, 2007).

4.8 Verification and validation

The empirical illustrations reported in this study and the coherence of the simulation models are determined by verification and validation. Verification ensures that the model behaves as intended, while validation ensures that the model behaves like

Step	Medical step	Resources	Triangular process time (minute)
1	Physical examination	Physician	(9,10,15)
2	Intravenous (IV) line placement	Nurse, physician	(3,8,10)
3	X-ray	Nurse, physician	(4,5,9)
4	Ensure the treatment	Physician	(18,20,23)
5	Medication and discharge	Nurse, physician	(3,5,6)

Table III. Distributions and resources of each step

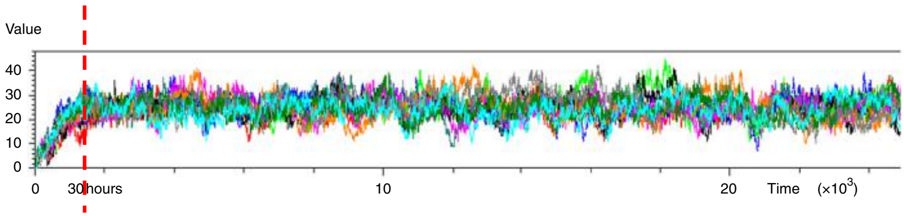

Figure 6. Work-in-process (WIP) warm-up

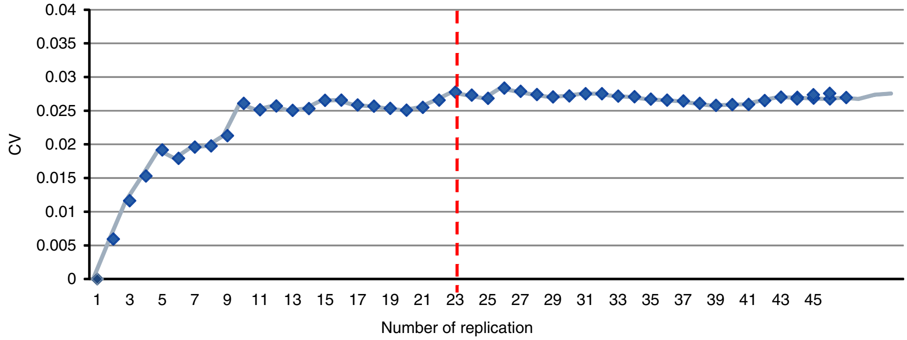

Figure 7.
Coefficient of variation (CV) chart

the real system. As seen in the validation results shown in Table IV, the discrepancy in waiting time and throughput are 5.13 and 3.13 percent, respectively.

4.9 Staff assignment optimization

Four CM alternatives (CM 1-4) are developed, each exhibiting one of the following features: *U*-shaped layout, non-split cells, split cells and a linear layout, respectively. Simulation experiments are conducted to compare the performance. For CM 1, all five steps are to be performed placed with the *U*-shaped layout. Cells are located in Areas 1 and 2, as shown in Figure 8. In this design, third-step patients waiting in another area have to be transported back to the cells when the fourth medical step is ready for execution.

For CM 2, shown in Figure 9, with the front cell in Area 1 and back cell in Area 2, while for CM 3, shown in Figure 10, the two cells are split, with the front cell in Area 2 and the back cell in Area 5. Medical steps 1-3 are performed in the front cell and medical steps 4-5 are administered in the back cell. The main differences between these two designs are that split-cell design (CM 3) does not allow workload sharing and involves transportation of patients for fourth-step care.

Figure 11 shows a linear layout of CM 4. As can be seen, all five steps are to be performed into cells with a linear layout, located in Area 1. The design indicates the situation which patients must be transported back to cells when step 4 is ready for execution.

