Simulation-Based Models of Emergency Departments:
Operational, Tactical and Strategic Staffing: Online Supplement
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The Emergency Department (ED) of a modern hospital is a highly complex system that gives rise to numerous managerial challenges, spanning the full spectrum of operational, clinical and financial perspectives, over varying horizons: operational – few hours or days ahead; tactical – weeks or a few months ahead, and strategic - which involves planning on monthly and yearly scales. Since realistic ED models are intractable analytically, one resorts to simulation for an appropriate framework to address these challenges, which is what we do here. Specifically, we apply a general and flexible ED simulator to address several central wide-scope problems that arose in a large Israeli hospital. The paper focuses mainly, but not solely, on workforce staffing problems over the above time horizons. First, we demonstrate that our simulation model can support real-time control, which enables short-term prediction and operational planning (physicians and nurse staffing) for several hours or days ahead. To this end, we implement a novel simulation-based technique that utilizes the concept of offered-load and discover that it performs better than a common alternative. Then we evaluate ED staff scheduling that adjusts for mid-term changes (tactical horizon, several weeks or months ahead). Finally, we analyze the design and staffing problems that arose from physical relocation of the ED (strategic yearly horizon). Application of the simulation-based approach led to the implementation of our design and staffing recommendations.

Categories and Subject Descriptors: I 6.3 [Simulation and Modeling] – Applications – Health care.

General Terms: Simulation and modeling, health care, queues, queueing theory
Additional Key Words and Phrases: Emergency departments, offered load, operational planning, tactical planning, strategic planning
ACM File Format:

1 SIMULATION-BASED MODELING FOR REAL-TIME CONTROL AND OPERATIONS PLANNING: INTEGRATION WITH DECISION-SUPPORT SYSTEM IN ED

In order to provide to decision makers (e.g. ED department manager) access to operational solutions described in Section 5 of the main paper, integration between our simulation and a Decision Support System (DSS) should be performed. Collecting real-time data from various sources can give a snapshot of the current situation and by using the methodology above, such a system can provide predicted information based on the current ED state. Then this information can be presented to the decision maker in various ways. For example, the ED manager can use this system trying to avoid a future possible lack of resources (e.g. physicians, beds, nurses, etc.).

Based on the above methodology, we were able to develop the InEDvance DSS (Greenshpan et al. 2009). InEDvance is a decision support system that can record, process, simulate, and present event data that hospital IT systems record and send, along with current and forecasted performance measures (see Figure 1). The InEDvance system comprises algorithms that assist the ED manager in planning resources allocation for the next several hours, in order to handle forecasted resource scarcity. In particular, InEDvance has, at its core, a simulation-based module that is fed (in real-time) by data from the hospital IT systems and then, through simulation (as described in Section 5 of the main paper), identifies and presents patients flow bottlenecks (e.g. excessive lines at the X-Ray) and consequently alerts ED management.
Input to the InEDvance system originates from numerous data sources. For example, ED current state is based on information from a multitude of hospital IT systems such as the Admit Discharge Transfer (ADT) system, the Radiology Information System (RIS), the Lab Order Reservation system and the Electronic Medical Records system. Yet these systems provide only minimal operational information such as start and end of an activity. In particular, no information on queue lengths or waiting times is available. Therefore, the need for simulation-based capabilities of ED state completion and prediction arises. In the future, an increasing number of data sources will provide more and more information about the current state of the ED. A very significant upgrade of data collection capabilities can be achieved by the incorporation of an RFID (Radio Frequency Identification) system (see Section 2) that will provide information about location of patients, physicians, equipment, etc.

The information arriving from the various IT systems generates a dashboard of past, present and predicted activities within the ED. We sample-demonstrate the use of such a dashboard by combining it with our ED simulator, and graphically presenting (potentially in real-time) information on the dashboard, using a graphical user interface. Figure 2 shows a snapshot of the dashboard that presents, in various ways, past and current occupancy of different ED rooms. Figure 3 demonstrates a dashboard tab that could alert, based on calculated forecasting indicators, on predicted congestion and resource shortage.

