Inventory management of perishable health products: a decision framework with non-financial measures

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Abstract

Purpose – This research proposes a decision framework for using non-financial measures to define a replenishment policy for perishable health products. These products are perishable and substitutable by nature and create complexities for managing inventory. Instead of a financial measure, numerous measures should be considered and balanced to meet business objectives and enhance inventory management.

Design/methodology/approach – This research applies a multi-methodological approach and develops a framework that integrates discrete event simulation (DES), analytic hierarchy process (AHP) and data envelopment analysis (DEA) techniques to define the most favourable replenishment policy using non-financial measures.

Findings – The integration framework performs well as illustrated in the numerical example; outcomes from the framework are comparable to those generated using a traditional, financial measures-based, approach. This research demonstrates that it is feasible to adopt non-financial performance measures to define a replenishment policy and evaluate performance.

Originality/value – The framework, thus, prioritises non-financial measures and addresses issues of lacking information sharing and employee involvement to enhance hospitals' performance while minimising costs. The non-financial measures improve cross-functional communication while supporting simpler transformations from high-level strategies to daily operational targets.

Keywords Perishable inventory management, Substitutable, Decision systems

Paper type Research paper

1. Introduction

Management of inventories involving health products, which are typically perishable and substitutable, is a difficult problem with many particular challenges (Salehi *et al.*, 2019). These challenges come from the fact that these products have a limited lifetime and the requirement for the trade-off between inventory costs and the fill rate (Dreyfuss and Giat, 2019). For example, consider blood platelets, which are a standard product in hospitals. Blood platelets can be stored up to seven days before their function is destroyed (Lin *et al.*, forthcoming). An inventory manager aims to lower the inventory level of blood platelets to lower inventory costs and the loss from outdated stock. On the other hand, when required, patients should be able to be transfused with the same blood platelet as their own or a compatible platelet; otherwise, lives may be lost. In dealing with this challenge, the objective of hospital inventory management is to develop a framework that enables information sharing (Yu and Cao, 2019) and identifies replenishment policy that reduces inventory levels without lowering the fill rate level (Moons *et al.*, 2019).

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Hospitals often generate replenishment policies by minimising total cost or maximising total profit functions, which may include some or all relevant financial factors (e.g. holding cost, ordering cost) (Lin *et al.*, forthcoming). This financial approach is based on the inventory theory in which cost factors are assumed to be known exactly. However, the exact value of these factors could be challenging to define. Consequently, the optimal policy may not result in the minimum cost or maximum profit (Elgazzar *et al.*, 2019). Additionally, financial measures have been criticised as too one-dimensional (Micheli and Mura, 2017); e.g. focusing too much on the fill rate level may lead to high inventory level or high expired quantity. Rather than optimising a financial measure, researchers (e.g. Dreyfuss and Giat, 2019; Dweekat *et al.*, 2017; Vidalis *et al.*, 2014) have called for the use of non-financial measures when generating replenishment policies. Using non-financial measures enables the connection of performance measures to strategy and hence provides enhanced control of the overall performance in a more cooperative and integrated routine (Dweekat *et al.*, 2017).

Motivated by that call, this research aims at answering questions: is it possible (RQ1) and how (RQ2) to use non-financial measures to define a replenishment policy for perishable health products? To answer the RQ1, we base on the work of Cannella *et al.* (2013), who proposed a set of non-financial measures to evaluate performance for a whole supply chain. We identify the most common costs in perishable inventory models, namely, holding cost, purchase cost, lost sales cost and outdated cost (Kouki *et al.*, 2014). These costs are translated into non-financial measures including fill rate (FR), average inventory (AI) and order rate variance ratio (ORVR) by using the definition of non-financial measures from Cannella *et al.* (2013).

