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A model for quantifying the value of RFID-enabled equipment tracking in hospitals

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ABSTRACT

US hospitals spend millions of dollars on lost, misplaced and stolen equipment every year. Radio frequency identification (RFID) technology provides potential solutions to this problem. The nation's top healthcare providers installing RFID have demonstrated the benefits of RFID. However, most other providers have not followed suit due to the lack of models available to provide measurable steps in successful RFID installation and sustainability, and to predict legitimate returns on investment. To respond this need, we propose a Markov chain model that could quantify the benefits of RFID from reducing equipment shrinkage and staff time of searching for equipment and increasing equipment utilization in hospitals. Using the proposed Markov chain model, a sensitivity analysis is conducted to investigate the performance improvement by RFID-enabled equipment tracking in a hospital. Our results demonstrate that an RFID-enabled equipment tracking system could significantly increase equipment utilization. In addition, the proposed model may be used to evaluate the equipment preparation and maintenance policies in hospitals with RFID, and could be easily extended to quantifying the benefits of RFID tracking systems in other industries.

1. Introduction

Effectively and efficiently monitoring and controlling the operations of the entities in a hospital, although difficult, is vital to patient care [1,2]. The slightest mistake could mean the difference between life and death and, often, lead to vast increases in healthcare costs. Due to the rise in patient awareness and tighter requirements from accreditation and compliance agencies such as the Joint Commission on Accreditation of Healthcare Organizations (JCAHO) and the Food and Drug Administration (FDA), hospitals are facing pressure to create equipment visibility [2,3]. The push for system visibility and assessment has centered the latest buzz in hospital information systems on radio frequency identification (RFID) [4–7].

The nation's top healthcare providers have implemented RFID systems for tracking people, assets, and information [5,7,8]. The top five RFID applications in hospitals are asset (equipment) tracking and management, staff tracking/monitoring, patient tracking/monitoring, patient and staff safety, and pharmacy prescription fill [5]. System visibility provided by RFID allows hospitals to improve patient care, reduce costs, and increase safety [4,7,9–11]. Although these healthcare institutions developed internal methods of evaluating RFID programs, estimated returns on investment and shared their experience of implementing RFID systems [8–10], there exist few models that provide measurable steps in successful RFID installation and sustainability and/or predict legitimate returns on investment. As a result, in many cases, mandates or market pressures have coerced hospitals towards integration without insights to the long-term implications of RFID [2,12].

In consideration of the barriers involved in the analysis of RFID benefits, we introduce a Markov chain model that can quantify the benefits of RFID-enabled equipment tracking in hospitals. The following section provides a literature review on hospital best practices in equipment tracking and the benefits of equipment traceability. In Section 3, we propose a Markov chain model capturing the status change of one piece of hospital equipment. In Section 4, we discuss and demonstrate how to use the proposed Markov chain model to quantify the benefits of RFID-enabled equipment tracking in hospitals. After that, a sensitivity analysis is conducted to compare the system performance with or without RFID in Section 5. Finally, conclusions are drawn in Section 6.

2. Literature review

Hospitals are some of the most complex networks of information, people and materials. Tracking equipment, suppliers and people remains a major challenge in hospital operations [1,6,11]. For the average hospital administrators, these complexities are clearly obvious [1]. RFID provides potential solutions to this challenge because, unlike bar codes which are read only in a line of sight, RFID can remotely identify and track tagged objects as they move around a hospital [2,4,5]. In this section, we review RFID

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applications in hospital equipment tracking and discuss the benefits of RFID-enabled equipment tracking in hospitals.

2.1. RFID technology for hospital equipment tracking

RFID is an automatic identification method that stores and can remotely retrieve data. There are two primary types of RFID tracking systems: active RFID tracking and passive RFID tracking [6,7,9,13]. An active RFID tracking system includes active RFID tags and readers, while a passive RFID tracking system including passive RFID tags and readers [13]. Active RFID tags use energy from an internal power source to constantly transmit radio signals, which are received by active RFID readers within a few hundred feet and then relayed to a computer system [7,9]. Therefore, compared to passive RFID tags, active RFID tags are much bigger and more expensive, and have longer range in which their radio signals could be picked up [7,9]. An active RFID tag costs between $10 and $200 [10], and typically has a range from 100 feet to 300 feet [7]. Thus, an active RFID tracking system is an appropriate solution for tracking patients or large and expensive equipment [5,7,9].

Passive RFID tags do not have any internal power source. They use the energy emitted from a passive RFID reader to transmit radio signals back to the reader upon command [7,9,13]. As a result, passive RFID tags are smaller and cheaper, and have limited detectable range [7,9]. A passive RFID tag costs between $0.5 and $1 [10,13], and has a range less than three feet [4]. Thus, passive RFID tracking systems are suitable for access control, theft prevention and inventory tracking of small, inexpensive items [7,9].

2.2. RFID applications in hospital equipment tracking

Effective equipment management in hospitals is critical to deliver high quality care as well as reducing healthcare cost. However, US hospitals spend hundreds of thousands of dollars on lost, misplaced and stolen equipment [2]. For example, Bon Secours Health System in Virginia was losing about 10% of equipment inventory annually prior to RFID installation, and Jackson Memorial Hospital in Florida reported an astonishing $4 million in lost equipment [5]. It is estimated that US hospitals lose 5–15% of their equipment inventory annually, which costs hospitals about $4000 per bed [5,7]. Meanwhile, hunting for equipment wastes nurses' time and diverts their focus away from patient care. For example, nursing staff in Bon Secours Health System spent 25–33% of their time searching for equipment prior to RFID installation [5].