Figure 1 - InEDvance system architecture

Figure 2 - Dashboard snapshot showing rooms occupancy

Figure 3 - Predicted arrivals and physicians load
2 SIMULATION-BASED MODELING FOR SCENARIO VALIDATION: VALUE ASSESSMENT OF RFID TECHNOLOGIES IMPACT

2.1 Related work: Applications of RFID technology in health care

Significant research and development efforts have been devoted to the search after efficient and accurate Indoor Location Tracking (ILT) systems. While the Global Positioning System (GPS) has become the de-facto standard for outdoor tracking, and it serves as the foundation for many location tracking applications, GPS has yet no equivalent leading technology, which is suitable for indoor tracking (Lee et al. 2006).

ILT systems are also referred to as RFID, after the technology of Radio Frequency IDentification. RFID technology has recently become widespread due to its many merits. Basically, RFID provides unique identifications to objects, hence it can be used as the foundation for objects tracking, monitoring and control (Hightower and Borriello 2001; Hightower, Want and Borriello 2000).

RFID has traditionally been used for tracking passive entities, such as consumer package goods, medications and medical equipment. Yet this same technology can be used for uniquely identifying humans, e.g. patients and care personnel in hospitals. Applying RFID for indoor location tracking requires an additional layer, which associates the RFID tag with a specific location. This association can be implemented via two conceptually different approaches (Saha et al. 2003):

- Cell-based location tracking – location identified through the location of the reader of the RFID tag.
- Triangulation – location calculated from radio frequencies, used in the communication between the RFID tag and scattered RFID readers (Bahl and Padmanabhan 2000).

RFID-based ILT systems have been recently developed for addressing specific needs that arise in patients' care. For example, MASCAL (Emory and Leslie 2005) is an integrated solution for tracking patients and equipment during events of mass causality; MASCAL is based on the 802.11 communication network, and it is integrated with the hospital's clinical database. As another example, an RFID-based system was deployed in Taiwan (Wang et al. 2006), for identification and tracking of potential SARS cases; the system provides active patient-location tracking information as well as body temperature indication. In this present work, RFID it the technology behind our proposed ILT systems enabling data-based business process management - in particular transformation towards improvement.

Two issues often arise in connection with RFID technologies: radiation exposure and privacy considerations. Both issues are relevant for health care organizations. See the report of the World Health Organization (2006) and Flint (2006) for general surveys on radiation exposure and potential privacy problems, respectively.

2.2 Research goals and description of technologies

In this section, we consider the validation of RFID technology implementation in ED. It is obvious that the actual introduction of RFID technology is costly and demands thorough re-design of ED processes and IT system. Therefore, there is a strong need to estimate benefits and costs of such implementation in advance and using relatively inexpensive evaluation procedure. The simulation based modeling is a natural answer to this challenge. In this section, we consider implementation of two alternative existing RFID technologies: WiFi (802.11) and short range passive RFID.

WiFi (see Emory and Leslie 2005, for example) is currently the most standardized and usable indoor wireless communication technology. Simple location tracking mechanisms can be built on top of an existing WiFi infrastructure. WiFi is designed to cover wide areas such as the overall hospital campus; hence, it can provide wide location tracking capabilities. The location tracking precision of WiFi, on the other hand, is poor. Naïve implementation uses the tag only for access point association and hence provides only room level resolution. Such installations may have also difficulties in distinguishing locations within two adjacent hospital floors. WiFi is based on active tag communication hence provides continuous location tracking.

Passive RFID systems, on the other hand, offer very accurate location tracking, as tags can be identified only within short distances from the reader. The limited coverage issue can be resolved via additional readers, and by placing readers in designated frequently-accessed spots such as doors, pathways, mobile medical equipments (e.g. ECG machine) and patient beds. A significant advantage of passive RFID system is low tag cost. Passive RFID tags are disposable and require little to no maintenance. Thus, widespread deployment is more likely because tags can be given to patients, caregivers, families and visitors with little significant additional cost. Tags within a Passive RFID
tags can be identified only during the reading transaction itself, hence they do not render continuous location tracking and monitoring.