To answer the RQ2, we develop a framework including simulation, analytic hierarchy process (AHP) and data envelopment analysis (DEA) to use these non-financial measures and identify a replenishment policy. A simulation tool is useful for evaluating various performance measures of complex systems (Heidary and Aghaie, 2019). These measures usually conflict with each other. Furthermore, the preferences for which performance measures to use vary between managers. Therefore, the simulation tool should be combined with other multi-criteria decision-making (MCDM) methods (Choi *et al.*, 2016). Among MCDM methods, AHP has been used widely as its abilities in quantifying criteria (Moktadir *et al.*, 2019). The AHP has been integrated with DEA to avoid difficulties when having too many alternatives (Ho and Ma, 2018). The integration of simulation, AHP and DEA can take advantage of the strengths of each method (Choi *et al.*, 2016) and support framework for complex systems (Bonney and Jaber, 2014; Ho and Ma, 2018). The framework is demonstrated with a numerical example. The results are shown to be comparable with those from Kouki *et al.* (2014), where a similar system is studied with financial measures, and thus the similarity confirms the contribution of this research to the literature. The results prove that non-financial measures can be used effectively to generate replenishment policies.

Two interesting findings emerged from this research. First, this research uses non-financial measures (AI, FR, and ORVR) by themselves to define a replenishment policy. These are the most common measures in the blood supply chain problem, i.e. the number of outdated units, the number of units short of demand and the stock level (Ahmadi *et al.*, 2019). The direct use of non-financial measures helps stakeholders better understand the overall performance of a company or its subordinates (Esch *et al.*, 2019). While Vidalis *et al.* (2014) demonstrated the transformation of non-financial measures into a profit function and selection of the replenishment policy that maximised total profit, it is not easy in practice to transform all non-financial measures into a profit function due to delays in collecting information or the inaccuracy of information over the supply chain (Moons *et al.*, 2019). In contrast to Vidalis *et al.* (2014), this research does not transform non-financial measures into cost factors; therefore, replenishment policies are easily communicated and comprehended. The framework, therefore, prioritises non-financial measures and addresses issues of lacking information sharing and employee involvement (Moktadir *et al.*, 2018) to enhance overall hospitals' performance.

Second, the framework is relevant to the call of developing a user-friendly approach which can be used by healthcare managers to evaluate a set of limited scenarios rather than developing a sophisticated programme or model (Ahmadi *et al.*, 2019). There are practical difficulties in managing trade-offs between requirements when developing replenishment policies for blood products, as demand is difficult to forecast because it is affected by the availability of other items (Syntetos *et al.*, 2016). The use of mathematical algorithms to define an optimal replenishment policy that reduces costs while achieving fill rate levels has been criticised due to the complexity of the calculations (Zhang *et al.*, 2014). Moreover, as cost factors change across suppliers and hospitals, the optimal replenishment policy will change accordingly. Thus, an easily used and understandable framework to define the optimal replenishment policy in hospitals must be developed to enhance practice.

The next section reviews inventory management of perishable health products, the use of non-financial measures in inventory management, and defines the gaps in the literature. Section 3 describes the research methodology and presents the framework to define the most favourable replenishment policy. Section 4 presents a numerical example and illustrates the application of the framework. Section 5 discusses the results. Section 6 concludes the research and provides future research directions.

2. Literature review

2.1 Perishable health products

There is limited literature on inventory management for perishable health products (Hosseinifard and Abbasi, 2018). However, these products are perishable; thus, general perishable inventory theory can be employed to its management. There are comprehensive reviews of perishable inventory management (Janssen *et al.*, 2016) and hospital inventory management (Ahmadi *et al.*, 2019) that provide an extensive overview of relevant literature. Specifically, the primary challenge managing perishable health products is that their lifetime is shorter than other perishable products, and this adds complexity to the management challenges and results in greater research on this characteristic.

In contrast to a single-echelon model, few studies consider a perishable inventory model for a two- or multi-echelon model due to the complexity of a multi-echelon problem (Janssen *et al.*, 2016). Moreover, blood substitution could be used in emergencies when the same blood type is unavailable (Dillon *et al.*, 2017). In this case, the consideration of blood substitution is a valid mechanism to improve the performance of the inventory management system (Hamdan and Diabat, 2019).

