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Modelling and analysis of inventory management systems in healthcare: A review and reflections

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ABSTRACT

Inventory management in a healthcare system needs to be compatible with its operations and critical characteristics ensuring minimization of inventory-related cost as well as maximization of service level with a significant reduction in the price of treatment and wastage of resources. Over the years, numerous approaches and methodologies have been developed by the researchers and practitioners for modelling and analysis of varieties of inventory management systems in the healthcare sector considering these aspects. In this paper, the existing modelling approaches and solution methods concerning inventory systems in healthcare are classified and critically reviewed. An integrated research framework as applicable in the present context is presented as a direct consequence of the review of the literature with future research directions.

1. Introduction

Due to the rapid growth in healthcare expenditure worldwide and simultaneous growth of demand for healthcare services, developing efficient and effective healthcare systems has become an essential area of concern for governments and healthcare decision-makers (Ahmadi-Javid, Jalali, & Klassen, 2017). The core competency of a healthcare system reflects its ability to provide treatment and care to the patients. The prime focus has always been towards providing highly knowledgeable and experienced physicians, surgeons, well-trained nurses, and medical staffs with well-established infrastructure, advanced medical equipment, the right quality medicines, and medical and surgical supplies (De Vries, 2011). However, of late, the focus has driven towards the management side of the healthcare systems. Healthcare management systems include capacity planning, resource allocation, inventory management systems, demand forecasting, scheduling, and other operational activities (Brailsford & Vissers, 2011).

A significant part of the healthcare system is the hospital system. Hospital systems consist of multiple departments, such as pharmacy, operating rooms, emergency rooms, intensive care units, wards. These departments provide services like diagnosis, medication treatment, critical care, surgery, etc. to the patients. Each department has specific functions to carry out. For example, the pharmacy maintains the optimal stock of healthcare items to distribute to individual patients and various locations within a hospital system (Gebicki, Mooney, Chen (Gary), & Mazur, 2014; Maestre, Fernández, & Jurado, 2018). Emergency rooms try to minimize the time between prescribing and administering of life-saving medicines and other vital healthcare items (Duclos, 1993). Reducing the number of staff members leaving the room for supplies and maintaining schedules for medicine delivery are the main functions in the operating room and wards (Rappold, Roo, Martinelly, & Riane, 2011; Roni, Jin, & Eksioglu, 2015; Saedi, Kundakcioglu, & Henry, 2016). The overall performance of a hospital system is dependent on the performance of all the departments.

An important factor that affects the managerial and operational performance of healthcare systems, in general, and hospital systems, in particular, is the inventory management system. Inventory management refers to managing and controlling a large number and great variety of items stocked in a healthcare system (Gebicki et al., 2014; Nicholson, Vakharia, & Selcuk Erenguc, 2004). Essential healthcare items, directly or indirectly, are required in the patient healing process and its monitoring and control. Hence, inventory control systems are recommended to be aligned with the patient condition (Vila-Parrish, Ivy, King, & Abel, 2012). Technically and scientifically, the demand for healthcare items is closely linked to physician recommendations based on patient conditions (Abdulsalam, Gopalakrishnan, Maltz, & Schneller, 2018). Even though inventory management systems use cost-based models, hospitals need to focus on the patient service level. Availability of healthcare items of high quality in an uncertain and continuously fluctuating environment is challenging (Bijvank & Vis, 2012).

The ultimate objective of healthcare systems is to provide proper treatment and care to patients. However, an appropriate procedure of

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treatment requires preparation of specific steps of processes before the arrival of the patient, such as maintaining a stock of medicines and medical and surgical items in the hospital (Fitzsimmons & Fitzsimmons, 2006). A well-maintained inventory control system helps the patient to receive medication without any delay and prevent out-of-stock situations in hospitals. On the other hand, an inadequate inventory control system results in several critical issues, such as the worsening of the patient's condition or development of antimicrobial resistance due to delay in treatment procedures (Management Sciences for Health, 2012).

Overall, inventory is held to maintain confidence in the system. If stock-out occurs regularly, patients and medical personnel may lose faith in the system. On the other hand, holding a high level of inventory can lead to substantial investments on the excess inventory and create unavailability of capital for other purposes (Maestre et al., 2018). Therefore, it is necessary to hold inventory to ensure availability at the time of requirement. However, it is very challenging to accurately predict the demand in a healthcare system due to uncertainties and randomness, such as changing patient conditions, dynamics in physicians' prescriptions, and variation in responses of the individual patient to treatment procedures (Montoya, Netzer, & Jedidi, 2010; Vila-Parrish et al., 2012). Therefore, the development of optimal inventory control policy which allows absorption of such uncertainties and randomness is essential.

Therefore, while managing the inventory in healthcare settings, the pharmacists or healthcare inventory managers have to consider various characteristics as highlighted in the literature. Some of these characteristics that may significantly affect healthcare inventory management systems are as follows:

i. **Continuous changing of patient condition:** A patient may arrive in a hospital system in a particular medical condition. Its medical condition varies with time according to the treatment procedures and responses during their length-of-stay in the hospital. Such changes in patient conditions make the underlying demand for healthcare items highly uncertain (Vila-Parrish et al., 2012).
ii. **Variability in length-of-stay of the patient:** The patient may stay in the healthcare setting for a short time, reasonable time or a long time based on their medical condition and physician recommendation (Taylor, McClean, & Millard, 2000). Hence, the demand for healthcare items varies depending on the patient's total length-of-stay.
iii. **Transfer of patient from one care unit to another:** At the time of admission of the patient, hospital allocates care unit (intensive care unit, high dependency unit, and wards) to each patient based on the initial assessment. With time, the allotted care unit may change depending on the patient's condition, leading to transfer of the patient to another type of care unit. The corresponding demand for items may also vary with the care unit (Akcan & Kokangul, 2012).
iv. **Heterogeneity of patients and physicians:** The individual patient has a unique demand for healthcare items based on their medical condition. Besides, physicians are also heterogeneous and exhibit dynamic prescription behaviour due to clinical uncertainty, variation in patient characteristics, differences in physicians' practising styles, knowledge, and experience (Montoya et al., 2010). Such scenarios call for specialized inventory management systems.
v. **Demand dependency among items:** There are possibilities of associations among different medicines prescribed to patients (Doubova, Reyes-Morales, Torres-Arreola, & Suárez-Ortega, 2007). Such associations can have an impact on the demand of the medication, and thus, calls for specialized inventory management systems.

Hence, healthcare inventory management systems are complex systems linked with several influencing factors. Its performance requires continuous improvement to enhance the accessibility and affordability of healthcare services. To consider all these factors, a careful and structured modelling and analysis for inventory management systems fulfilling the needs of the healthcare sector is a prime necessity. Though it is a critical approach, various developments have taken place, and many researchers and practitioners are working on it. Therefore, a review is required to perfect the knowledge-base in two aspects: (i) modelling approaches and (ii) solution methodologies.

Over the years, numerousmethods have been developed by the researchers and practitioners for modelling and analysis of varieties of inventory management systems in the healthcare sector. There have been many attempts by researchers and practitioners to carry out a critical review on certain issues and aspects of inventory management in healthcare systems, such as, material logistics (Moons, Waeyenbergh, & Pintelon, 2019; Volland, Fügener, Schoenfelder, & Brunner, 2017), surgical and sterile instruments (Ahmadi, Masel, Metcalf, & Schuller, 2019), blood products (Beliën & Forcé, 2012), lean engineering practices (D'Andreamatteo, Ianni, Lega, & Sargiacomo, 2015) and RFID technology (Yao, Chu, & Li, 2012).

In this paper, an effort has been made to review the existing modelling approaches and solution methodologies for inventory management problems of pharmaceutical products, and medical and surgical supplies in healthcare systems considering the current developments. The aim is to appraise the advancement of existing modelling approaches and methodologies.

The main contribution of this review can be summarized as follows:

- The review paper considers articles on modelling and analysis of inventory management systems for pharmaceuticals, and medical and surgical supplies.
- The literature review comprises studies till the year 2019 as per a proposed structured framework.
- This review identifies several factors influencing the performance of inventory management systems in healthcare.
- Based on the identified factors, the review classifies different inventory problems in healthcare systems.
- Appropriate modelling approaches based on the characteristics and types of inventory problems in healthcare are identified.
- The review also discusses the inherent characteristic features and selection norms of the existing solution methodologies.
- Critical appraisal of existing modelling approaches and solution methodologies is presented, which identifies some noteworthy research issues.
- An integrated framework is developed to add essential elements to the existing literature of modelling and analysis of the healthcare inventory management systems. The proposed framework may guide researchers and practitioners dealing with similar kinds of problems to improve the system.
- Lastly, the review paper recommends some important future research directions in the field of inventory management systems in healthcare.