2.3 Required process changes

As the first step, it is necessary to define how various components of the ED processes will change given the new data provided by RFID. In addition, it is necessary to define which measures, or metrics, will improve due to the process change(s). It is important to specify the metrics that are expected to improve since only through these quantitative metrics, can the value of the RFID system be estimated (or the values of several RFID alternatives be compared) – see Section 2.4.

In general, there are three different types of metrics: clinical, operational and financial. In this research, we explore operational metrics that measure the operational efficiency of the ED and emphasize their relation to clinical and financial metrics. Average Length of Stay (ALOS) is an important example of an operational metrics. ALOS is the average amount of time a patient spends in the ED before either being released from the hospital or being admitted to a ward; one could account separately for patients who "left" due to other reasons, for example death or LWBS (see Fernandes, Price and Christenson 1997). Another important operational metric is workload - the average amount of work-time required from the staff, or a subset of it (nurses, physicians), quantified as a function of time.

Note that the three above-mentioned types of metrics are interdependent. For example, if a patient waits for a long time before first examination by a physician, this may adversely affect an operational outcome such as ALOS which, in turn, could result in clinical deterioration, hence increased workload (more care required by the staff), and additional costs.

For concreteness and demonstration purposes, we have chosen three ED processes whose importance for our hospital was established, for assessing the value of their improvements:

- From the operational point of view, implementing an alerting RFID system will help reduce unnecessary waiting times. We focus on patients who are "forgotten" in two Imaging areas: (a) in a remote CT area after completing their scan. Based on practice, we are assuming that 25% of such patients experience an average of one hour waiting before returning to the ED, when compared against an average of 10 minutes for regular waits. (b) the patients that are waiting after an X-Ray scan. Here "forgotten" patients wait just half an hour instead of the regular 10 minutes. (The X-Ray is relatively close to the ED and easier to locate "forgotten" patients at.)
- From the financial point of view, using patients RFID prevents abandonments of unregistered patients, and thus increases ED's turnover rate and, in turn, enhances hospital income. In essence, we measure the operational metrics – LWBS fraction, which in its turn can help to determine the increase of hospital income.
- From the clinical point of view, using staff (nurses, physicians) RFID exposes physical layout problems, such as poor placement of rooms or equipment in the ED, which have adverse clinical consequences. Again, a related operational metrics – staff walking distance, is considered. Excessive walking distances would indicate physical layout problems.

2.4 Simulation experiments

To evaluate the benefits of using an RFID system for our three example processes, we have used an ED simulation model, described in Section 4 of the main paper, and programmed it to process six types of patients: Orthopedic, Surgical, and Internal, each in two conditions – Walking and Acute (those in need of a bed). In addition, we made changes to the simulation in order to accommodate the expected impact of the two RFID technologies that are tested.

For the process improvement, based on tracking abandonment, we made the following assumptions:

- Since data of actual abandonment times is currently unavailable, we distributed 4% abandonment (historical average for LWBS fraction) over five process steps: (1) waiting for a nurse to take patients anamnesis; (2) waiting for a physician's initial diagnosis; (3) after the physician's first examination and before sending additional tests; (4) while waiting for a physician to collect all the relevant data for further evaluation; (5) after further evaluation, while waiting to be released, hospitalized or for additional intensive tests.
- We assumed that WiFi technology identifies 100% of the abandonments and feeds those patients back into the process1. Passive RFID, on the other hand, succeeds in only 50% of the cases. The difference arises because

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1 This assumption is, of course, a certain simplification. In fact, 100% of LWBS patients cannot be persuaded to stay. However, it will be possible to locate LWBS patients, talk with them and, probably, solve their problems. In addition, hospital managers assume that an installation of such system will prevent many patients from LWBS attempts.
some patients would not abandon with their tags, while others might use vehicles, just as an example, to circumvent the passive sensors near the gates, which otherwise would detect them.

- Abandoning patients are not included in calculating lengths of stay, and they are naturally excluded from those who contribute to hospital profit.