There are six possible staff assignments for each cell, as shown in Table V. To evaluate each alternative among the three shifts in a day, there are 93,312 scenarios ($2 \times 6^3 \times 6^3$) based on the criteria of waiting time and service level. Optimization finds the best solution to the problem, which can be expressed in the form of an objective function and a set of constraints. Therefore, the difference between the model that represents the system and the procedure that is used to solve the optimization problems is defined within this model. The optimization procedure uses the outputs from the simulation model as an input, and the results of the simulation run are fed into the next simulation. This process iterates until the stopping criterion is met. The interaction between the simulation model and the optimization is shown in Figure 12 (Glover *et al.*, 1996).

Table IV.
Validation results

Measure	Unit	System	Simulation	Error (%)
Waiting time	Minutes/patient	78	82	5.13
Throughput	Patients/day	96	99	3.13

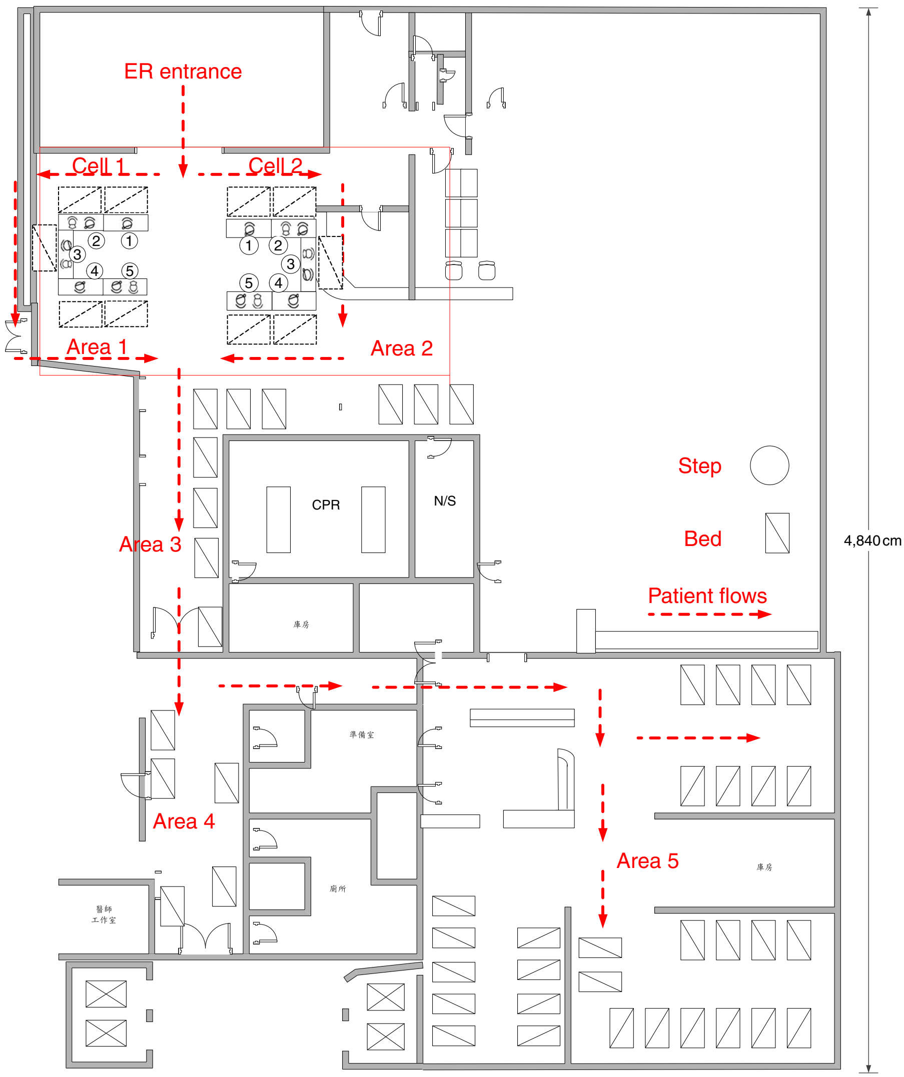

Figure 8.
U-shaped layout of CM 1

The required notations for the formulation are defined as follows:

Parameters:

i = shifts type; $i=1$, day shift, $i=2$, midnight shift, $i=3$, night shift,

j = type of staff member; $j=1$, physician, $j=2$, nurse,

l = emergency severity; $l=1$(level 1), $l=2$ (level 2), $l=3$ (level 3), $l=4$ (level 4), $l=5$ (level 5),

h = cell type; $h=1$, the first cell, $h=2$, the second cell,

s' = the probability that delays in initial care amount to less than the recommended assessment time of current system,

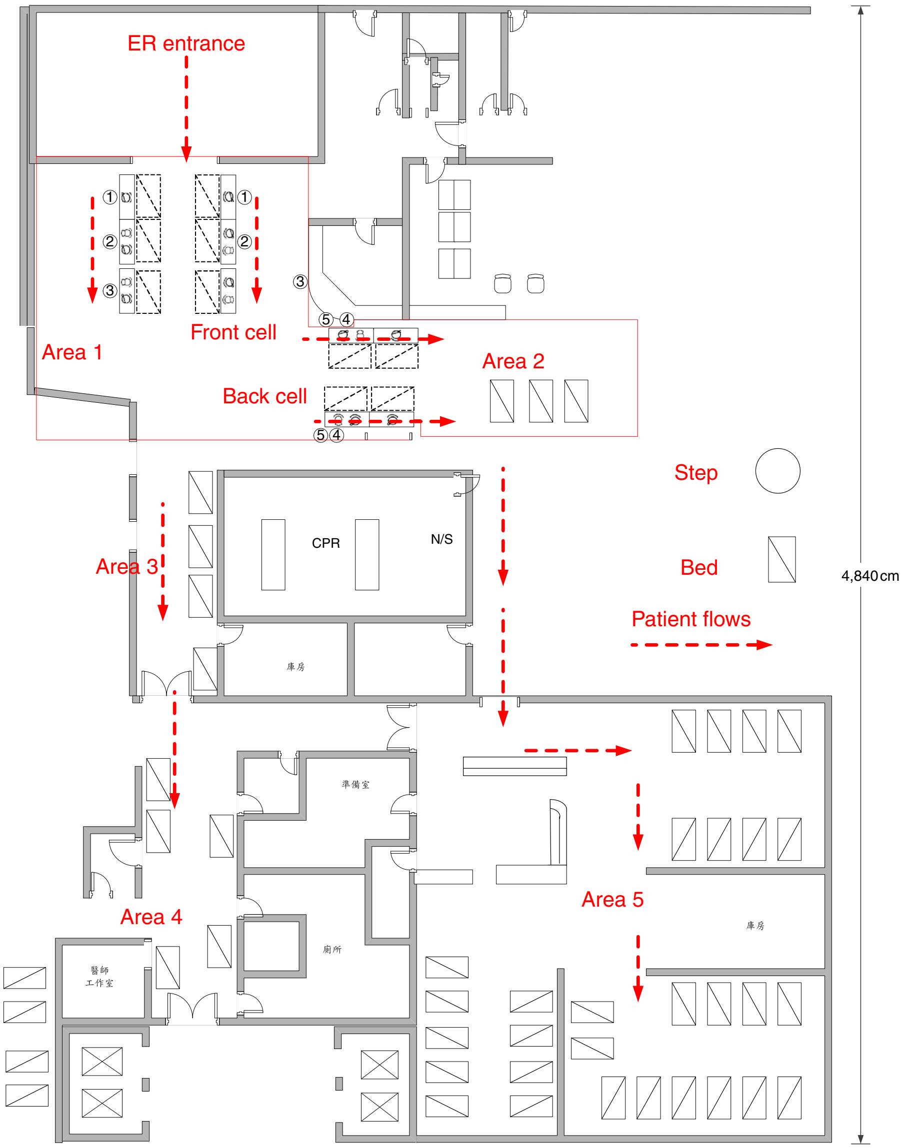

Figure 9. Non-split front and back cells in CM 2

d_j = the total number of staff members per day, t = average waiting time per patient, n = total number of out patients, ol = number of l patients, which lead to a time is less than the recommended assessment time under the ESI system, s = probability that delays in initial care amount to less than the recommended assessment time after adjusting the decision variables.