The structure of the remaining paper is as follows. Section 2 presents the review methodology. Section 3 provides different kinds of inventory problems related to healthcare. Section 4 presents the existing modelling approaches and their solution methodologies are discussed in Section 5. The critical appraisal is presented in Section 6. An integrated framework for modelling and analysis of inventory management systems in healthcare is proposed in Section 7. Finally, the paper ends with conclusions and future research directions in Section 8.

2. Review methodology

This study presents a critical review of relevant publications on healthcare inventory management systems following the methodology of Bhattacharjee and Ray (2014); and Mukherjee and Ray (2006). The objective of this chapter is to review the existing literature on various kinds of modelling approaches and solution methodologies applied to healthcare inventory problems. The collection of review of literature is from multiple peer-reviewed journal papers and conference proceedings written in the English language. These publications are selected from numerous databases, such as ScienceDirect, Web of Science, IEEE Explore Digital Library, INFORMS PubsOnLine, Taylor & Francis Online, Wiley Online Library, ResearchGate, JSTOR archive, ProQuest and Google Scholar using keywords, such as 'healthcare', 'hospital', 'pharmaceutical', 'medicine', 'drug', 'medical', and 'surgical' in combination with 'inventory'. This review focuses mainly on inventory management of pharmaceutical products and medical and surgical supplies. The review paper does not include studies on blood inventory management due to their unique characteristics that require special attention. Specific attributes of blood inventory management in healthcare systems are efficient utilization of blood resources and addressing variability in age of the blood products when transfused to patients (Prastacos, 1984; Rajendran & Ravi Ravindran, 2017).

The main challenge in this review is to propose a classification of existing literature while maintaining the consistency and uniformity among each classified categories. The study consists of 80 research papers directly related to healthcare inventory management systems with 66 peer-reviewed journal papers and 14 conference papers. Out of the 80 research papers, 57 studies demonstrate the application of operations research tools and techniques for modelling and analysis. These papers are critically reviewed and classified based on healthcare inventory problems. Critical appraisal of each such study captures the essential characteristics features of modelling approaches and solution methodologies for different kinds of inventory problems in healthcare.

3. Overview of healthcare inventory problems

A healthcare system may face several inventory control-related problems. They are classified appropriately based on the various factors affecting the healthcare systems. The influencing factors and healthcare inventory problems are in the sub-sections below.

3.1. Factors influencing inventory control systems

Several factors are influencing the inventory control systems in healthcare. These factors may be completely observable, unobservable or partially observable to the healthcare decision-makers. The following are the ten leading factors.

3.1.1. Demand and supply of inventory items

An important factor affecting the inventory systems of healthcare is the demand for healthcare items. Various traditional forecasting techniques can predict the stationary demand for healthcare items (Ramírez et al., 2014; Varghese, Rossetti, Pohl, Apras, & Marek, 2012). However, consumption of healthcare items are non-stationary, i.e. the demand depends on various sources of randomness, such as the number of patients in hospital care units, patient treatment stages, patients' conditions, reaction to the medication, and physicians' recommendation (Vila-Parrish et al., 2012). However, advanced modelling tools and techniques can estimate the dynamic and uncertain nature of non-stationary demand. In hospital settings, a few studies have assumed independent and constant consumption for healthcare items (Adriana, Alexandru, & Olimpia, 2010). However, the real scenario requires consideration of stochastic demand following a particular probability distribution like Normal, Poisson, and Negative Binomial (Attanayake, Kashef, Andrea, & Carolina, 2014; Guerrero, Yeung, & Guéret, 2013).

Apart from the demand uncertainty, there exists a risk in the supply-side of the system. For example, immediate supplies of ordered quantity with zero lead time (Little & Coughlan, 2008; Uthayakumar & Karuppasamy, 2017) or supply with a specific time lag. The time lag can be constant (Bijvank & Vis, 2012; Maestre et al., 2018), or variable following particular probability distribution like exponential and uniformdistributions (Attanayake et al., 2014; Roni et al., 2015; Roni, Eksioglu, Jin, & Mamun, 2016). Moreover, sometimes the quantity ordered and delivered may vary due to unavailability of the ordered items from the supplier-side. Besides, predicting and expressing the actual availability of the amount requested from any supplier (reliable or unreliable) is technically challenging. Lack of complete information from the supplier-side makes the system unobservable or partially observable (Gebicki et al., 2014; Saedi et al., 2016). Therefore, it is necessary to incorporate this factor while modelling healthcare inventory management systems.

3.1.2. Type of healthcare inventory items

Typically, healthcare inventory items include medicines like tablets, capsules and injections (Vila-Parrish et al., 2012), surgical and medical supplies like syringes (Adriana et al., 2010; Hani, Basri, & Winarso, 2013), gloves (Zhou & Olsen, 2017), surgical kits (Rappold et al., 2011), surgical linen (O'Neill, Murphy, Gray, & Stoner, 2001), sterile instruments (Dellaert & Van De Poel, 1996; Hafnika, Farmaciawaty, Adhiutama, & Basri, 2016), and medical equipment (X-ray machine, ECG machine, etc.). The traditional approach of classification of healthcare items includes ABC analysis (based on annual usage value), VED analysis (based on the criticality of medicines and other medical supplies) and a combination of both ABC and VED (Gupta, Gupta, Jain, & Garg, 2007; Kant, Haldar, Singh, & Kankaria, 2015; Kumar & Chakravarty, 2015; Manhas, Aubid, Rashid, Sheikh, & Syed, 2012). Danas, Roudsari, and Ketikidis (2006) introduced a comprehensive classification approach using a decision tree analysis considering critical factors, such as the patient treatment, price of items, storage space, expiration date, and usage rate. Similarly, classification is done by Al-Qatawneh and Hafeez (2011). Each class of inventory requires specialized inventory control technique.

3.1.3. Nature of inventory item and storage facility

In the hospitals with compounding facilities, inventories of certain medicines may be stored in two stages, i.e., as raw materials and as finished goods made by processing the raw materials, for example, intravenous injections. The pharmacists check the inventory level of the raw material and plan the production of finished goods as per the predicted demand (Vila-Parrish et al., 2012). Maintaining such multi-stage inventory within a healthcare facility differs from the single-stage inventory system. Apart from that, certain healthcare items are perishables like injections and may require a specific temperature for storing. However, the space in various storage facilities within a healthcare system is highly limited and shared among multiple medicines (Bijvank & Vis, 2012; Maestre et al., 2018). Thus, healthcare inventory management decisions consider such factors.

3.1.4. Nature of the inventory distribution system

Within a healthcare system, the inventory flows to various departments or locations (Jayaraman, Burnett, & Frank, 2000). The requirement of healthcare items in each hospital department depends on the type of treatment facilities and the illness of the patient. For example, the emergency department may require certain life-saving drugs which need to be in stock even if there is no demand for several periods. Also, the intravenous solutions are stocked more in the emergency department as the patient is in extremely critical condition and need to be treated immediately without any delay (Duclos, 1993; Osei et al., 2014). In contrast, the operating room inventory comprises of treatment-specific surgical kits based on the surgeons' preferences (Harrell, 1990; Melson & Schultz, 1989; Rappold et al., 2011). Subsequently, in the wards and critical care units, physician-prescribed medicines are stocked for individual patients or unit-dose (Chen, Monteiro, Wang, & Marcon, 2018). Hence, depending on the distribution system, the inventory is managed at each location.

3.1.5. Replenishment policy

Inventory replenishment policies are classified broadly as continuous review, periodic review and the combination of both. These policies are measured based on inventory-related cost and service level. The continuous-review policies include the reorder level, order quantity (s, Q) policy (Priyan & Uthayakumar, 2014; Roni et al., 2016, 2015; Rosales, Magazine, & Rao, 2015; Uthayakumar & Priyan, 2013) and reorder level, order-up-to-level (s, S) policy (Kelle, Woosley, & Schneider, 2012). The periodic review policies include review period, order-up-to-level (R, S) policy (Gebicki et al., 2014) and review period, reorder level, order-up-to-level (R, s, S) policy (Bijvank & Vis, 2012; Esmaili, Norman, & Rajgopal, 2019). Generally, healthcare systems follow hybrid strategies that include both continuous and periodic review policies and joint replenishment criteria for multiple items (Rosales et al., 2015; 2019).

3.1.6. Maximization of service level

In any healthcare system, the patient demand needs to be fulfilled without any delay to avoid any fatal consequences. Hence, maximization of service level by minimizing the probability of stock-out and stock-out risk is the prime objective (Bijvank & Vis, 2012; Chang, Lu, & Shi, 2019). Backordering is generally not recommended to fulfill the unmet demand, though it exists in the literature (Çakici, Groenevelt, & Seidmann, 2011; Nicholson et al., 2004). Instead, expediting is encouraged which allow immediate fulfillment of demand by various alternative sources, such as nearby hospitals or local suppliers (Attanayake et al., 2014; Roni et al., 2016; 2019). However, repeated expedite orders may lead to an increase in the overall inventory-related cost as emergency ordering cost is generally more than the regular ordering cost. Hence, frequent emergency orders are not encouraged in a healthcare system to provide maximum service level.