For the process improvement, dealing with reducing waiting times in the Imaging (CT or X-Ray) wards, we made the following assumptions and modifications:

- CT patients are waiting to return to the ED. Return timed is within 10 minutes for 75% of the patients and an hour for the rest.
- Passive technology is more effective than WiFi in this case: Passive technology accurately tracks room relocations and, therefore, gives rise to 100% reduction of the waiting time to 10 minutes. WiFi, on the other hand, reduces waiting times of only 50% of those who are expecting prolonged 60 minutes waiting.
- Of the delayed X-Ray patients, 20%, on average, are waiting 10 minutes and the others 30 minutes.

The Passive and WiFi systems were compared against two additional scenarios: an "ideal RFID system" and the prevailing situation without RFID. An “ideal RFID system” combines benefits of the Passive and WiFi systems: it succeeds to identify 100% of abandonments and tracks all customers who are forgotten at CT and X-Ray. Since the RFID influence on the two processes is intertwined (less abandonment can imply larger workload and waits), we decided also to check the influence of two changes (reduction of waiting times and preventing LWBS) separately.

One week was used for simulation warm-up and three months of data for analysis, eleven simulation runs were performed for each case.

Table 1 provides us with a summary of simulation results. It includes simulation averages for overall number of patients and LWBS patients, ALOS estimate, standard deviation of ALOS estimate $\sigma$(ALOS), based on variability between 11 simulation runs, and finally, $\sigma$(LOS) – standard deviation of individual customer LOS. We shall analyze Table 1 data from several points of view.

### Average Length of Stay

Comparing the first three lines of Table 1, we observe that ALOS decreases once we reduce waiting times in the Imaging Units. Consistently with the story above, Passive RFID technology implies more significant improvement than WiFi. In contrast, LWBS reduction or elimination increases ALOS. Since patients are fed back into the process, congestion increases to a certain extent. (Garnett, Mandelbaum and Reiman, 2002, analyze such operational consequences of abandonments.) Finally, given the full implementation of RFID solution (Imaging waiting decreases and LWBS is reduced), Passive RFID provides ALOS that is slightly smaller with respect to the basic state while WiFi implementation leads to ALOS increase. (Passive RFID reduces wait more significantly than the WiFi alternative and feeds less customers back into the process.)

### Number of LWBS patients

Table 1 shows that, in our simulation experiment, RFID technology fed back significant number of patients into the process. It should have both positive clinical and financial impacts: LWBS patients often return to an ED when their condition deteriorates; we also block attempts to leave the ED without providing payment guarantees.

Another operational aspect of RFID implementation is captured by the intra-day staff workload, displayed in Figure 3. We calculate the workload in order to check that implementation of RFID will not lead to any unexpected operational phenomena. (Physicians that treat Internal Acute patients are chosen for this example). We observe that differences between RFID scenarios are not too large.

<table>
<thead>
<tr>
<th>RFID System</th>
<th>Number of patients (3 months)</th>
<th>LWBS (3 months)</th>
<th>ALOS</th>
<th>$\sigma$(ALOS)</th>
<th>$\sigma$(LOS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without RFID</td>
<td>24,037</td>
<td>945 (3.9%)</td>
<td>178.9</td>
<td>0.9</td>
<td>128.4</td>
</tr>
<tr>
<td>WiFi, wait reduced</td>
<td>24,012</td>
<td>951 (4.0%)</td>
<td>175.3</td>
<td>0.9</td>
<td>127.9</td>
</tr>
<tr>
<td>Passive RFID, wait reduced</td>
<td>24,001</td>
<td>949 (4.0%)</td>
<td>172.1</td>
<td>0.7</td>
<td>127.3</td>
</tr>
<tr>
<td>WiFi, LWBS eliminated</td>
<td>23,977</td>
<td>478 (2.0%)</td>
<td>190.7</td>
<td>0.8</td>
<td>135.8</td>
</tr>
<tr>
<td>Passive RFID, LWBS reduced</td>
<td>24,026</td>
<td>0</td>
<td>184.6</td>
<td>0.9</td>
<td>132.7</td>
</tr>
<tr>
<td>WiFi</td>
<td>23,987</td>
<td>475 (2.0%)</td>
<td>186.8</td>
<td>0.9</td>
<td>133.9</td>
</tr>
<tr>
<td>Passive RFID</td>
<td>24,087</td>
<td>0</td>
<td>177.2</td>
<td>0.7</td>
<td>128.9</td>
</tr>
<tr>
<td>Ideal RFID (Passive + WiFi)</td>
<td>24,118</td>
<td>0</td>
<td>184.2</td>
<td>0.7</td>
<td>133.6</td>
</tr>
</tbody>
</table>