2.2 Reasons for using non-financial measures

The complexity of inventory management has risen recently and is exacerbated by a lack of collaboration among involved participants (Ekinci and Baykasoğlu, 2019). In this context, non-financial measures have been identified as an essential research topic as they can capture the dynamics of the inventory management and enable collaboration in inventory management (Dominguez *et al.*, 2018). Non-financial measures can reflect important outcomes of the business, improve information sharing more efficiently, and help ensure that decision-makers have sufficient information to make appropriate decisions (Cannella *et al.*, 2013).

Three critical arguments for using non-financial measures in inventory management has been advanced (Table 1). First, a supply chain model is multi-dimensional and should be analysed from multiple perspectives. As Kaplan and Norton (2005) stated, '[w]hat you measure is what you get. Senior executives understand that their organization's measurement system strongly affects the behaviour of managers and employees'. Therefore, it has been strongly argued that non-financial measures are a better choice as they capture multiple perspectives of the system (Dominguez *et al.*, 2018). Second, inventory management is a part of wider operations and plays a supportive and active role in improving overall company and supply chain performance. Decision-making in inventory management is subject to the power and settings of multiple departments or company settings (Dreyfuss and Giat, 2019). It is a dynamic process that involves many participants with conflicting objectives. It is a common practice for companies with higher bargaining power to require actions from their suppliers to reduce inventory. Thus, a total function is more suitable for a single department as it does not accommodate different departments with different objectives. Third, it is difficult to establish the cost or profit elements in the financial formulas. The use of financial measures has been criticised as they are too aggregate, too late, and one-dimensional (Micheli and Mura, 2017), and the values of input parameters are inaccurate (Bonney and Jaber, 2014). Therefore, the optimal performance of a particular department may negatively affect the overall performance of a company (Wetzel and Hofmann, 2019) and non-financial measures have been recognised as effective alternatives (Asiaei and Bontis, 2019).

In line with this trend, hospitals are being encouraged to use non-financial measures to improve performance (Abdallah *et al.*, 2017). A financial focus may conflict with the mission-oriented nature of hospitals where patient safety is the top priority. Non-financial measures could provide management with overall performance. They can clarify and gain consensus about hospitals' strategies, communicate strategies throughout departments, obtain feedback from patients and employees to improve strategy (Kaplan and Norton, 2005). Non-financial measures can strengthen patient relations, refocus internal operations, or increase loyalty and returns of value. They give a more comprehensive and accurate view of the complex work of hospitals than financial measures (Abdallah *et al.*, 2017). It is worthy to note that, since 2003, the UK NHS has used more non-financial measures to determine improvements in hospitals (Malmmose, 2019). Thus, this research advocates the use of non-financial measures in managing inventory for perishable health products.

2.3 Gaps in using non-financial performance measures

Despite the advantages of using non-financial performance measures, two disadvantages limit the application of these measures to select the most favourable replenishment policy. First, various non-financial measures can be used, but for a perishable inventory model, these non-financial measures are normally considered with total cost or profit function. For instance, the total cost function is considered with the bullwhip effect ratio for a medication inventory system (Gebicki *et al.*, 2014), with blood shortage and wastage (Dillon *et al.*, 2017), or with blood delivery time and the number of outdated units (Hamdan and Diabat, 2019). Alternatively, Minner and Transchel (2017) investigated the effect of a retailer's order variability on the total profit at the supplier in a perishable inventory model. So far, a range of non-financial measures has been used together with financial measures of perishable inventory model.

Table 1.
Comparison between financial and non-financial measures

Financial measures	Non-financial measures
Focus on one dimension	Capture multi-dimensional nature of the supply chain
Suitable for one department or one company	Suitable for the whole supply chain (i.e., multi-department or multi-companies)
Difficult to estimate the values of input parameters	Do not need to establish the cost or profit functions

Second, non-financial measures conflict with each other, and thus, no unique and well-defined framework can be followed step-by-step for a decision-making process (Moreira and Tjahjono, 2016). In these contexts, simulation optimisation has been commonly used; for instance, to evaluate the performance of hospital supply chains (Kochan *et al.*, 2018) or inventory policies (Gebicki *et al.*, 2014; Minner and Transchel, 2017). Using non-financial measures supports sharing information between departments and motivates the performance of people (Senot *et al.*, 2016); however, the use of simulation optimisation limits the applicability of non-financial measures in practices (Zhang *et al.*, 2014).