3.1.7. Patient medical conditions

There is no generally accepted definition of a patient condition that is independent of diagnosis (Rothman, Rothman, & Beals, 2013). In healthcare settings, there is a correlation between the patient's medical condition and medicine requirement (Vila-Parrish et al., 2012). The demand for varieties of drugs arises due to the various clinical conditions of the patients and their response to the treatment and medication administered, which are often unobserved or partially observed. Furthermore, the patient condition may worsen due to unavailability or delay in availability of medicines resulting in an extended length-of-stay in hospital, and the following medication requirement (Vila-Parrish et al., 2012; Vila-parrish, Ivy, & King, 2008). Hence, the daily need of healthcare items depends on the patient arrival rate, their illness, transferral to another care unit, and length-of-stay in the hospital (Akcan & Kokangul, 2012; Saha & Ray, 2019).

3.1.8. Physician prescribing behaviour

Physicians play an essential role in inventory management. They are the surrogate buyers of healthcare items (Abdulsalam et al., 2018). However, many of the characteristics ofphysicians' recommendation determining the treatment and prescription of medicines are unobserved or partially observed to the pharmacists (Gönül, Carter, & Wind, 2000; Miao-Sheng & Yu-Ti, 2008; Montoya et al., 2010). Physicians exhibit dynamic prescription behaviour influencing the demand for healthcare items. The prescribing practice may vary depending on the clinical uncertainty, patient information, physicians' knowledge, and experience. Hence, it calls for a specialized inventory management system.

3.1.9. Criticality of inventory items

Healthcare inventory items are classified based on their criticality by the VED analysis (Kant et al., 2015; Manhas et al., 2012). However, in a healthcare system, all pharmaceutical and medical and surgical supplies are critical for the treatment and care of patients. The criticality of the healthcare inventory items depends on the patient medical condition and the treatment procedure for which the inventory is required (Gebicki et al., 2014). For instance, there is a patient health state that does not allow delay in administering medicines. Such a situation makes the dose very critical at that time for the patient. Thus, the criticality of the item depends on the individual patient and their medical condition, which is often not wholly observable. Hence, this factor is important to consider in healthcare inventory management systems.

3.1.10. Interactions among items

Treatment and care of patients with multi-morbidity require a large number and variety of drugs that may lead to a potential risk of drug interactions (Dumbreck et al., 2015). Adverse drug reactions due to these interactions result in uncertain and unplanned demand of other drugs and may call for specialized inventory management models (Doubova et al., 2007; Goldberg, Mabee, Chan, & Wong, 1996). However, for ease in modelling and solution purpose, no dependency among healthcare items is assumed (Nicholson et al., 2004). Dependent demand generally exists among items in surgical kits used in the operation room (O'Neill et al., 2001; Rappold et al., 2011; Steinberg, Khumawala, & Scamell, 1982), and among medicines due to multi-morbidities in patients (Held et al., 2017). Hence, it is recommended that dependent demand is considered while modelling inventory management in healthcare systems.

3.2. Classification of healthcare inventory problems

Depending on the influencing factors, inventory problems are divided into two categories: problems under certainty and problems under uncertainty. The classification proposed is based on decision-making, and selected based on its considerable merit (Starr & Miller, 1962).

3.2.1. Under certainty

An inventory problem under certainty is the case where the factors influencing the performance of healthcare inventory systems are known over the period of time. In most cases, demand and lead time may be constant or vary; however, in both cases, they are known. Since the demand and lead time is known with certainty, there is generally no need to consider possibilities of excess stock and shortages. However, healthcare inventory management problems under certainty are not frequently encountered as the demand is never known with certainty. It rather depends on various random factors, such as patient arrivals and discharges, the number of patients in a hospital unit, and patient medical condition. However, problems under certainty may be applicable for general medical items purchased in bulk, such as syringes, examination gloves, certain intravenous fluids, and vaccines (Hafnika et al., 2016; Stecca, Baffo, & Kaihara, 2016; Uthayakumar & Karuppasamy, 2017).

3.2.2. Under uncertainty

Healthcare systems face several uncertainties, such as a change in the number of patient arrivals, transfer and discharge rates, patient's length of stay in the hospital, clinical conditions of the patient and their response to treatment, physician's prescribing behaviour, availability from suppliers, demand for medicines and lead time. (Addis et al., 2015; Harper, 2002). Nevertheless, inventory decisions are taken despite these uncertainties (Aringhieri, Bruni, Khodaparasti, & Van Essen, 2017). Inventory problems under uncertainties are further divided into two categories: (i) inventory problems under uncertainty with the complete knowledge concerning the probability distribution of random variables, and (ii) inventory problems under uncertainty without the complete knowledge concerning the probability distribution of random variables.

The random demand size for pharmaceuticals, and medical and surgical supplies generally follows normal distribution (Little & Coughlan, 2008; Nicholson et al., 2004; Uthayakumar & Priyan, 2013), Poisson distribution (Bijvank & Vis, 2012; Guerrero et al., 2013; Saedi et al., 2016), and negative binomial distribution (Rappold et al., 2011). Moreover, the time between the demand events may be exponential with demand size following a discrete distribution (Gebicki et al., 2014; Rosales et al., 2015). Apart from that, the lead time if considered variable, it is assumed to be uniform (Akcan & Kokangul, 2012; Attanayake et al., 2014), and exponential (Roni et al., 2015). Due to such randomness, there is a possibility of having insufficient stock or excess stock (Gebicki et al., 2014; Hani et al., 2013). Modelling and analysis of inventory problems under uncertainties involve balancing the situation between out-of-stock and over-stock of items in the system.

Majority of the existing literature considers healthcare inventory problems under uncertainties by assuming a particular probability distribution of the random variables. However, in the real world, data is not precisely known or measured, and hence, complete knowledge of probability distribution is unknown. Mostly such problem arises in emergency rooms, intensive care units, and operating rooms for items like intravenous injections, medicines, and surgical supplies (Ahmadi, Masel, & Hostetler, 2019; Priyan & Uthayakumar, 2014; Savadkoohi, Mousazadeh, & Torabi, 2018). However, there is a dearth of studies under this category as it is challenging to determine inventory control strategies with the fact that the decision-maker is ignorant of the probability distribution of random variables.

4. Existing modelling approaches

A large number of modelling approaches has been developed by researchers to solve the various kinds of healthcare inventory problems. These may be classified as deterministic, stochastic, and distribution-free approaches. Inventory problems under certainty are modelled as deterministic, whereas, inventory problems under uncertainty with complete knowledge concerning the probability distribution of random variables are modelled as stochastic. Furthermore, inventory problems under uncertainty without complete knowledge concerning the probability distribution of random variables are modelled as distribution-free. The modelling approaches are further classified based on the formulated objective function(s) with or without constraint(s) as mixed-integer programming (MIP), non-linear programming (NLP), constraint programming (CP), chance-constraint programming (CCP), stochastic programming (SP), stochastic dynamic programming (SDP), robust optimization and possibilistic programming. Fig. 1 provides a general classification of different modelling approaches.

4.1. Deterministic approach

Most of the inventory problems under certainty in the healthcare inventory literature for medicines, intravenous fluids, and vaccines are modelled as deterministic models and are formulated using EOQmethod (Kapur, 1987; Kwak, Durbin, & Stanley, 1991), and using MIP optimization technique (Hovav & Tsadikovich, 2015; Stecca et al., 2016). MIP considers two types of variables: binary and integer. The binary variables in the healthcare inventory problem are regarded as whether the suppliers have delivered the required item to the hospital pharmacy or not, whether the pharmacy delivered them to the ward or not, and whether the clinic is assigned to the distribution centre or not (Hovav & Tsadikovich, 2015). The integer variable is the order quantity of medicines (Stecca et al., 2016). The deterministic modelling approach is often used to model inventory problems that are less affected by the uncertainties caused by random patient demand, supplier uncertainty, uncertainty in patient condition and physician preferences. Typical complications of deterministic models include limited space constraints with multiple products and multiple storing locations.