Table 1 – The simulation results: comparison of different RFID systems
Another dimension that we checked is the physical layout of the ED. From the simulation, we found that orthopedic physicians are walking about 2 kilometers per shift, between the walking-patients area and the acute area (most times, there is just one orthopedic physician available for both locations. A second one would join from the orthopedic ward, when needed). Further investigation revealed that the distance between the two locations was excessive (about 100 meters) and the hospital managers took it into account in a redesigned ED. (See also Section 7.4 of the main paper where the issue of excessive walking distances is discussed.) With the distance being that long, both WiFi and Passive systems identified (and could quantify) this problem easily. (WiFi, however, is less appropriate for measuring short-distance movements.)

Considering all three aspects (clinical, economical, operational), which RFID solution should the manager implement? In our case, Passive RFID technology seems to be a reasonable option: it does not increase overall ALOS and prevents significant number of customers from abandonment. In addition, it is much less expensive than the WiFi implementation. However, in general, there is no clear-cut answer to this question. A decision-maker should take into account simulation results (especially ALOS, bed utilization and LWBS), implementation costs of different solutions, revenue from abandonment blocking, hospital preferences etc. In the ideal case, the cost/revenue optimization problem should be solved. However, it is not always easy to quantify financial impact of ALOS decrease or increase, often the impact depends on the staffing-level changes that can be implemented due to the change in the workload. Our simulation model can help to answer such sort of questions.

2.5 Integration with decision-support system: RFID-based control views

The contribution of an RFID system to a hospital's environment should encompass two main aspects. First, RFID should have impact on daily routine and hospital staff; second, long-term impact for strategic planning is desirable. Both aspects are implemented in the Decision Support System, introduced in Section 1. The system was designed on an IBM Cognos BI.

Examples of interfaces with the processes in Section 2.3 will be now demonstrated. Online View in Figure 4 supports real-time decisions by hospital staff and executives depicting detailed events of hospital processes. These events contain information about specific patients, staff and services provided by the hospital. For our demonstration, we used our main discrete-event simulator. Figure 4a demonstrates how such an “online view” alerts on extreme waiting times of patients after CT services (the first process discussed in Section 2.3). Figure 4b shows how a deci-
sion-maker is alerted on the presence of patients who attempt to abandon the ED (the second process discussed in Section 2.3), together with details of the process they have undergone until their abandonment attempt.

![Figure 4](image)

**Figure 4.** Online view showing: a) patients waiting time for CT services b) patient abandonment

The second “Offline View” in Figure 5 should be used for supporting long term planning. Therefore, it shows high-level details, aggregated over a pre-specified horizon. This view is to be used for high-level understanding and analysis of hospital processes, for example staff workload, quality of service, impact of decision-making and planning etc. Figure 5a displays patterns of patients arrivals rate over hours of a day and along days of week. (The arrival rate is measured in the standard deviation units with respect to the historical mean of the corresponding day-of-week. For example, zero value corresponds to the historical daily mean.) It also highlights the magnitude of the gradient, thus pointing at the times of day when pattern-changes are the most significant. In such a view, we display averages over a year, which are to be used for planning and assessment of strategic and longer run tactical decisions. Figure 5b depicts workload on physicians at the hospital, through the analysis of patients waiting time for service – excessive waits could trigger an alert.

![Figure 5](image)

**Figure 5.** Offline view showing: a) Averaged patient arrival rate b) Averaged patient wait time for physician

**REFERENCES**