This research aims at filling the gaps in using non-financial performance measures for perishable health products. First, a set of non-financial measures is selected for the multi-echelon model. Second, a framework is developed to define the most favourable replenishment policy by using non-financial measures.

3. Research methodology

3.1 Basic model

This research considers a centralised blood inventory model, including a blood centre that supplies blood platelets to two hospitals. This studied model is designed according to suggestions that a region with one blood centre operates most economically (Hosseinifard and Abbasi, 2018). The blood centre receives demands from hospitals and makes decisions on when and how many to replenish. This centralised model is beneficial for the whole supply chain network due to the low inventory cost and the high fill rate level (Duan and Liao, 2014). For substitution, we consider three highly compatible ABO types (A, B and O) (Duan and Liao, 2014) (e.g. a patient with blood type A+ can receive blood from types A+, A−, O−, or O+). These blood platelets are substitutable and have a random lifetime as the platelets received may not completely fresh (Hamdan and Diabat, 2019). Items are dispatched and used under the first in first out rule (FIFO) as it is the optimal rule in the blood inventory management (Hosseinifard and Abbasi, 2018). The blood centre and hospitals replenish inventory according to the periodic review inventory policy (T, S). The lead time L, $L \leq T$ to ensure there is at most one outstanding order at any time and to reduce the complexity of the model (Kouki *et al.*, 2014). Under the stock-out situation, doctors can substitute a blood type with another one or delay the treatment. The focus is on the trade-off between fill rate levels and inventory costs. Increasing the inventory level could lead to high fill rate levels, but the inventory costs are also high (Ahmadi *et al.*, 2019; Duan and Liao, 2014).

In contrast to extant research, this research does not optimise a total financial function to define the most favourable replenishment policy because inventory costs in hospitals are intangible and difficult to measure (Moons *et al.*, 2019). To avoid this difficulty, we adopted non-financial measures that cover these inventory costs in the hospitals.

3.2 Justification for the performance measures adopted

This two-echelon model bears similarity to the bullwhip effect research as demand information passes over two echelons that are vulnerable to external factors (e.g. emergencies) and creates high demand fluctuations and the bullwhip effect (Cannella *et al.*, 2013). The bullwhip effect is also a concern in hospital supply chains. Gebicki *et al.* (2014) empirically showed that the bullwhip effect not only presents at the hospital, but its degree is also significant (over 100%). In response, this research includes a performance measurement system developed by Cannella *et al.* (2013) based on the review of the bullwhip effect literature. Cannella *et al.* (2013) suggested that performance measurements should assess internal process capacity and customer satisfaction at both local and systemic performance levels. Then, the authors proposed that non-financial measures, including ORVR, AI, inventory variance ratio, work in progress (WIP) variance ratio, zero-replenishment, backlog and FR.

3.3 *Non-financial measures*

From recent works (e.g. Ahmadi *et al.*, 2019; Kouki *et al.*, 2014), we identify common costs in perishable inventory management, including ordering cost, holding cost, outdated cost, and stock-out cost. Using the guidelines outlined by Cannella *et al.* (2013), we convert these costs to three non-financial measures, namely, AI, FR, and ORVR. The AI is the mean of the inventory level during an inspection time to assess inventory investment. This measure provides information on inventory investment, probability of expiration, stock capacity utilization, and relates to holding and outdated cost. The FR is the percentage of orders delivered on time and is representative of other customer satisfaction measures. This measure relates to the customer service level and stock-out cost. The ORVR, defined as the ratio of the order variance at an echelon to the order variance of the consumer (or market demand), is the most common measure used to identify the bullwhip effect. This measure provides information on the cost of procurement and subcontracting.