4.2. Stochastic approach

Most of the healthcare inventory problems under uncertainty with the complete knowledge concerning the probability distribution of random variables are modelled by applying stochastic approaches, and are generally formulated using MIP (Rappold et al., 2011; Roni et al., 2015), NLP (Nicholson et al., 2004; Uthayakumar & Priyan, 2013), CP (Little & Coughlan, 2008) and CCP (Maestre et al., 2018). A single-location single-item inventory system at a hospital facing both regular and emergency demands to obtain an optimal inventory policy for medicines is formulated by MIP (Roni et al., 2015). An inventory system for pharmaceuticals in intensive care units and surgical supplies in the operating room are also modelled as MIP (Cappanera, Nonato, & Rossi, 2019; Rappold et al., 2011). In MIP models, the objective function and constraints are linear, while in NLP formulation, either the objective function or any of the constraints are non-linear. In the context of healthcare inventory system, the expected total cost in multi-echelon inventory system for medical supplies is expressed as a non-linear function (Nicholson et al., 2004; Uthayakumar & Priyan, 2013). The complications for these models arise due to the various constraints and conditions, such as service level and space capacity for which CP is also considered for formulating inventory problems of medicines in intensive care units (Little & Coughlan, 2008). In case the constraints are probabilistic, CCP is used (Maestre et al., 2018). Moreover, existing literature consists of a number of stochastic inventory models formulated as stochastic programming and stochastic dynamic programming (Guerrero et al., 2013; Kelle et al., 2012).

4.2.1. Stochastic programming

In stochastic programming (SP), the assumption that all the required data of the problem are known and constant is relaxed. As an alternative, a subset of the parameter values is characterized by probability distributions. The inventory model for medicines in hospital pharmacy to minimize the expected total inventory costs with the service level and space constraints are formulated as SP to minimize the expected total number of orders (Kelle et al., 2012). The model is quite complicated due to a large number of variables, non-linearity, and stochastic constraints. The stochastic constraint is the service level, i.e. the probability of no shortage of medicines. Furthermore, a two-stage SP is used to formulate the problem of inventory allocation of surgical supplies in multiple locations in a healthcare system (Ahmadi et al., 2019).

4.2.2. Stochastic dynamic programming

The commonly used stochastic approach for dealing with inventory problems under uncertainty with known probability distributions of random variables is the Markov decision process (MDP) which use functional stochastic dynamic programming equations in most of the cases (White, 1993). The inventory level as it moves through time may be a stochastic process of a particular sort, i.e., MDP, where the state is generally represented as the on-hand inventory level, demand process, and availability of the item, and assumed to follow Markov property. Pharmaceutical inventory problem under non-stationary demand is modelled as MDP with demand process modulated as a Markovian process (Saha & Ray, 2019; Vila-parrish et al., 2008, 2012). Continuous-time Markov chains and Semi-MDP are used when a continuous review of inventory systems is considered for medicines and medical supplies (Rosales et al., 2015; Saedi et al., 2016). The on-hand inventory level of disposable medical supplies and infusions is modelled as a Markov chain, and closed-form expressions are derived from setting the threshold levels (Bijvank & Vis, 2012).

4.3. Distribution-free approach

In many instances, there may be a little or unavailability of past data due to various reasons, such as recent changes in the inventory system

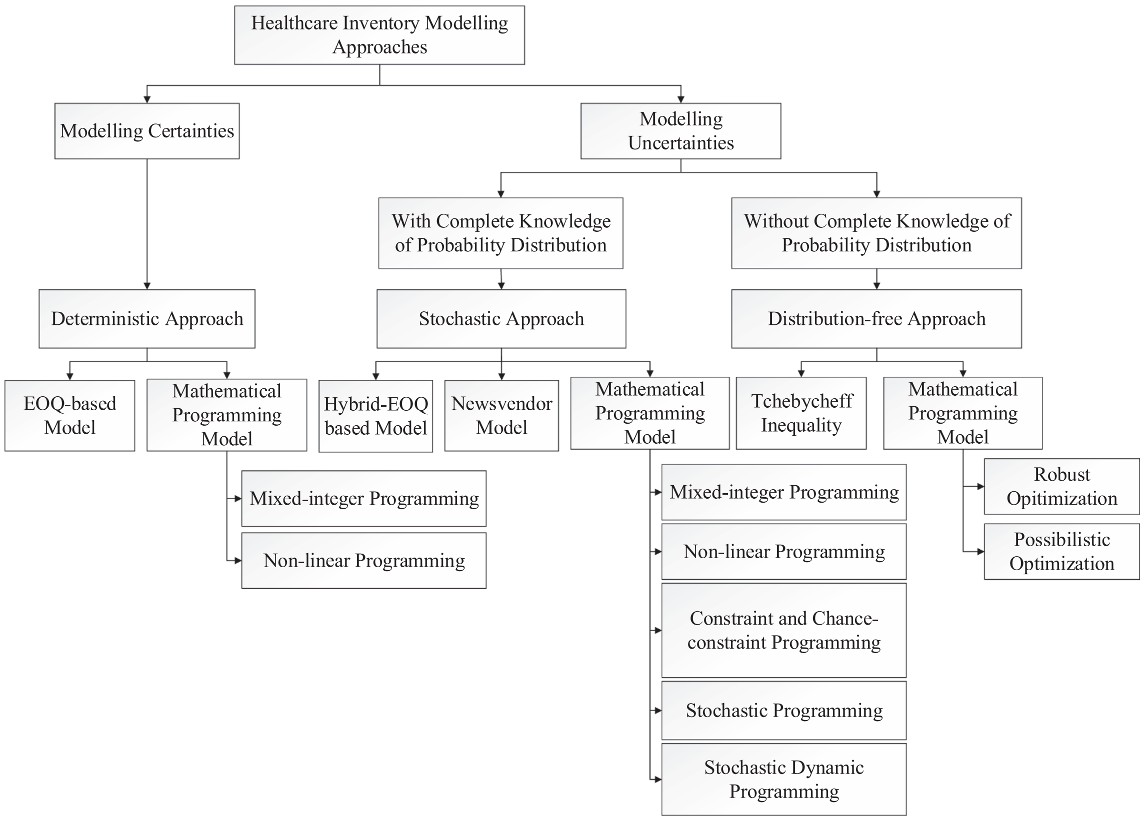

Fig. 1. Classification of modelling approaches used in healthcare inventory literature.

environment, or new inventory item introduced. Therefore, the probability distributions may not be precisely estimated. At many times, the critical inventory input variables and parameters, such as cost parameters are non-specific and may change with time. It is unfortunately very often true that the underlying distribution of the uncertain parameter is not known. The distribution-free analysis techniques, such as Tchebycheff inequality and Pearson measure of skewness (Starr & Miller, 1962), and mathematical programming approaches like robust optimization and possibilistic programming models are proposed to deal with inventory problems under uncertainties without complete knowledge concerning the probability distributions of random variables (Ahmadi et al., 2019; Priyan & Uthayakumar, 2014; Savadkoohi et al., 2018).

Among the techniques mentioned above, robust optimization models do not assume complete knowledge of the probability distributions, but as an alternative, they deal with uncertainty by finding the optimal solutions in a min-max setting (Meng et al., 2015). In traditional robust optimization models, uncertainty is distribution-free described by an uncertainty set, mostly convex set (Gorissen, Yanıkoğlu, & Hertog, 2015). In healthcare, a robust model is proposed for managing patient arrivals by considering patient admissions and departures as uncertainties (Meng et al., 2015). For inventory allocation of surgical supplies in multiple locations in a healthcare system (Ahmadi et al., 2019) and inventory control of medicines in hospital pharmacy (Velarde et al., 2014) robust models are applied. This modelling technique is popular because of its computational tractability for many classes of uncertainty sets and problem types; however, there are limited studies in healthcare inventory systems considering robust optimization. Another way in which imprecise and uncertain quantities may be incorporated into decision-making is possibilistic programming. It provides a flexible approach to handle uncertainty in inventory problems as it allows the model to include expert opinions in determining critical parameter estimates (Priyan & Uthayakumar, 2014). A particular case of inventory routing problem for medicines is formulated by this approach (Niakan & Rahimi, 2015). Later, Savadkoohi et al., 2018 developed an inventory problem considering pharmaceutical network design with uncertainty in demand, cost and capacity. Although distribution-free approaches are suggested for coping with inventory problems under uncertainties; however, studies in healthcare inventory systems considering distribution-free approaches are limited.

5. Existing solution methodologies

Existing solution methodologies to obtain the optimal or near-optimal solution(s) are classified as analytical, heuristic-search, and simulation-based approach.

5.1. Analytical methods

The analytical approaches are standard processes that use mathematical principles (lemmas, theorems and their proofs) to achieve optimal solutions. Over the years, such methods have obtained substantial consideration in the healthcare inventory literature. These methods are mainly used to form closed expressions, to prove optimal inventory policy or specific properties of the optimal inventory policy, and to compare various inventory policies or to present bounds on optimal objective functions (Çakici et al., 2011; Hafnika et al., 2016; Hani et al., 2013). Results obtained from analytical methods may be used to develop effective and efficient algorithms (Cappanera et al., 2019; Vila-Parrish et al., 2012). The closed-form equations are simple to implement in practical applications compared to the approaches which are recommended to capture uncertainties (Kapur, 1987; Kwak et al., 1991). Generally, analytical methods are applied in problems of small complexity.