Recently, RFID technology has begun to be used to track and identify people, equipment and products in manufacturing, retail, construction, and health care sectors [2,5,14,15]. In healthcare, equipment tracking in hospitals is one of the most popular applications of RFID. For example, three hospitals in Bon Secours Health System installed active RFID systems to track about 12,000 pieces of mobile equipment [2,5,6]. The RFID equipment tracking system eliminated some shrinkage by sending alarms to hospital security when a piece of equipment is moved beyond its boundary [5]. It is a conservative estimate that Bon Secour could save at least $203,000 in the first year due to less shrinkage, fewer rentals and deferral of new purchases [5]. In addition, the RFID equipment tracking system saved nurses 30 min per shift by eliminating equipment searches [6].

Another example is an active RFID system installed in the Wayne Memorial Hospital in North Carolina. The system tracks about 1300 medical devices housing specially designed active RFID tags, which could transmit the current status of medical devices (in use, needs cleaning or ready for use) to a reader [16]. In the first few months, the RFID tracking system saved the hospital about $303,000 by improving its infusion pump utilization [16]. In addition, the tracking system reduced patient waiting time between services because when a service is done, it takes less time now to get medical devices ready for next service. This significantly improved patient satisfaction [16].

2.3. Benefits from RFID-enabled equipment tracking in hospitals

In the literature, many benefits from RFID-enabled hospital equipment tracking are reported and discussed. These benefits can be classified into three groups. Firstly, RFID-enabled hospital equipment tracking reduces equipment losses and improves asset management in hospitals. RFID-enabled inventory systems can reduce equipment shrinkage by remotely tracking equipment, and also permit accurate inventory replenishment and consumer invoicing. For example, with an RFID tracking system, Advocate Good Shepard Hospital in Illinois cut inventory losses by 50% [5]. The Carolina Medical Center showed that iRISupply, an RFID-enabled asset management system, produced a savings of nearly $65,000 annually due to more accurate billing processes [17].

Second, RFID-enabled equipment tracking systems can improve equipment utilization and staff productivity by ensuring the availability of equipment when needed and reducing the time staff spends in locating equipment and managing inventory [5,9]. For an instance, the RFID tracking system installed in the Wayne Memorial Hospital improved its infusion pump utilization by 20% in the first few months [16].

Third and more vital, such tracking systems can reduce medical errors and improve patient care because locating equipment may disrupt medical processes [7]. RFID-enabled equipment tracking systems ensure the availability of medical equipment at the place when needed, which prevents nursing staff from diverting their time and focus away from patient care [1,7,9]. Although one study conducted in the Netherlands reports significant incidents of electromagnetic interference (EMI) by high-frequency RFID on medical equipment in a non-clinical setting [18], a clinical study in the United States demonstrates that EMI from real-life high-frequency RFID systems does not disrupt medical equipment such as blood pressure monitors, infusion pumps, and EKG monitors [19,20].

Previous studies of high performance hospitals have presented RFID applications in hospital asset tracking and management as low-risk, high-reward projects that healthcare organizations select for starting RFID programs [2,5,6]. Although vast benefits of RFID in hospital equipment tracking are promised by experts or demonstrated by pioneer hospitals, measurable steps in successful RFID installation and sustainability and credible return-on-investment models are rarely provided in literature. Meanwhile, no quantitative return-on-investment models for RFID applications in healthcare exist in the literature [2].

2.4. Quantifying the benefits of RFID applications

RFID-related research has focused in the information system and supply chain management areas. Vast conceptual models and a few analytical models for RFID applications have been proposed in the two areas (see reviews by Angeles [14], Lee and Özer [12], and Dutta et al. [21]). There are two ways to quantify the benefits of RFID applications. One way is to conduct pilot studies and then infer the value from observing the results in these pilot studies. For example, time and motion studies are used to estimate the labor cost savings in early RFID applications at manufacturers, warehouses, and retailer stores [8,21,22].

The other way is to model the influence of RFID applications on the fundamental operations in a system, and then analyze the changes in the system performance by using these models to enhance planning and operational decisions. Lee and Özer investigate the values of visibility provided by RFID by considering misplacement, shrinkage, and transaction errors in periodical or continuous review inventory systems without RFID [12]. Comparing the lower and upper bound models for the systems with and without RFID yields a maximum value and a minimum value for RFID [12]. Ustundag and Tanyas develop a simulation model to determine the expected benefits of an integrated RFID system on a three-echelon supply chain [23]. The benefit of RFID is evaluated in terms of the changes of labor cost, inventory holding cost, ordering cost, and lost sales by implementing an integrated RFID system [23]. These two studies quantify the value of RFID at supply chain level. Meanwhile, a few studies propose probability models to quantify the value of RFID at operations level [24,25]. Using probability models, Gaukler and Hausman quantify the process saving and rework saving of an RFID implementation in automotive assembly operations [24] and Hsu et al. evaluate the reductions of inventory cost and labor cost in an RFID application in import cargo customs clearance process [25]. In this paper, we propose a Markov chain model for quantifying the value of RFID in hospital equipment tracking, which estimates the benefits of RFID at item level.

3. Markov chain model

In this study, a Markov chain model is developed to capture the status changes of one piece of equipment in a hospital. Before defining our system and how equipment may transition among different states, we first briefly introduce Markov chain models.