Since these non-financial measures conflict with each other, it is impossible to find a replenishment policy which optimises all three measures simultaneously (Choi *et al.*, 2016). Instead of that, this research aims at developing a framework that finds the most favourable replenishment policy, which is the best trade-off between these three non-financial measures.

3.4 *Decision framework*

As the perishable and substitutable inventory model has a wide of range of replenishment policies, simulation has been used to evaluate the performance of each policy (Heidary and Aghaie, 2019). These performance measures reflect different dimensions, such as customer service or inventory level. They usually conflict with each other and reflect on the different perspectives of different people. Thus, it calls for the combination of simulation and multi-criteria decision-making (MCDM) methods (Choi *et al.*, 2016).

Among MCDM methods, AHP developed by Saaty (2008) has been applied in many studies such as business, management, education, engineering, and manufacturing. The AHP method simplifies the decision process and supports decision-makers to quantify criteria (Moktadir *et al.*, 2019). However, Falsini *et al.* (2012) identified some practical problems in the AHP method: It needs a high number $(n\,(n-1)/2)$ of pairwise comparisons for n elements and requires a high consistency index. It also entails the replication of the procedure when there are variations in the number of alternatives and/or criteria. Therefore, AHP has been integrated with other methods to avoid these problems (Moktadir *et al.*, 2018). Particularly, AHP could be integrated with DEA to construct a ranking model and this integration reduces the pairwise comparisons (Ho and Ma, 2018).

Given the advantages and disadvantages of simulation, AHP and DEA, and considering research objectives, this research proposed the integration of these three methods to define the most favourable replenishment policy. Integration is the right solution to manipulate the advantages and overcome the disadvantages of these methods (Choi *et al.*, 2016). This framework is in line with the suggestion by Bonney and Jaber (2014) to formulate a decision support framework for complex systems.

The integrated framework has three steps (Figure 1). First, the studied supply chain model was simulated, and each scenario (i.e. replenishment policy) was executed in the simulation model. The performance measures of each scenario were extracted and recorded. Second, the importance of each performance measure was ranked using AHP. Third, each scenario was evaluated and ranked using DEA. The scenario that has the lowest DEA efficiency score was selected as the most favourable replenishment policy.

4. Numerical example

In this section, we conduct a numerical example to illustrate the utility of the framework in finding the most favourable replenishment policy. The mathematical formulation of the basic model is described next.

4.1 Model description

The notations and formulas are formed and presented as follows:

i The number of hospitals $i = 0, 1, 2$

$i = 0$ means the blood centre

j The number group of blood platelets $j = 1, 2, 3$

t The number of periods in model $t = 1 \ldots T$

β The required fill rate level

S_j^i Maximum inventory level of item *jth* at *ith* blood centre and hospitals

$I(t)_j^i$ The inventory level of group j at the hospital i at the beginning of period t

$D(t)_j^i$ The demand of group j at the hospital i for the period t

$p_{jj'}^i$ The probability that group j is substituted with group j' at the hospital i if the group j is out of stock at the hospital i

l The lost sales probability

λ Rate of Poisson distribution of demand

$1/\delta$ Rate of exponential distribution of lifetime

L Replenishment lead time

T Review period

S Order-up-to level or inventory target

$s^2_{Or(t)_j^i}$ The order variance of group *jth* at the blood centre and hospital *ith*

$s^2_{DE(t)_j^i}$ The variance of demand for group *jth* at the blood centre and hospital *ith*

In the inventory management problem, the demand function is first defined. As blood groups are substitutable, the demand of one group includes the original demand and the demand due