Various analytical techniques, such as Lagrangian multiplier and exterior point penalty function are used to solve the non-linear programming problem with linear constraints to obtain the optimal ordering policy for multi-stage inventory problems with random demand (Chang et al., 2019; Uthayakumar & Priyan, 2013; Zhou, Luo, & Wu, 2013). The existence of uncertainty in inventory systems makes it challenging to propose efficient analytical methods for healthcare inventory problems. However, a number of analytical methods exist in the literature that solves realistic problem instances (Hovav & Tsadikovich, 2015; Stecca et al., 2016; Uthayakumar & Karuppasamy, 2017). Almost all proposed MDP models of small-size are solved analytically by dynamic programming algorithms. For instance, backward induction algorithm (Saha & Ray, 2019; Vila-parrish et al., 2008, 2012), value iteration algorithm (Haijema, 2014) and linear program algorithm is used to solve various types of MDP models (Rosales et al., 2015).

Performance of optimization solvers has improved substantially in recent times to solve these problems in reasonable time; however, in case the total inventory-related cost functions with underlying constraints are not linear, and linearization requires several additional variables, solving such a model using optimization solver may increase the computational time substantially.

5.2. Heuristic-search

Inventory problems under uncertainties are difficult to solve using analytical methods. When the system is involved with non-linear objective function subjected to non-convex or convex constraints, there are limited effective analytical solution methods. Hence, heuristics are developed to solve such a challenging problem. A large number of researchers have developed various heuristics to solve complex problems, such as multi-stage inventory systems to obtain the near-optimal order quantity and reorder level of multiple medical and surgical supplies (Nicholson et al., 2004; Rosales et al., 2015; Bijvank & Vis, 2012), and decentralized and centralized inventory model in pharmacies and nursing units to find near-optimal inventory levels (Shan, Yoon, Khasawneh, & Gandhi, 2011). Moreover, heuristic-search techniques are also used to solve complex stochastic inventory models formulated as Markov chains (Diamant, Milner, Quereshy, & Xu, 2018; Guerrero et al., 2013; Saedi et al., 2016). Apart from that, for parameter optimization technique, Tabu search-based heuristics is recommended for an inventory problem with split delivery for medicines with variable lead time (Roni et al., 2016). Finding solutions for inventory problems under uncertainty is very difficult; however, heuristics are appropriate for pharmaceutical inventory network design problems considering uncertainty in demand, cost and capacity (Savadkoohi et al., 2018).

Furthermore, inventory allocation problems for surgical supplies stored in multiple locations are also solved by heuristic-search techniques to obtain near-optimal solutions (Ahmadi et al., 2019). Recent trends show that heuristic-search based approaches are highly suggested for coping with healthcare inventory problems under uncertainties. They are suitable for complex inventory systems consisting of multiple healthcare items at multiple stages. Through heuristic-search approaches, near-optimal solutions can be obtained efficiently for large-size complex problems formulated as stochastic and distribution-free models.

5.3. Simulation-based approaches

A simulation-based approach is recommended for inventory problems in healthcare due to their inherent capability of representing complexities and uncertainties. It is an excellent tool for exploring real-life problems with a testing variety of what-if analysis. It is flexible and may be used to solve complex stochastic inventory models (Akcan & Kokangul, 2012; Attanayake et al., 2014). Simulation is an excellent approach to consider various sources of uncertainties, such as the number of patient arrivals and discharges, transitions in patient condition, and demand for medicines (Akcan & Kokangul, 2012; Vila-parrish et al., 2008, 2012). The analytical method is based on mathematical formulations and derivations with various assumptions and approximations. Complex demand distribution characteristics like multi-modal demand distributions and seasonal demand, and complex cost structures are challenging to incorporate using analytical and heuristics methods. In such a situation, simulation is used to solve the problem. Simulation is used to mimic the inventory control systems in healthcare (Liu, Zhang, Liu, & Lin, 2013). When the input changes with time, such as patient flow, number of patients and their medical condition and type of treatment, and if they require continuous monitoring, simulation is the most appropriate solution methodology to address such issues (Akcan & Kokangul, 2012; Kilpatrick & Freund, 1967; Vila-parrish et al., 2008). Simulation has been extensively used to model the inventory control system of a hospital because of the complexities in the problem dimensions regarding the large number and great variety of healthcare items (Liu et al., 2013; Zhang, Meiser, Liu, Bonner, & Lin, 2014).

Over the years, different kinds of simulation-based approaches, such as system dynamics and discrete-event simulation (DES), have been used to solve various inventory problems in healthcare systems (Wang, Cheng, Tseng, & Liu, 2015; Gebicki et al., 2014). System dynamics simulation is used to investigate the overall system behaviour and performance over time, and it contains independent and dependent variables along with feedback dynamics (Azzi, Persona, Sgarbossa, & Bonin, 2013). Many researchers have used system dynamics simulation to analyze the relationships among several variables. For example, a system dynamics simulation for inventory management in pharmacies and wards in a healthcare network consisting of 15 hospitals, 149 wards, and 3394 beds is developed (Azzi et al., 2013). A system dynamics for a drum-buffer-rope type inventory control system addresses the change in the inventory replenishment decisions with the difference in the input information like demand characteristics (Wang et al., 2015). A particular case of inventory pooling is presented by system dynamics simulation to investigate the entire process from demand to supply of pharmaceuticals in the hospital (Wu, Rossetti, & Tepper, 2013). Furthermore, Rosales et al., 2019 developed joint replenishment policies in a healthcare system by applying system dynamics simulation approach.

However, to take decisions at the operational level, such as determining inventory policy parameters, DES is more suitable (Attanayake et al., 2014; Gebicki et al., 2014). An integrated hospital inventory model for 1544 items is tested in a simulation study before its implementation with multiple performance measures, such as service level, number of orders and total inventory costs (Dellaert & Van De Poel, 1996). DES is appropriate for building an integrated medication inventory control system in a hospital to evaluate different kinds of inventory policies (Gebicki et al., 2014).

Apart from that, for ease in the implementation, simulation using the spreadsheet as a tool has become the choice of many researchers and practitioners (Kelle et al., 2012; Liu et al., 2013; Shang, Tadikamalla, Kirsch, & Brown, 2008). Also, many researchers have combined simulation with optimization for inventory policy parameter optimization (Rosales, Magazine, & Rao, 2014). Complex models like multi-dimensional MDP models are difficult to solve analytically due to the curse of dimensionality (Vila-parrish et al., 2008). In such cases, simulation is recommended (Haijema, 2014). Moreover, insights from the simulation methods may be applied into the heuristic-search techniques for further analysis (Liu et al., 2013; Shang et al., 2008; Zhang et al., 2014).

Hence, existing literature reveals that simulation-based approaches have been used to solve the healthcare inventory problems under uncertainties with known probability distributions of random variables. Many researchers have successfully modelled the complexities and dynamics of an integrated inventory control system in healthcare through simulation methods. Therefore, simulation is a powerful tool to solve problems that are challenging to formulate mathematically and difficult by analytical methods.

Table 1
Classification of healthcare inventory problems.