Decision variables:

x_{ih} = the number of staff assignments in shift i of cell h:

$$\text{Minimize } Z = E\,(t), \tag{13}$$

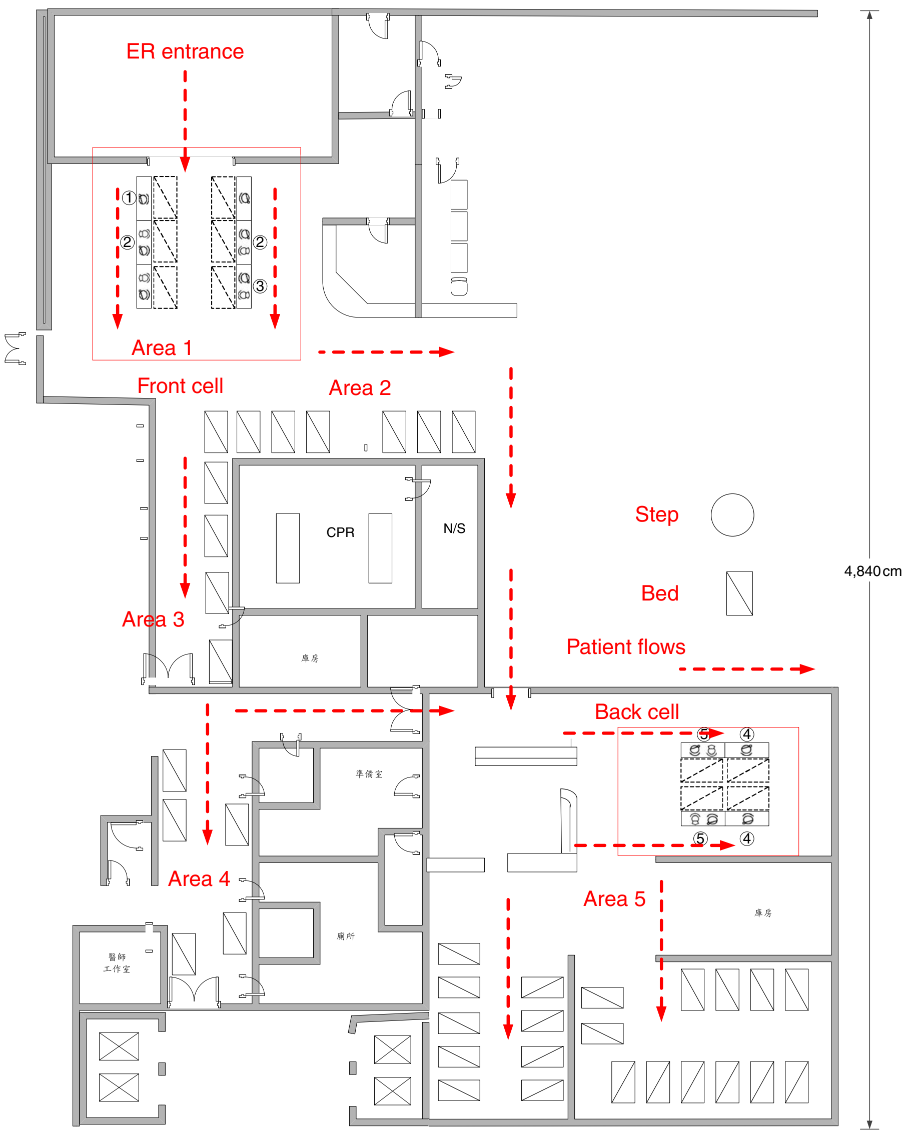

Figure 10.
Split front and back cells in CM 3

subject to:

$$s' \leqslant E(s), \tag{14}$$

$$s = \frac{\sum_{l=1}^{l=5} o_l}{n}, \tag{15}$$

$$d_1 \leqslant 15, \tag{16}$$

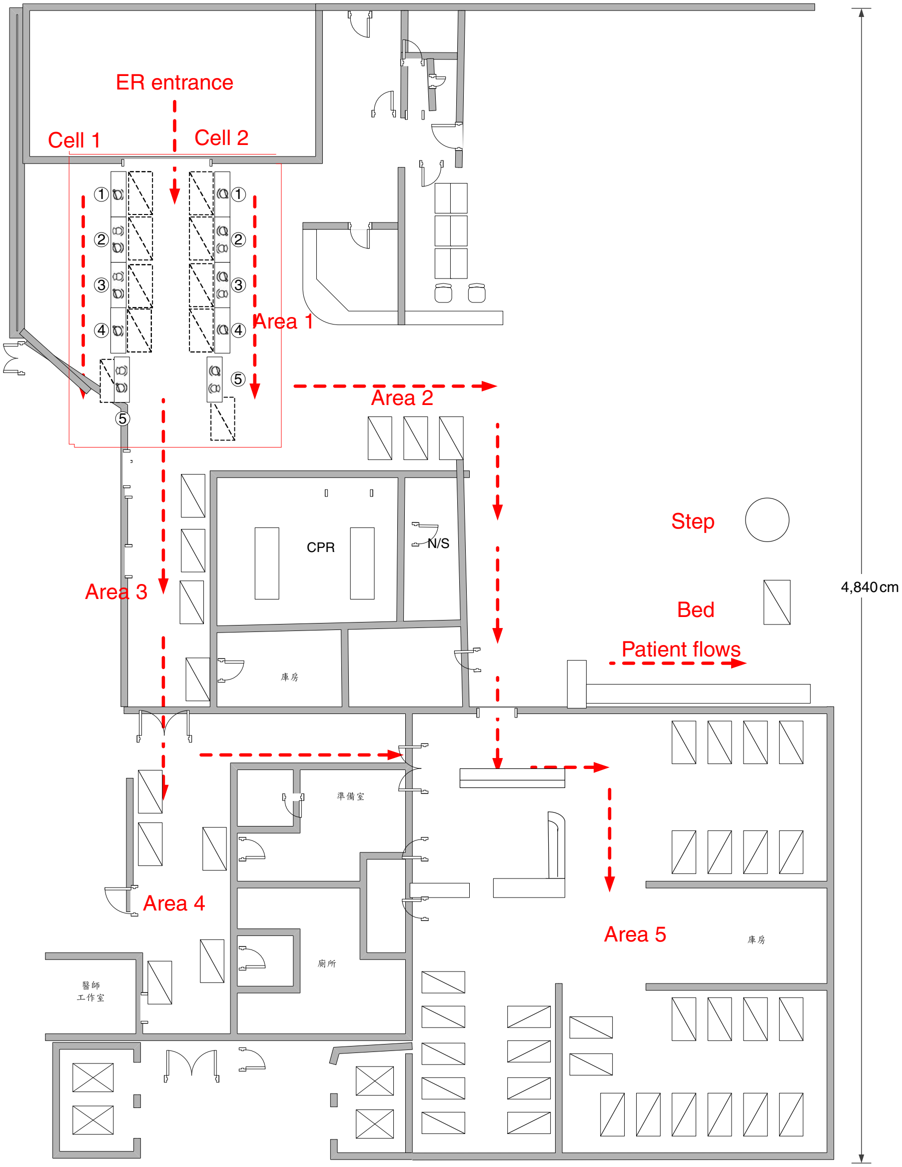

Figure 11.
Linear layout
of CM 4

$$d_2 \leqslant 9, \tag{17}$$

$$0 \leqslant x_{ih} \leqslant 6. \tag{18}$$

The minimum average waiting time is defined in Equation (13) for the-smaller-the-better response. Equation (14) shows that the service level of the new strategy must be greater than or equal to that of the current system. Equation (15) defines the service level. Equations (16) and (17) limit the number of staff assignments to 15 per day for physician and to nine per day for nurse. Equations (18) establish the number of possible staff assignments per cell per shift.