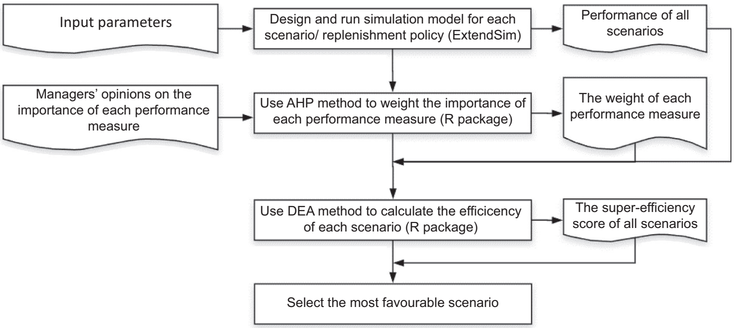

Figure 1.
Integration framework of the simulation/AHP/DEA model

to the substitution of other groups. The substitution demand is equal to the excess demand multiplied by the substitution ratio, and the effective demand is a total of the original demand and the substitutable demand (Duan and Liao, 2014). Hence, the effective demand function is defined as:

$$DE(t)^i_j = D(t)^i_j + \sum p'_j j^i \left(D(t)^i_{j'} - I(t)^i_{j'}\right)^+, \text{ where } x^+ = \max(x, 0) \tag{1}$$

The substitution ratio is calculated by the substitution matrix method used by Agrawal and Smith (2019). The substitution ratio formula is:

$$p'_j j^i = \frac{1-l}{j-1} = \frac{1-l}{2} \tag{2}$$

Then, the inventory level, outdated quantity, and shortage quantity are calculated based on the effective demand function. The inventory level in a period is calculated from the target inventory level, demand quantity, outdated quantity, and shortage quantity, as suggested by Kouki *et al.* (2014):

$$I(t)^i_j = \left(S^i_j - DE(t)^i_j - O(t)^i_j + SE(t)^i_j\right)^+ \tag{3}$$

where the shortage quantity of group *jth* at the blood centre and hospital *ith*, which includes the shortage because of substitution with other items, is

$$SE(t)^i_j = \left(DE(t)^i_j - I(t)^i_j\right)^+ \tag{4}$$

Moreover, the outdated quantity of group *jth* at the blood centre and hospital *ith* is

$$O(t)^i_j = \delta * I(t)^i_j \tag{5}$$

The order quantity of product *jth* at the blood centre and hospital *ith* is

$$Or(t)^i_j = S^i_j - I(t)^i_j \tag{6}$$

The performance measures for the inventory management model are calculated below using the formulas presented in the work of Cannella *et al.* (2013).

The ORVR at the blood centre and hospital *ith* for group *jth* is

$$ORVR^i_j = \frac{s^2_{Or^i_j}}{s^2_{DE^i_j}} \tag{7}$$

The AI of the group *jth* at the blood centre and hospital *ith* is

$$AI^i_j = E\left[I(t)^i_j\right] \tag{8}$$

The FR of the group *jth* at the blood centre and hospital *ith* is

$$FR^i_j = \frac{I(t)^i_j - SE(t)^i_j}{DE(t)^i_j} \tag{9}$$

As this research develops an alternative approach for finding the replenishment policy, it is necessary to compare the results of this research and similar research; therefore, similar parameters are adopted to those used by Kouki *et al.* (2014). The demand of these groups follows a Poisson distribution with a mean of 15; the lifetime of blood platelets follows an exponential distribution with a mean of 6, the fixed lead-time is 1, and the lost sales probability is 0.9.

4.2 Numerical results

This section presents the results received from the non-financial framework in this research. First, a simulation model was built on ExtendSim software to evaluate the performance of each replenishment policy. Events follow the sequence: (1) perished blood platelets are discarded, (2) a replenishment order arrives and is updated to inventory, (3) demand is observed and filled, (4) the inventory level is reviewed if it is a review period and (5) a replenishment order is triggered. Each replenishment policy was replicated ten times, the length of each simulation was 200,000 units of time (i.e. days), and the first 5,000 data were discarded from calculating the system's performance because of the warm-up period.

There are 88 possible replenishment policies with the range of T and S, which are reused from Kouki *et al.* (2014) as follows:

(1) $T \geq T_{min} = L = 1$

(2) $T \leq T_c = 4$, T_c: review period in case the product has an infinite lifetime

(3) $26 \leq S \leq 47$,

The replenishment policies were evaluated by three conflicted performance measures: AI, FR and ORVR. Different managers have different perspectives on the importance of each measure, e.g. a financial director may prioritise reducing inventory while a surgeon prefers high inventory to have blood products whenever she wants. A selected replenishment policy must be a trade-off between these opinions. This research uses the AHP method to synthesise these opinions to determine the overall importance of performance measures.