Problem Types	Modelling Approaches	Authors	Types of Analyses	Solution Methods
Problems under Certainty				
Deterministic Approaches	Mixed-integer Programming	Hovav and Tsadikovich (2015)	Inventory control system for vaccines	Analytical
		Stecca et al. (2016)	Network design and inventory control system for medicines	Analytical
	Non-linear Programming	Duncan and Norwich (1973)	Inventory ordering policy formulation	Analytical
		Kapur (1987)	Inventory valuation	Analytical
		Kwak et al. (1991)	Inventory control system for intravenous fluids	Analytical
		Adriana et al. (2010)	Inventory control system for medical supplies in the consulting room	Analytical
		Rachmania and Basri (2013)	Demand forecasting and inventory policy evaluation	Analytical
		Zhou et al. (2013); Uthayakumar and Karuppasamy (2017)	Inventory control system for deteriorating healthcare items	Analytical
Problems under Uncertainties with Complete Knowledge of Probability Distribution				
Stochastic Approaches	Mixed-integer Programming	Rappold et al. (2011)	Inventory control system for dependent items in the operating room	Analytical
		Roni et al. (2015)	Inventory control for regular and emergency demand	Analytical
		Roni et al. (2016)	Inventory control with spilt-delivery	Heuristics
		Cappanera et al. (2019)	Inventory control system for drugs considering the impact of healthcare stakeholders	Analytical
	Non-linear Programming	Satir and Cengiz (1987)	Inventory control of medicines with expiration cost	Analytical
		Dellaert and Van De Poel (1996)	Integrated inventory control systems in hospitals	Analytical and Simulation
		Nicholson (2002); Nicholson et al. (2004)	Outsourcing inventory control decisions	Heuristics
		Shang et al. (2008)	Developing a decision support system for managing inventory in a pharmaceutical company	Heuristics and Simulation
		Çakici et al. (2011)	Inventory shrinkage control	Analytical
		Shan et al. (2011)	Analyzing the centralized and decentralized inventory distribution system	Heuristics
		Akcan and Kokangul (2012)	Inventory control system with a variable patient number	Analytical and Simulation
		Uthayakumar and Priyan (2013)	Inventory control system with permissible payment delay	Analytical and Heuristics
		Hani et al. (2013)	Inventory control of medical consumables	Analytical
		Liu et al. (2013)	Inventory parameter optimization	Heuristics and Simulation
		Azzi et al. (2013)	Outsourcing inventory control decisions	Simulation
		Rosales et al. (2014)	Point-of-use inventory control in hospitals	Heuristics and Simulation
		Attanayake et al. (2014)	Conceptual model and operational model for inventory optimization in hospitals	Simulation
		Gebicki et al. (2014)	Inventory control considering drug characteristics	Simulation
		Zhang et al. (2014)	Inventory control system for in-store pharmacies	Heuristic and Simulation
		Wang et al. (2015)	Inventory control with the demand-pull model (buffer adjustment)	Simulation
		Wu et al. (2013)	Inventory pooling in hospitals	Simulation
		Hafnika et al. (2016)	Analyzing excess inventories	Analytical
		Paul and Venkateswaran (2018)	Inventory control of medicines in hospital in case of epidemics	Simulation
		Rosales et al. (2019)	Joint replenishment policies and dual sourcing in healthcare systems	Simulation
		Chang et al. (2019)	Production-inventory healthcare system with Poisson demands	Analytical
	Constraint Programming	Little and Coughlan (2008)	Inventory control system under variations in space and delivery patterns	Heuristics
	Chance-constraint programming	Jurado et al. (2016); Maestre et al. (2018)	Inventory control under probabilistic storage and order constraints	Analytical
	Stochastic Programming	Kelle et al. (2012); Woosley and Wiley-Patton (2009)	Decision support system for inventory control of pharmaceuticals in hospitals	Simulation
		Ahmadi et al. (2019)	Inventory allocation of surgical supplies	Heuristics
	Markov Decision Process (MDP)	Vila-parrish et al. (2008); Vila-Parrish et al. (2012)	Multi-stage inventory control of perishable pharmaceuticals considering patient information.	Analytical and Simulation
		Haijema (2014)	Inventory control policies for perishable products	Analytical and Simulation
		Zhou and Olsen (2017)	Inventory control system for long-life perishable products	Analytical
		Saha and Ray (2019)	Patient condition-dependent inventory replenishment policies for medicines under Markovian demand process.	Analytical
	Semi-MDP	Rosales et al. (2015)	Point-of-use inventory control of medical supplies	Heuristics
	Markov chains	Kilpatrick and Freund (1967)	Inventory control of oxygen tanks	Simulation
		Bijvank and Vis (2012)	Point-of-use inventory control of disposables and infusion fluids	Heuristics
		Guerrero et al. (2013)	Inventory-distribution problem with batching constraints	Heuristics
		Saedi et al. (2016)	Inventory control system under random disruptions	Heuristics
		Diamant et al. (2018)	Inventory control of reusable surgical supplies	Heuristics

(*continued on next page*)

Table 1 (*continued*)

Problem Types	Modelling Approaches	Authors	Types of Analyses	Solution Methods
Problems under Uncertainty without Complete Knowledge of Probability Distribution				
Distribution-free Approaches	Robust model	Velarde et al. (2014)	Inventory control in hospital pharmacy	Analytical
		Ahmadi et al. (2019)	Inventory allocation of surgical supplies	Heuristics
	Possibilistic Programming	Priyan and Uthayakumar (2014)	Analysis of an integrated inventory control system	Heuristics
		Niakan and Rahimi (2015)	Inventory routing problem for medicines	Analytical
		Savadkoohi et al. (2018)	Network design and inventory parameter optimization	Heuristics

6. Critical appraisal

A sound inventory management in healthcare organizations is achieved by following a systematic approach to optimize the inventory-related cost and reduce variations. As an epilogue to the critical appraisal of the literature on inventory management in healthcare, the following observations are worth mentioning:

(i) There exists a substantial body of knowledge in the field of inventory management in healthcare for optimal replenishment of pharmaceuticals, and medical and surgical supplies.
(ii) Various inventory control methodologies have been applied in real-world situations to fulfil the varying requirements of the hospital pharmacists, physicians, patients, and other medical personnel.
(iii) There has been an enormous effort by researchers to make these methodologies easy to use, implement and interpret (Guerrero et al., 2013; Little & Coughlan, 2008).
(iv) Most researchers in this area aim to minimize the total inventory cost subject to various constraints and conditions, and obtain the solutions by using optimization tools and techniques.

However, it has been observed that a systematic approach for inventory management systems in healthcare incorporating all the influencing factors is lacking (Rossetti, Buyurgan, & Pohl, 2012). Thus, a holistic and integrated approach to healthcare inventory management is recommended, and if applied, it is beneficial for real-life situations. Deterministic approaches do not consider the dynamics of a healthcare inventory system, and are easier to solve. However, stochastic and distribution-free approaches consider the inherent complexities, variability, and uncertainties involved, and require advanced tools and techniques to solve such problems. Nevertheless, to model close to the real system, stochastic and distribution-free approaches are encouraged with efficient solution methods. The types of healthcare inventory problems, existing modelling approaches, and solution methods are used in Table 1 to appraise a number of research papers on modelling and analysis of inventory management systems in healthcare.

A critical appraisal results in the identification of essential characteristic features and selection norms of existing solution methods and is highlighted in Table 2, respectively.

Different modelling approaches and solution methods, as discussed in previous sections, are used by the researchers for modelling and analysis of inventory management in healthcare systems, predominantly in hospitals. Each department in a hospital (pharmacy, emergency, operation theatre, and other specialized departments like cardiology, gynaecology, radiology, etc.) has distinct managerial and operational issues, and over the years various unique characteristics have been considered while modelling the inventory systems in each department of a hospital system. The unique features which are widely used to model the inventory control systems in multiple locations within the hospitals, viz. (i) central pharmacy, (ii) emergency room, (iii) operating room, (iv) intensive care unit, and (v) wards and other departments are summarized in Table 3.

7. An integrated framework for modelling and analysis of inventory management in healthcare systems

In this section, with the pre-requisite knowledge from the review of the existing literature, understanding the merits and demerits of modelling approaches and solution methods, and considering potential areas of improvement, an integrated framework for modelling and analysis of healthcare inventory management system is considered to be of prime necessity. The details of the framework are explained with a flowchart, as presented in Fig. 2**.** The framework consists of six phases, viz., preliminary phase, data collection phase, data analysis phase, modelling phase, verification and validation phase, and

Table 2
Essential characteristic features and selection norms of solution methods.

Solution Methods	Essential Characteristic Features and Selection Norms
Analytical	(i) It is appropriate when a single healthcare item in single-location within a hospital system is considered. (ii) Suitable when the number of patients in a system, demand for healthcare items and lead time for items are assumed to be known. (iii) Suitable for solving small-size problems.
Heuristics	(i) Suitable for complex inventory system consisting of multiple healthcare items at multiple stages in a healthcare system. (ii) Suitable when inventory problems under uncertainties in demand, lead time, and capacity for healthcare items in pharmacies and nursing units are considered. (iii) It is used to obtain near-optimal solutions for large-size complex problems formulated as stochastic and distribution-free models.
Simulation	(i) The entire process from demand to supply of healthcare items used in hospitals can be investigated. (ii) It is appropriate for addressing sources of randomness and uncertainties in healthcare systems, such as patient arrivals, their illness, multiple treatment stages and uncertain treatment responses. (iii) Suitable when the problem is difficult to formulate mathematically and cannot be solved efficiently by analytical methods. (iv) Suitable for solving large-size complex problems.

implementation phase. The steps involved are described below.

Step-1 (Preliminary Phase): The initial step includes observation of a real healthcare system to select a sub-system that requires prime focus. Observations include number and type of inventory items, the present classification system followed, the current replenishment policies, the process of distribution of the items from the hospital pharmacy to various point-of-use locations, the resource utilization and multiple constraints and conditions, such as space limitations and service levels. Such observations help to get an initial idea about the complex issues faced by the system, their causes, and provide scope for model development and improvements. After the selection of the system and sub-systems, healthcare inventory problems are classified through a critical review of the literature. Then, the research issues are identified, and the objective(s) are set.