3.1. Markov chain [26]

A Markov chain is a stochastic process $\{X_n, n = 0, 1, 2, \ldots\}$ that takes on a finite or countable number of possible values and may transition from one possible value into another possible value only depending on the present value. Usually, the set of possible values of a Markov chain is denoted by a set of positive integers $\{1, 2, 3, \ldots\}$. If $X_n = i$, then the process is said to be in state i at time n. Since a Markov chain is a memoryless stochastic process, the probability of a Markov chain proceeding into state j depends only on the present state. Thus, the probability of transitioning from state i into state j in one step, denoted by P_{ij}, is defined as $P_{ij} = P\{X_{n+1} = j | X_n = i\}$. The probabilities P_{ij} for $i = 1, 2, \ldots$ and $j = 1, 2, \ldots$ are also called one-step transition probabilities. Since the process must transition into some state, we have $\sum_{j=1}^{\infty} P_{ij} = 1$. Let a matrix

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} & \cdots \\ P_{21} & P_{22} & P_{23} & \cdots \\ \vdots & \vdots & \vdots & \\ P_{i1} & P_{i2} & P_{i3} & \cdots \\ \vdots & \vdots & \vdots & \end{bmatrix} \quad (1)$$

denote the one-step transition matrix of a Markov chain.

3.2. Assumptions

Since active RFID tracking systems are appropriate and commonly used to track equipment in hospitals [5,9,10], we consider relatively expensive equipment, such as beds, infusion pumps, defibrillators, and sequential compression devices (SCDs), because these types of equipment are essential to hospital operations, and large enough to house active RFID tags. Since most hospital equipment needs cleaning, sanitizing, or changing parts between two uses [4,7,27], it is assumed that each piece of equipment needs to be prepared after each use. Depending on the type of equipment, each piece may be prepared onsite immediately after use (such as cleaning and changing parts), or pooled before preparation (e.g. sanitizing and packaging).

Additionally, we assume that there is a limited supply of one equipment type and a critical stock level. Thus, if a piece of equipment is lost for a certain time period (denoted τ_2), that piece of equipment is considered out of system and must be replaced immediately. It is also assumed that if lost equipment is found in a short-time period (denoted by τ_1), it is still in usable condition, but if lost equipment is found beyond time period τ_1, it needs maintenance before used for patient care. Fig. 1 depicts this equipment lost-found-replacement policy.

In a hospital, most patients are admitted from the Emergency Department, while some patients are admitted due to elective surgeries or scheduled treatments [28]. Since the arrival of unscheduled patients is a Poisson process [29,30], we assume that the arrival of demand for one piece of equipment is also a Poisson process. Meanwhile, since the length of stay in each type of care units could be approximated by an exponential distribution [29,30], it is assumed that the time of equipment being in use is exponentially distributed. In addition, the times of equipment being in preparation and in maintenance are approximated by exponential distributions, too. Thus, the transactions among the states of one piece of hospital equipment could be captured using a Markov chain model.

3.3. Markov chain model for equipment tracking

The life span of one piece of equipment is divided into finite time intervals according to the scanning interval of an active RFID tracking system. Thus, a Markov chain could model equipment state transitions between tracking system updates. To evaluate the utilization of one type of equipment, four equipment states are considered: idle state, in-use state, in-preparation state, and maintenance state. To investigate the time spent on searching equipment and the probability that a piece of equipment is lost, we consider three more equipment states in the Markov chain model: in-search state, lost state, and out-of-system state. Table 1 describes the seven equipment states in the Markov chain model and Fig. 2 illustrates the possible transitions between the seven states.

Next, we derive the one-step transition matrix for the Markov chain model. For a processing state i, such as in use (state 2), in preparation (state 3), or maintenance (state 5), we denote T_i as the exponentially distributed time spent in state i. Therefore, since the time interval is much shorter than $E(T_i)$, the probability of staying in state i is approximated by $1 - 1/E(T_i)$, and the probability of transitioning from state i to other states is approximated by $1/E(T_i)$, where $E(T_i)$ denotes the expected time spent in state i. $E(T_i)$ is also referred to as the process duration of state i, which could be estimated based on data or hospital staff experience. We define β_{ij} as the proportion of transitions from state i immediately to state j. If the equipment state could not transition from state i directly to state j, then $\beta_{ij} = 0$. If the equipment state could transition from state i only to state j, then $\beta_{ij} = 1$. Thus, for a state i with a given expected service time, the probabilities of transitioning from state i to other states in one step can be determined by

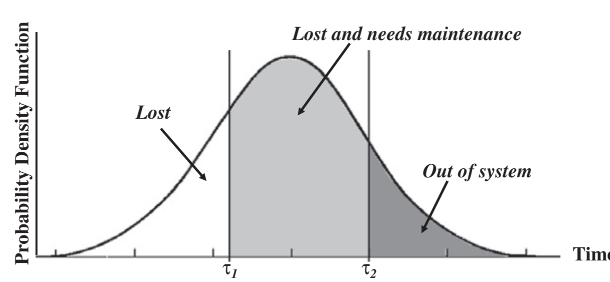

Fig. 1. Equipment lost-found-replacement policy.

Table 1
Definitions of seven equipment states.