5. Empirical results and analysis

The optimal setting and the results are summarized in Table VI. In this table, from columns 2 to 4 show the staff assignment for each cell under three shifts. Columns 5 and 6 show the optimal staff assignment. Column 7 shows the performance. CM 1, 2 and 4 demonstrate that the waiting time and service level are improved by the methodology. A linear layout design of CM 4 is deemed to be the most effective in solving the proposed problem. The average waiting time for patients was reduced from 78 to 38 minutes, a 51 percent improvement; while the service level was increased from 54.86 to 88.55 percent, a 61 percent improvement, as shown in Table VII. Moreover, a linear layout was determined to be more effective for staff assignment, with the number of nurses reduced from nine to six.

6. Conclusions and further research

This study applies VSM to the design and analysis of the ED. Decisions of cell formation and layout are addressed simultaneously by CM design, with the optimal staff assignment for converting batch processing into continuous processing. According to the scenario analysis conducted in this study, a linear layout outperformed a *U*-shaped layout in terms of both waiting time and service level.

A number of conclusions can be drawn from an analysis of the results. First, we acknowledge that the general triage system of prioritization and the current layout

Possibility	Number of physicians	Number of nurses
1	1	1
2	2	1
3	3	1
4	1	2
5	2	2
6	3	2

Table V. Possible staff assignments

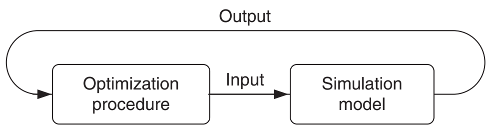

Figure 12. Relationship between simulation model and optimization

Table VI.
Summary of experimental results

CM		Staff (x_{ih})	Cell 1 (h_1) Day	Mid.	Night	Cell 2 (h_2) Day	Mid.	Night	Number of physicians	Number of nurses	Performance Waiting time	Service level (%)
1		Physician	3	2	2	4	1	3	15	9	38.49	87.94
		Nurse	2	1	1	2	1	2				
2	Front	Physician	2	2	2	2	2	2	15	9	40.11	56.22
		Nurse	1	1	1	1	1	1				
	Back	Physician	1	1	0	1	0	0				
		Nurse	1	1	0	1	0	0				
3	Front	Physician	2	3	2	0	2	2	15	9	113.83	55.09
		Nurse	1	1	1	1	1	1				
	Back	Physician	1	1	2	0	0	0				
		Nurse	1	1	1	0	0	0				
4		Physician	3	2	2	3	2	3	15	6	38.42	88.55
		Nurse	1	1	1	1	1	1				

Table VII.
Best results

	Waiting time (minute)	Service level (%)	Staffing level reduction
Original system	78	54.86	9
Optimal solution	38	88.55	6
Improvement (%)	51	61.41	33.33

design used in many EDs is an imperfect descriptor of individual treatment path steps. In the current system, physicians would see multiple patients and write orders sequentially in a batch. The average waiting time for patients will increase because of the variability of batching according to the *VUT* equation. Second, *U*-shaped exemplified by the Toyota Production System is arguably the most common manufacturing solution layout used. However, for a long building, a linear layout was determined to be more effective in terms of performance than a *U*-shaped layout.

It is necessary to reflect on the main limitations of this research which require further study. First, the actual arrival rate during the study period, and they do account for diurnal variation. The distribution function should reflect seasonal variation. Second, the unique aspects of patients' responses require specialized training staff. The staffing levels varied widely because of nursing shortages and other staffing issues. The constant variations in staffing levels were not tracked for research purposes over the period we studied. Therefore, we were unable to model changes in staffing levels for the tests of model accuracy. This limitation will bias the accuracy toward a less accurate match. Other limitations of this study involve the accuracy of individual patient treatment paths. Although a substantial amount of data regarding patient care can be assembled through the same procedures, the percentages requiring both laboratory and radiology tests are 100 percent in this study. However, the relative priorities of individual patient care steps can be dynamic. Finally, 25 percent of the cited contributors to ED overcrowding, based on the inability to move admitted patients into beds, were not considered in the study. The issue of delays in transferring a patient to an inpatient bed will be addressed in future studies.

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