Step-2 (Data Collection Phase): After the problem is clearly defined and understood and objective(s) are set, the next step is to collect the data required to construct the model. The information collected is organized into three broad categories: (i) patient-specific information, and (ii) physician-specific information, and (iii) healthcare item-specific information. The patient-specific information comprises of the patient name with identification number, date of arrival, type of care unit in which individual patient is admitted, the transfer date and time in case of shifting of patient from one care unit to another, the provisional and final diagnosis of the patient, their treatment stage, length of stay, insurance scheme and finally, the discharge date. Secondly, the physician-specific information includes the name of the physician, their field of specialization, name of the patient under their supervision, date of prescription, and type and dosage of medicines prescribed. The healthcare item-specific information consist of item code, name of the item, the request for replenishment date and issuance date, the quantity issued to the requested location (emergency room, operating room, wards in each floor, and other specialty departments), or to individual patient (in case of individual patient-specific medication administration) and the price of the item. The data are collected through hospital information systems, discussion with healthcareprofessionals, and real-time observations.

Step-3 (Data Analysis Phase): The collected data is analyzed with the help of systematic and appropriate statistical tools and techniques,

Table 3
Inventory management at various hospital departments.

Hospital Departments	Unique characteristics	References
Hospital Pharmacy	Decisions are made for purchasing and distribution to other departments; Often periodic review; Maintain safety stock; Minimize inventory-related cost but prevent stock-out; Places emergency order to other hospitals	Augusto and Xie (2009); Danas, Ketikidis, and Roudsari (2002); Gebicki et al. (2014); Habuchi, Takenouchi, and Motomura (2009); Huynh et al. (2013); Maestre et al. (2018); Rosenthal, Tsao, Tsuyuki, and Marra (2016); Saedi et al. (2016); Velarde et al. (2014); Zhao, Yun, Liu, and Wang (2008)
Emergency Room	Minimize [Min] time between prescribing and administering; [Min] staff leaving the room for supplies; [Min] excessive room supplies; Frequent supplies are maintained in easily assessable place; Infrequently used items are stored in nonessential areas or are removed	Duclos (1993); Alkaabi, Abd El Halim, and Mahmoud (2006); Xu, Wong, Chin, Wong, and Tsui (2011); Amaral and Costa (2014); Muthoni, Kimani, and Wafula (2014); Osei et al. (2014); Roni et al. (2015); Zeinali, Mahootchi, and Sepehri (2015)
Operating Room	Operation schedule specific items; Safety stock of standard surgery-specific items/kits; Specialized items used by specific surgical departments (orthopaedic screws, etc.); Sterilization of items; Demand depends on the surgeon's preferences; High availability rate required on time within a limited space	Melson and Schultz (1989); Harrell (1990); Van De Klundert, Muls, and Schadd (2008); Zhang, Murali, Dessouky, and Belson (2009); Guerriero and Guido (2011); Rappold et al. (2011); Koksalmis, Hancerliogullari, and Hancerliogullari (2014); Diamant et al. (2018)
Intensive Care Unit	Minimal storage space; Often continuous review; Places emergency order to the hospital pharmacy	Ridge, Jones, Nielsen, and Shahani (1998); Little and Coughlan (2008); Vila-Parrish et al. (2012); Kelle et al. (2012); Bijvank and Vis (2012); Guerrero et al. (2013); Hosseinifard, Abbasi, and Minas (2014); Pagel et al. (2017); Cappanera et al. (2019)
Wards/other departments	Often high-volume, low-cost medicines; Maintain schedule for drug delivery; Aggregate drug orders to minimize fixed order cost and bulk delivery	Azzi et al. (2013); Borghans, Kool, Lagoe, and Westert (2012); Dean, van Ackere, Gallivan, and Barber (1999); Gebicki et al. (2014); Nicholson et al. (2004); Stecca et al. (2016); Zhou et al. (2013)

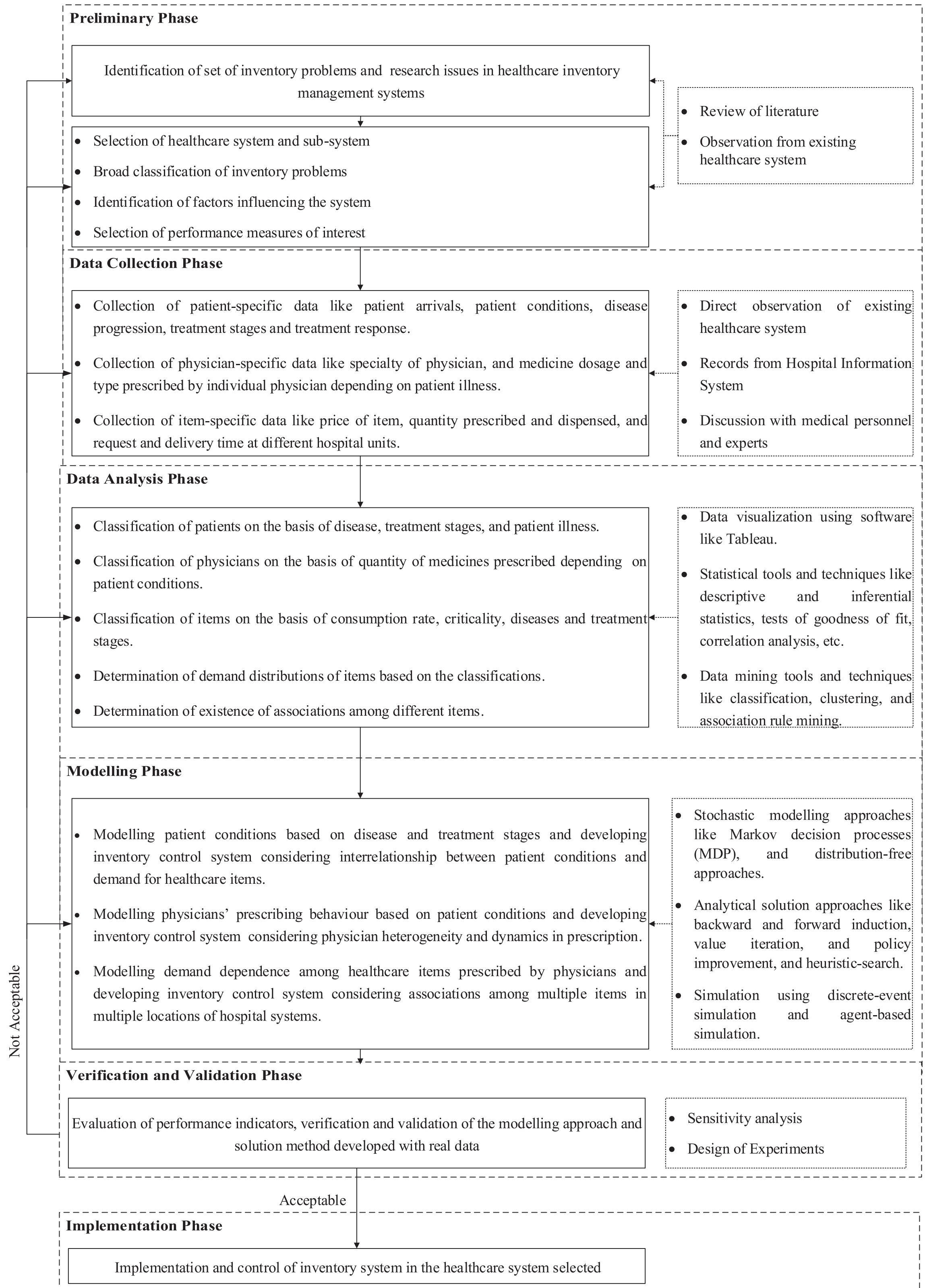

Fig. 2. An integrated framework for modelling and analysis of inventory management system in healthcare.

such as descriptive and inferential statistics, tests of goodness of fit, correlation analysis, regression analysis, and data mining tools like classification, clustering and association rule mining. The patients can be classified based on disease, treatment stages, and severity of illness. The physicians can be clustered based on the quantity of medicines prescribed as per the patient conditions. Classification of items can be done based on the consumption rate, criticality, patient conditions and physicians' preferences. Based on these classifications, the probability distributions of demand for the items in each class are determined. Furthermore, the presence of hidden patterns in the prescription database and the existence of associations among different items are investigated.

Step-4 (Modelling and Analysis Phase): Modelling of the inventory problem comprises of three essential steps, viz. (i) identification of various influencing factors, input variables, system parameters and performance indicators, (ii) representation and formulation of the objective function depending on the decision variables subject to constraints and conditions, and (iii) development of the model and analyzing them.

To address the identified problems and research issues, three models are proposed for an effective healthcare inventory management system:

(i) Modelling patient conditions based on disease and treatment stages and develop an inventory control system considering the interrelationship between patient conditions and demand for healthcare items.
(ii) Modelling physicians' prescribing behaviour based on patient conditions and develop an inventory control system considering physician heterogeneity and dynamics in prescription.
(iii) Modelling demand dependence among healthcare items prescribed by physicians and develop an inventory control system considering associations among multiple items in multiple locations of a hospital system.