Index	State name	Description of state
1	Idle	State of equipment with a known location while being unoccupied
2	In use	When equipment is in service for patients
3	In preparation	When equipment is being serviced for its next use, such as cleaning
4	In search	When equipment is in demand but has an unknown location
5	Maintenance	When equipment has been declared as broken or requires preventative maintenance
6	Lost	When equipment is not located upon searching
7	Out of system	When equipment no longer belongs to the associated ward or hospital

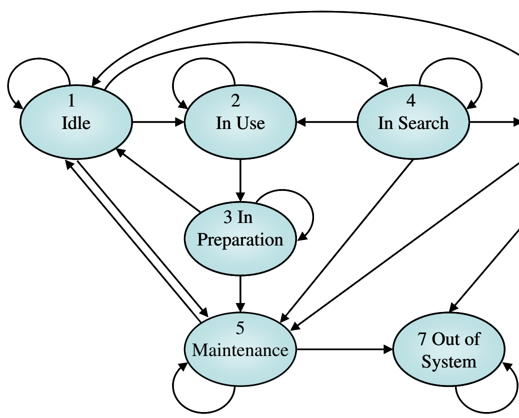

Fig. 2. Transition diagram of equipment states.

$$P_{ij} = \begin{cases} 1 - \frac{1}{E(T_i)}, & \text{for } j = i \text{ and } i = 2,3,5 \\ \frac{\beta_{ij}}{E(T_i)}, & \text{for } j \neq i \text{ and } i = 2,3,5 \end{cases}, \tag{2}$$

where $\sum_{j\neq i}\beta_{ij} = 1$ for $i = 2$, 3, and 5.

For the idle state, the probabilities of transitioning from it to in-use state and maintenance state are approximated by the demand arrival rate for using equipment (denoted by λ_2), and the maintenance frequency for equipment (denoted by λ_5), respectively. When a piece of equipment is needed for patient care or maintenance, sometimes hospital staff does not know its location and has to search for it. Let β_1 denote the probability that a piece of equipment has to be searched when a request for use or maintenance arrives. Thus, the probabilities of transitioning from the idle state to other states in one step can be estimated by

$$P_{1j} = \begin{cases} 1 - P_{12} - P_{14} - P_{15}, & \text{for } j = 1 \\ (1-\beta_1)\lambda_2, & \text{for } j = 2 \\ \beta_1(\lambda_2 + \lambda_5), & \text{for } j = 4 \\ (1-\beta_1)\lambda_5, & \text{for } j = 5 \\ 0, & \text{otherwise} \end{cases}. \tag{3}$$

When a piece of equipment is in search (state 4), the time to find it (denoted by T_4) and the time to quit searching (denoted by T'_4) are random. If T_4 is greater than T'_4, then the equipment is found; otherwise, the equipment is declared lost. Thus, the probabilities of transitioning from the in-search state to other states in one step can be estimated by

$$P_{4j} = \begin{cases} 1 - P_{42} - P_{45} - P_{46}, & \text{for } j = 4 \\ \frac{\lambda_2}{(\lambda_2+\lambda_5)E(T_4)}, & \text{for } j = 2 \\ \frac{\lambda_5}{(\lambda_2+\lambda_5)E(T_4)}, & \text{for } j = 5 \\ \frac{1}{E(T'_4)}, & \text{for } j = 6 \\ 0, & \text{otherwise} \end{cases}, \tag{4}$$

where $E(T_4)$ and $E(T'_4)$ are the expectations of T_4 and T'_4, respectively.

When a piece of equipment is in lost state, it may be found later. Let T_6 denote the random time period in which lost equipment is found. According to our equipment lost-found-replacement policy, if T_6 is longer than τ_2, then equipment state transitions from the lost state to the out-of-system state. If T_6 is shorter than τ_1, then equipment state transitions from the lost state to the idle state. If T_6 is between τ_1 and τ_2, then equipment state transitions from the lost state to the maintenance state. Thus, the probabilities of transitioning from the lost state to other states in one step can be estimated by

$$P_{6j} = \begin{cases} 1 - \frac{1}{E(T_6)}, & \text{for } j = 6 \\ \frac{P\{T_6 \leqslant \tau_1\}}{E(T_6)}, & \text{for } j = 1 \\ \frac{P\{T_6 \leqslant \tau_2\} - P\{T_6 \leqslant \tau_1\}}{E(T_6)}, & \text{for } j = 5 \\ \frac{1 - P\{T_6 \leqslant \tau_2\}}{E(T_6)}, & \text{for } j = 7 \\ 0, & \text{otherwise} \end{cases}. \tag{5}$$

4. Performance measure to quantifying the value of equipment traceability

According to the literature, an RFID-enabled equipment tracking system could reduce equipment losses and the time nurses spend searching for equipment, and could improve equipment utilization. The average time of a piece of equipment being lost could indicate the cost caused by the loss of service due to the loss of equipment. When a piece of equipment is lost for a certain time period, a new piece will be ordered or rented to replace it. The cost to purchase or rent a new piece of equipment could be estimated based on the average number of replacements for a piece of equipment over its normal life span. Meanwhile, the average time of a piece of equipment being in search reflects the time nurses spend in searching for equipment, while the average time of a piece of equipment being in use indicating equipment utilization. Therefore, in this study, we evaluate the value of equipment traceability in terms of the average number of replacements and the average times of a piece of equipment being in use, in search, and lost over its life span.