Various approaches are available to formulate the proposed models, such as stochastic modelling approaches like MDP to model the patient conditions, and partially-observed MDP to model physicians' prescribing behaviour. Once a mathematical model of the specific problem has been established, the next step is to solve the problem to achieve the optimal or near-optimal solutions through different kinds of existing solution methods, such as analytical method, heuristics, and simulation. Depending on the essential characteristic features and selection norms of the existing solution methods (Table 2), the appropriate method is applied to solve the developed model. Several performance indicators, such as inventory levels, inventory costs and service level are then analyzed to find the relationships between them and the influencing factors, such as patient conditions, physician prescribing behaviour and demand dependence among healthcare items, and decision variables like order quantity and replenishment policies of healthcare items are obtained.

Step-5 (Verification and Validation Phase): As the model is solved and the results are obtained, the next important step is to review the obtained results to see whether the results make sense and the underlying decisions are in a position to be implementable. The rationales for verifying and validating the solution are: (i) the model may not have considered all the constraints and conditions of the problem while simplifying the model, and (ii) the data considered may have been under- or over-estimated, and hence, may provide unacceptable results. In the case of unacceptable results, the influencing factors, input variables, and system parameters are revised accordingly. An error by the hospital management in determining the input parameters, such as demand for healthcare items, and inventory-related cost parameters cause variations in the output (order quantity, replenishment policy, and the total cost incurred). Under-estimating the demand may lead to an out-of-stock situation and over-estimating it leads to excess stock. Sensitivity analysis is generally presented to analyze the impact of estimation errors. For example, it is observed that on under-estimating inter-arrival rates of demand for items, lower economic benefits are obtained, and over-estimated values of stock-out cost decreased the benefit of using an optimal periodic review interval (Rosales et al., 2015).

Step-6 (Implementation and Control Phase): The final phase is the implementation and control phase where the solutions obtained are implemented in an existing system and is further checked and updated in the fluctuating environment. In case the results obtained are not applicable in a real system, it is required to study the system again, and identify whether any of the influencing factors, input variables, system parameters, constraints or conditions are neglected or incorrect during the formulation of the model. In all such cases, the problem formulation step is re-evaluated, and appropriate modifications are made to represent the specified problem with more accuracy.

8. Concluding remarks and future research directions

This paper provides a critical review of existing literature on healthcare inventory management systems, and the critical analyses result in the identification of appropriate modelling approaches and solution methods for various kinds of healthcare inventory problems. It introduces the applicability, potential and usefulness of the integrated framework for carrying out research in the area of inventory management systems in healthcare. Improving the performance of inventory control systems of healthcare items minimize the inventory-related costs, which may eventually lead to a reduction in the cost of treatment, and provide overall satisfaction to patients.

Based on the analyses, the following future directions for modelling healthcare inventory management are proposed.

(i) Existing research on healthcare inventory management ignores existence of numerous interactions among healthcare items. A joint order for multiple items would reduce the ordering cost at hospital pharmacies. There may be limitations for a joint budget. Besides, multiple items need to compete for storage space in the pharmacies or at the point-of-use locations in the hospital.
(ii) Healthcare inventory literature addresses a variety of healthcare items, such as pharmaceuticals (medicines, disposables, and non-disposables), medical equipment, surgical instruments, and other medical and surgical supplies. An integrated model considering all types of healthcare product may open new avenues for further investigation.
(iii) Sources of randomness and complexities, such as patient arrivals, their illness, treatment stages, and treatment responses may be considered during modelling and analysis of inventory control systems in hospitals. The advantage of queuing theory may be considered while modelling random patient arrivals, and Markov chains may be used to model the patient medical conditions, the transition of patients from one treatment stage to another, and its relationship with the demand for items. Besides, heuristics and simulation approaches are also encouraged to explore when the system is complex and challenging to formulate or solve analytically.
(iv) Multi-stage models, such as multi-stage stochastic programming, stochastic dynamic programming techniques may address problems related to dynamic inventory systems in healthcare settings. Moreover, multi-agent models, such as reinforcement learning models may be developed to address multi-echelon inventory control problems in healthcare systems wherein multiple healthcare decision-makers (agents) can decide after learning and analyzing the decisions taken by upper-stage agents (Pontrandolfo, Gosavi, Okogbaa, & Das, 2002).
(v) Existing literature often deals with the uncertainty by assuming known probability distribution of random variables, such as demand for medicines, patients conditions, and physicians' prescribing behaviour; however, there are situations where the distributions of random variables are unknown or partially known (Arifoğlu & Özekici, 2010; Bayraktar & Ludkovski, 2010). Modelling such complex but practical problems using hidden Markov models, partially-observable MDP, robust optimization and possibilistic programming techniques are encouraged for future-research.
(vi) Although the vast literature on inventory management in medicines is available, varying and inconsistent expiration dates in different batches of orders received are not yet considered. For

simplifying the modelling approaches, available literature disregards consideration of variation in expiration dates, even though there is a significant cost involved in the excess stock that ultimately results in spoilage after expiration (Ketzenberg, Gaukler, & Salin, 2018). Such consideration is expected in future research in this field.

(vii) No matter how precise the computations of inventory control parameters are, behavioural factors of healthcare stakeholders may force an adjustment on the final decisions taken. If the stakeholders believe that the computation is producing undesirable results, then their experience and judgment should be the deciding factor (De Vries, 2011). Till date consideration of behavioural factors in inventory management in healthcare is not considered. It is exiting and relevant scope for further investigation. The behaviour of the healthcare stakeholders may be (i) in response to or in anticipation of demand, and (ii) to induce demand for healthcare items. For example, the behaviour of hospital stakeholders like board of directors, head of departments, pharmacists, inventory managers, and nurses is to build an efficient inventory system to meet the expected demand, whereas, the behaviour of patients, physicians and patient-accompanying persons may induce demand (Johnson, 2014). The distinct interests of each stakeholder are presented in Table A1 in Appendix A. In this context, various advanced operations research tools and techniques, such as decision analysis, systems dynamics and agent-based simulation approaches may be applied to capture the behavioural aspects in modelling inventory management in healthcare systems.

In conclusion, this review indicates that even though the literature on healthcare inventory system is emerging, and some important issues have been addressed, there remain a number of problem aspects for which modelling and solution approaches are yet to be explored. Therefore, inventory management in healthcare systems remains an area with numerous exciting and multifaceted research opportunities.

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Appendix A

See Table A1.

Table A1
Behaviour of hospital stakeholders and their interests related to inventory management in healthcare.

Behaviour	Stakeholders	Interests
In response to or in anticipation of demand	Board of Directors	Minimizing overall hospital expenditure; Supply medicines to other regional health organization; Having a centralized hospital information system
	Head of Hospital Departments	Introducing new medicines; Maintaining medicines in stock; Preventing medicines from running out-of-stock; Avoiding emergency orders; Having a hospital information system on the service delivery process of each department
	Pharmacists	Recommends on administering and monitoring of medicines; Review patient profile before dispensing medication; Ensures accessibility, affordability and quality of medicines; Practice therapeutic substitution in case of stock-outs; Fulfils the required quantity of medicines to the patient; Prevents medicines from stock-out situation; Fast delivery of medicines; Avoids uncertainties about the preparation of medicines; A decision regarding on-hand inventory, frequency of placing orders and order quantity in response to or anticipation of patient demand
	Inventory Managers	Having accurate and reliable data about inventory-related costs and service delivery; Optimizing storage space Fast delivery; Minimizing inventory-related costs; An optimizing trade-off between under-stock and over-stock; Avoiding the expiration of medicines; Having a proper hospital information system; Reliable demand forecast; Avoiding rush orders; Long-term relationships with suppliers or GPOs; Provide service level as cost-effectively as possible reducing delivery costs while materials are not being over-stocked or becoming obsolescent
	Nurses or Other Medical Staff	Fast delivery of special and emergency medicines; Avoiding running out-of-stock; Look for high service level across all products and confidence of not running out-of-stock

(*continued on next page*)

Table A1 (*continued*)

Behaviour	Stakeholders	Interests
To induce demand	Patient	Patient with knowledge and information makes doctor to prescribe a drug or test; Patient does not want any delay due to unavailability of healthcare resources thus compelling hospitals to over-stock.
	Physician	Provide care and service; Prescribe medicines and other medical items; Follows professional norms; Physicians have freedom of choice in prescribing medications; Physicians influenced by pharmaceutical sales representatives (detailing and sampling); Induce demand by prescribing more medicines, preferred medicines, etc.
	Patient-Accompanying Person	Induce demand by recommending treatment or medicine due to extra care and concern

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