Using the proposed Markov chain model, we could determine the probabilities that a piece of equipment stays in each state in each time interval, and further estimate the average time of the equipment in each state. Let vector $\boldsymbol{\pi}(n)$ denote the probabilities of staying in each state in time interval n, where the ith entity, $\pi_i(n)$, represents the probability of staying in state i in time interval n. Since a piece of equipment always starts from the idle state, the probabilities of staying in each state in time interval 0 are $\boldsymbol{\pi}(0) = [1\,0\,0\,0\,0\,0\,0]$. Then the probabilities of staying in each state in time interval n can be determined by

$$\boldsymbol{\pi}(n) = \boldsymbol{\pi}(n-1)\mathbf{P}. \tag{6}$$

Thus, if the life span of a piece of equipment (denoted by T_L) is divided into N time intervals and the length of each time interval is

τ, we can estimate the expected time of the equipment in state i (denoted by q_i) by

$$q_i = \sum_{n=1}^{N} \pi_i(n)\tau. \tag{7}$$

Additionally, the expected number of replacements (denoted by K) can be captured by

$$K = \sum_{n=1}^{N} \frac{T_L}{n\tau}[\pi_7(n) - \pi_7(n-1)] = \sum_{n=1}^{N} \frac{N}{n}[\pi_7(n) - \pi_7(n-1)]. \tag{8}$$

Next, using the proposed Markov chain model, we demonstrate how to determine the utilization of an external defibrillator in a hospital without RFID. Defibrillators are electrical impulse generators that serve as the vital apparatus in treating cardiac arrhythmias, abnormal electrical activity in the heart. There are several forms of defibrillators. In the demonstration example and the performance comparison scenarios in the next section, we consider automated external defibrillators (AEDs) because AEDs are mobile, critical to patient care, and relatively expensive. An AED kit costs between \$1500 and \$2000, has a suggested life of 5 years, and may require maintenance after 2 years of use [31]. Therefore, in the demonstration example, the time horizon for the Markov chain model is 5 years, which is divided into 15,768,000 time intervals of 10 s each (i.e. N = 15,768,000 and τ = 10 s) based on the fact that the scanning interval of the active RFID tracking system is usually 10 s.

In the demonstration example, it is assumed that the daily patient demand for one defibrillator (λ_2) is 12 patients per day, and the average time of a defibrillator serves one patient ($E(T_2)$) is 10 min. Without RFID-enabled equipment tracking, we assume that the probability of searching for equipment (β_1) is 5%, the average searching time ($E(T_4)$) is 30 min, the average time until inquired equipment is declared lost ($E(T'_4)$) is 1 day, and the period to review inventory ($E(T_6)$) is 6 months. A decentralized preparation policy is considered in the example and the average time of a defibrillator waiting for preparation and in preparation ($E(T_3)$) is 15 min under the decentralized policy. The average time for a major maintenance ($E(T_5)$) is 7 days, which is estimated as needing 6 total days of shipping and 1 day repairing. In addition, in the demonstration example, the probability that equipment was found beyond repair (β_{57}) is based on the expected time until failure (3.5 years), a lost piece of equipment needs maintenance if it has been lost for longer than 1 month, and a lost piece of equipment is replaced by a new piece if it has been lost for longer than 12 months. Thus, in the demonstration example, $E(T_2) = 60\tau$, $E(T_3) = 90\tau$, $E(T_4) = 180\tau$, $E(T'_4) = 8640\tau$, $E(T_5) = 60{,}480\tau$, $E(T_6) = 1576{,}800\tau$, $\lambda_2 = 0.001389$ per time interval, $\lambda_5 = 1.5855 \times 10^{-7}$ per time interval, $\tau_1 = 262{,}800\tau$, $\tau_2 = 3153{,}600\tau$, and $\beta_1 = 0.05$. The transition diagram in Fig. 2 illustrates $\beta_{23} = 1$, $\beta_{31} + \beta_{35} = 1$, and $\beta_{51} + \beta_{57} = 1$. Since an AED needs maintenance after 2 years of use and its expected time until failure is 3.5 years, $\beta_{35} = 1.5855 \times 10^{-7}$ and $\beta_{57} = 9.0599 \times 10^{-8}$. Substituting these values into Eqs. (2)–(5), we obtain the one-step transition matrix

$$P = \begin{bmatrix} 0.99861 & 0.001319 & 0 & 6.945\times10^{-5} & 1.506\times10^{-7} & 0 & 0 \\ 0 & 0.98333 & 0.01667 & 0 & 0 & 0 & 0 \\ 0.01111 & 0 & 0.98888 & 0 & 1.762\times10^{-9} & 0 & 0 \\ 0 & 0.005555 & 0 & 0.9943 & 6.341\times10^{-7} & 1.1574\times10^{-4} & 0 \\ 1.653\times10^{-5} & 0 & 0 & 0 & 0.99998 & 0 & 1.498\times10^{-12} \\ 9.736\times10^{-8} & 0 & 0 & 0 & 4.510\times10^{-7} & 0.999999 & 8.583\times10^{-8} \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}. \tag{9}$$

Substituting the one-step transition matrix in Eq. (9) and $\boldsymbol{\pi}(0)$ = [1 0 0 0 0 0 0] into Eqs. (6)–(8), we can obtain the estimates to the expected time of an AED in each state and the expected number of replacements over its life span of 5 years. In this example, over a life span of 5 years, the expected times of an AED in idle, in use, in preparation, and in search are 374.83 days, 31.2 days, 46.81 days, and 4.59 days, respectively, and the expected number of replacements is 2.88.

5. Performance comparison

In the previous sections, we present a Markov chain model capturing the status of one piece of hospital equipment, and propose the metrics to compare the performances of systems with or without RFID-enabled equipment tracking. We also provide an example to demonstrate how to estimate the utilization of an automated external defibrillator (AED) using the proposed Markov chain model. In this section, using an AED as example, we compare the item-level performances of hospitals with or without an RFID-enabled tracking system. The performances of systems with or without RFID-enabled equipment tracking are compared in terms of the average number of replacements and the average times of an AED being in use, in search, and lost over its suggested life span of 5 years.

5.1. Experimental design

Operation characteristics and asset management policies vary among hospitals. To examine the impact of RFID tracking in a variety of hospital settings, we compare the performances of 48 scenarios with RFID to those of 384 scenarios without RFID. In those scenarios, we consider three groups of varying factors: (1) patient demand and service rate; (2) searching efficiency; and (3) preparation and maintenance policies. More scenarios without RFID are considered because the scenarios without RFID involve three more factors: the average time until lost equipment is found; the time until lost equipment needs maintenance; and the average time until inquired equipment is declared lost.

Daily patient demand for one defibrillator depends on hospital size, patient population, and inventory policy for defibrillators, which vary very much among hospitals. To investigate the impact of patient demand on the performance improvement by RFID-enabled equipment tracking, we examine daily patient demand for one defibrillator at three widespread levels: 2 patients per day; 12 patients per day; and 24 patients per day. With regard to patient service rate, the American Heart Association (AHA) suggests that most efficient use of defibrillators lasts for 3 min [32]. As a conservative estimate, a defibrillator may be pulled for preparation for its next use after 10 min of use with a patient. Accounting for possible delay, a longer average time of a defibrillator serves one patient, 30 min, is examined in the scenarios with and without RFID.

Searching occurs in hospitals with or without RFID-enabled equipment tracking because even with an RFID tracking system, staff members sometimes still need to locate available defibrillators through a computer system and walk to other place to retrieve one. However, according to the literature [5,7,11], the average searching time dramatically decreases with the installation of an RFID-enabled equipment tracking system. Therefore, we examine two levels of searching duration, 15 and 30 min, in the scenarios with RFID, and two levels of 30 and 90 min in the scenarios without RFID. In regards to the probability of searching for equipment, we assume that staff will not search for equipment unless there is an immediate demand (or a periodic review policy, later discussed). This rate of searching (β_1) is considered an operational inefficiency of 5–10%.

In a hospital without RFID equipment tracking, staff may eventually discontinue an equipment search and use the next available piece of equipment. Therefore, we test the impact of the average time until inquired equipment is declared lost at two levels: 1 day and 5 days. In addition, for a system without RFID, administrators may require a periodic inventory review policy during which lost equipment may be found. Thus, two review periods, every 6 months and every year, are considered in the scenarios without RFID. In a hospital with RFID, it is assumed that a defibrillator will be found after a short-time search.

For preparation policies, we assume that preparation occurs after each defibrillator use. We examine two preparation policies: centralized and decentralized. For the centralized policy, equipment waiting time for preparation, which is included in the preparation duration, is longer on average and has a higher variation because of equipment traveling between preparation and use/storage locations and a possibility of batch processing. In decentralized instances, equipment is prepared onsite, which minimizes equipment travel distance between preparation and use/storage locations and reduces equipment waiting time for preparation. Thus, we assume that the average time of a defibrillator in-preparation state is 30 min under a centralized policy and 15 min under the decentralized policy according to the AHA guideline that preparing a defibrillator should not require more than 30 min to complete without complications [32].

For maintenance policies, we assume that a major maintenance is required every 2 years, and takes 7 days on average. The probability that equipment was found beyond repair is based on the expected time until failure (3.5 years – the mean of a 2–5 year lifespan). In the scenarios without RFID, lost equipment may deteriorate over a long time period and may miss scheduled/preventative maintenance procedures. In the maintenance policy for lost equipment, we assume that a lost piece of equipment is sent to maintenance if it has been lost for longer than 1 or 3 months. All factors and their levels considered in the performance comparison scenarios are summarized in Table 2.

5.2. Performance comparison of systems with and without RFID-enabled tracking

To examine the performance improvement from adopting an RFID-enabled equipment tracking system, we compare the performance of 48 scenarios with RFID to 384 scenarios without RFID in terms of the average number of replacements and the average times of a defibrillator being in use, in search, and lost over a life span of 5 years, which are summarized in Table 3. The results in the table demonstrate that in a system with RFID, a defibrillator is almost never lost or replaced over its life span. On the other hand, in systems without RFID, on average, a defibrillator is lost for about 650 days and is replaced more than three times over 5 years. As for equipment utilization, the average time of a defibrillator being in use for the scenarios with RFID is three times longer than that for the scenarios without RFID. However, the average time of a defibrillator being in search for the scenarios with RFID is much higher than that for the scenarios without RFID. This observation is different from the benefit reported in the literature that an RFID-enabled equipment tracking system could reduce the time nurses spend in searching for equipment.

To investigate this observation, we compare the performance of four scenarios with RFID to four corresponding scenarios without RFID. The results in Table 4 support the same conclusion that RFID-enabled equipment tracking systems significantly improve the utilization of a defibrillator and lengthen the accurate life of a defibrillator. By comparing the performance metrics in the four pairs of scenarios with RFID versus without RFID, it can be noted that RFID-enabled equipment tracking systems increase the

Table 2
Factor levels for sensitivity analysis.

Factor group	Factor	Factor level	
		Scenarios with RFID	Scenarios without RFID
Patient demand and service	Daily patient demand, λ_2	2, 12, 24 patients	2, 12, 24 patients
	Average duration of patient service, $E(T_2)$	10 and 30 min	10 and 30 min
Searching efficiency	Average duration of search, $E(T_4)$	15 and 30 min	30 and 90 min
	Probability of search upon demand, β_1	5% and 10%	5% and 10%
	Average time until inquired equipment is declared lost, $E(T'_4)$		1 and 5 days
	Average time until lost equipment is found, $E(T_6)$		6 months and 1 year
Preparation and maintenance policies	Average time equipment spends in preparation, $E(T_3)$	15 and 30 min	15 and 30 min
	Time until lost equipment needs maintenance, τ_1		1 and 3 months

Table 3
Average performance of systems with and without RFID.

	Average time in each state (in days)						Number of replacements	
	In use		In search		Lost			
	With RFID	Without RFID	With RFID	Without RFID	With RFID	Without RFID	With RFID	Without RFID
Average	199.6	45.4	17.5	7.7	0	651.2	0	3.16
First quartile	70.4	14.4	6.1	2.6	0	526.9	0	1.72
Third quartile	306.7	54.6	25.9	10.9	0	803.5	0	4.31
Min	23.7	2.8	1.7	1.6	0	103.1	0	0.25
Max	514.9	285.2	61.8	25.5	0	963.0	0	7.98

Table 4
Performance comparison in four pairs of scenarios with and without RFID.

Scenario*	Average time in each state (in days)						Number of replacements	
	In use		In search		Lost			
	With RFID	Without RFID	With RFID	Without RFID	With RFID	Without RFID	With RFID	Without RFID
1	123.6	78.7	18.5	11.8	0	391.7	0	1.08
2	326.6	217.6	16.3	10.8	0	360.6	0	0.98
3	209.6	105.4	31.4	15.7	0	528.7	0	1.58
4	511.3	284.5	25.6	14.2	0	474.3	0	1.37

* In Scenario 1, $\lambda_2 = 12$ patients per day and $E(T_2) = 10$ min. In Scenario 2, $\lambda_2 = 24$ patients per day, and $E(T_2) = 10$ min. In Scenario 3, $\lambda_2 = 12$ patients per day and $E(T_2) = 30$ min. In Scenario 4, $\lambda_2 = 24$ patients per day and $E(T_2) = 30$ min. For all four scenarios, $E(T_3) = 15$ min, $E(T_4) = 30$ min, $E(T_4') = 5$ days, $E(T_6) = 0.5$ year, $\beta_1 = 5\%$, and $\tau_1 = 1$ month.

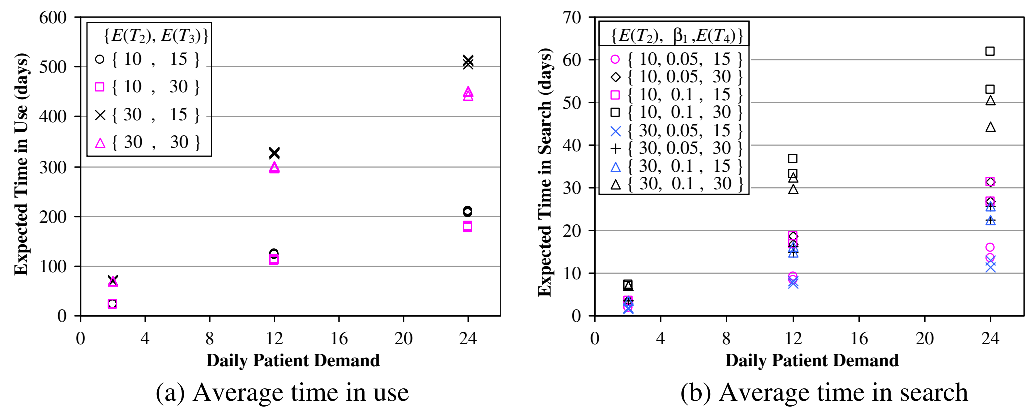

Fig. 3. Average times of equipment being in use and in search for systems with RFID. (a) Average time in use. (b) Average time in search.

average time of a defibrillator being in use by 50–100%. In addition, the results in Table 4 reveal that RFID-enabled equipment tracking systems do not affect the ratio of the average time of a defibrillator being in search to the average time of a defibrillator being in use. Therefore, to reduce the time nurses spend in searching for equipment, a hospital needs to reduce the average duration of each search and the probability of searching for equipment by fully utilize RFID potentials.

5.3. Sensitivity analysis of system performance

Fig. 3 illustrates the average times of a defibrillator being in use and in search for the 48 scenarios with RFID. Fig. 3(a) shows that the average time of a defibrillator being in use over its life span of 5 years increases as daily patient demand increases and/or the average time of a patient's equipment use ($E(T_2)$) increases. That means that equipment utilization increases with the increases in patient demand and/or the average service time. The other three factors have much less impact on equipment utilization. Fig. 3(b) reveals that the average time of a defibrillator being in search over its life span of 5 years increases with the increases in daily patient demand, the average duration of each search ($E(T_4)$) and/or the probability of searching for equipment (β_1). The impact of the other two factors increases as daily patient demand increases.

To compare the performance of systems with and without RFID, Figs. 4 and 5 demonstrate the average times of a defibrillator being in use and in search for the 384 scenarios without RFID. Comparing Fig. 3(a) and Fig. 4 reveals that at each level of daily patient demand, the expected times of equipment being in use for the scenarios with RFID are longer than those for the scenarios without RFID. While equipment utilization in the scenarios with RFID mainly depends on patient demand and the average time of a patient's equipment use, equipment utilization in the scenarios without RFID are affected by more factors, especially when daily patient demand is at higher levels.

When comparing Fig. 3(b) and Fig. 5, it can be noted that at the low level of daily patient demand, the expected times of equipment being in search for the scenarios with RFID are within the same range of those for the scenarios without RFID. On the other hand, at the higher levels of daily patient demand, the expected times of equipment being in use for the scenarios with RFID are much longer than those for the scenarios without RFID, and the expected times of equipment being in search for the scenarios with RFID are longer than those for the scenarios without RFID.

6. Conclusions

In this paper, we propose a Markov chain model to quantify the benefits of RFID-enabled equipment tracking in a hospital. Using the proposed Markov chain model, the average number of replacements and the average times of a piece of equipment being in use, in search, and lost over a time period could be estimated before implementing RFID equipment tracking in a hospital. Using an external defibrillator (AED) as an example, we compare the item-level benefits from an RFID-enabled tracking system. The model could be used to estimate the benefits of tracking other types of equipment by RFID, too.

The average number of replacements for a piece of equipment over its normal life span could be used to estimate savings from reducing equipment shrinkage. The average time of a piece of equipment being in search reflects a saving of the increase in nursing staff productivity due to the elimination of equipment search, while the average time of a piece of equipment being in use indicating an increase in equipment utilization. In addition, the average time of a piece of equipment being lost implies a potential reduction in equipment inventory level. The summation of these

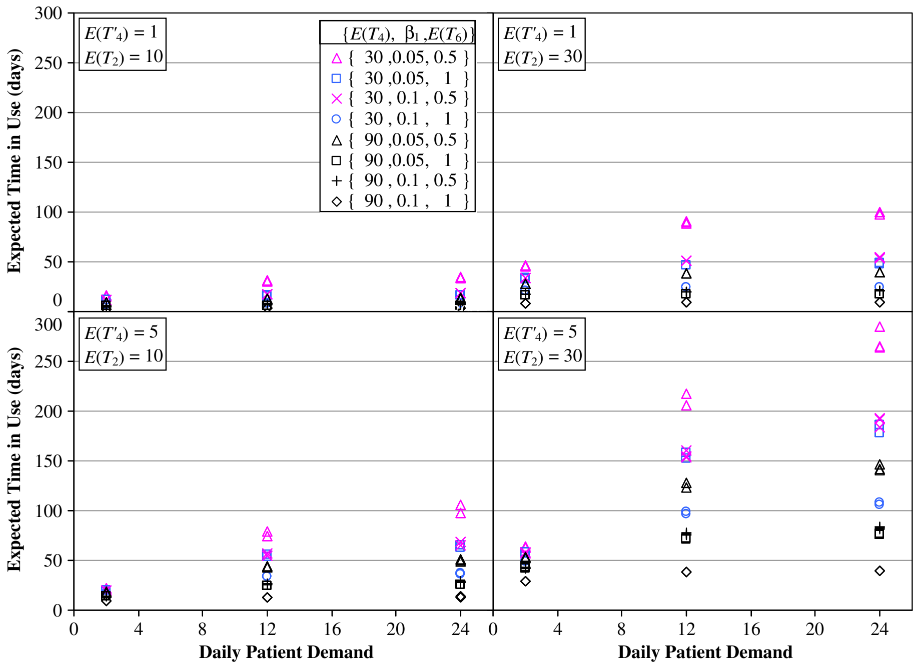

Fig. 4. Average time of equipment being in use for systems without RFID.

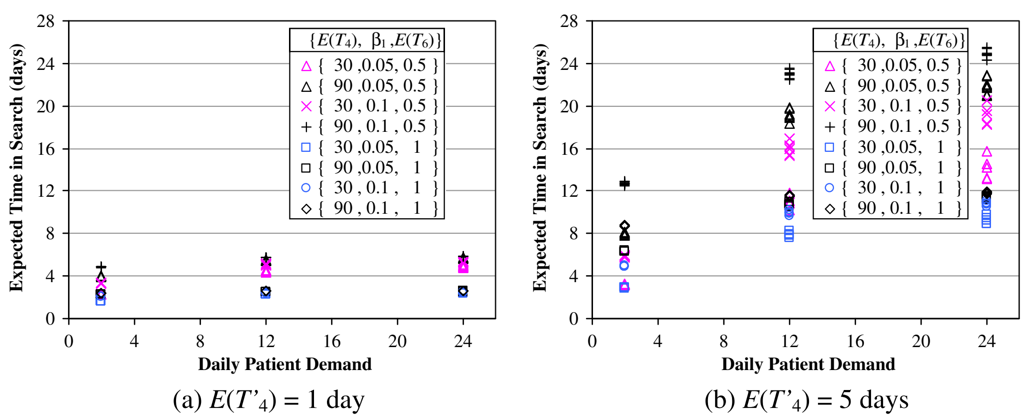

Fig. 5. Average time of equipment being in search for systems without RFID. (a) $E(T'_4)$ = 1 day. (b) $E(T'_4)$ = 5 days.

estimated savings is a conservative estimate of returns on investment because other benefits from RFID-enabled tracking, such as reducing medical errors and improving patient care, could not be captured by the proposed Markov chain model. The quantified benefits from the Markov chain model help hospitals to compare and choose RFID solutions and investment plans.

In addition, a sensitivity analysis is conducted to compare the performances of systems with or without RFID-enabled equipment tracking. The results demonstrate that an RFID-enabled equipment tracking system could significantly increase equipment utilization. The sensitivity analysis study reveals that the quantitative analysis tools are needed to predict the gains from RFID investments due to the variability in operations among hospitals.

This paper focuses on quantifying the benefits of RFID from reducing equipment shrinkage and increasing equipment utilization. However, the proposed model could be used to evaluate the equipment preparation and maintenance policies in hospitals with RFID equipment tracking. The model could be easily extended to quantifying the benefits of RFID tracking systems in other industries.

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