In the context of hospital operations, a stock-out situation may be fulfilled from an internal source (i.e. substitute with other items) or an external source (i.e. order the same items from other blood centres or hospitals). This research will consider only the internal substitution scenario because ordering from an external source incurs additional fees and long lead time (Vila-Parrish *et al.*, 2012). If the stock-out situation happens frequently, the treatment results may not be satisfactory. Thus, it is crucial to have appropriate inventory levels or high fill rate levels, and blood centres and hospitals consider FR is the most important performance measure.

These blood platelets have limited lifetime; keeping too much inventory could lead to high loss due to expired items. Ideally, the blood centre and hospitals aim to have a low inventory level that reduces costs (Moons *et al.*, 2019). Since the blood centre and the two hospitals are within a region, the ordering and procurement costs are not problematic. As these costs are relevant to ORVR, the ORVR is not problematic in this case study. This information is used to conduct pairwise comparisons for the AHP. The FR was the most important measure, followed by AI and ORVR.

Based on this information, the consistency and the importance of each measure are calculated by using the R package 'pmr' (Lee and Yu, 2013). The results showed that the consistency ratio was 3.9%, less than the critical value 10%; so there was no evidence of inconsistency (Saaty, 2008). Therefore, the pairwise comparisons can be conducted to calculate the importance of each measure. The weighting results for AI, FR, and ORVR were $w1 = 21.7\%$, $w2 = 71.7\%$, and $w3 = 6.6\%$, respectively.

Finally, the DEA method was used to evaluate and rank the performance of replenishment policies. The DEA model in this research has two inputs (i.e. T, S), and 27 outputs (i.e. $w1/AI$, *w2*FR, and w3/ORVR* for one blood centre, two hospitals, and three blood platelets). There is are 88 DMUs or replenishment policies, which are combinations of the review period and order-up-to level.

This research applied the super-efficiency method developed by Cook *et al.* (2009) due to its abilities in discriminating against the best DMU. Moreover, this research aims at improving the model's performance; the output-orientation is suitable for the model as recommended by Cook *et al.* (2009). The results showed that the replenishment policy (1, 26) had the lowest super-efficiency score at 0.45147 and, thus, was the most favourable replenishment policy. In the given a range of replenishment policies and a context of perishable inventory management for a blood centre and two hospitals, this replenishment policy best balances the three performance measures – AI, FR, and ORVR.

4.3 Sensitivity analysis

We conduct sensitivity analysis to understand the effects of different opinions on the weight of performance measures and the selected replenishment policy. We apply the sensitivity analysis technique used by Minner and Transchel (2017), where the weight of one measure is varied from low (10%) to high (90%) while the ratio of the other two measures is unchanged. Table 2 presents six scenarios or sets of weights associated with the change of each performance measure.

Figure 2 shows that while increasing AI from low value (10%) to high value (90%), the policy (1, 26) has the lowest super-efficiency score. Similar results are found in Figures 3 and 4 for the consideration of low and high values of FR and ORVR, respectively. The finding indicates that the policy (1, 26) is the most favourable replenishment policy under all studied situations, and thus, the selection of the most favourable replenishment policy is stable under the studied contexts.

5. Findings

In this research, the selected policy (1, 26) was comparable to the findings from Kouki *et al.* (2014). The AHP method conducted in this research showed that FR was the most important measure (71.7%), followed by AI (21.7%) and ORVR (6.6%). In this context, it was preferable to have a policy that has high FR or low lost sales quantity. Kouki *et al.* (2014) showed that for a given order-up-to level, the longer review period has a higher quantity of expired products and lost sales. Moreover, a short review period decreases the fluctuation of order quantity and, thus, ORVR. The short review period and order-up-to level also reduce the daily inventory level and the AI level. Therefore, the selected policy (1, 26) was reasonable and comparable with findings in Kouki *et al.* (2014). Because of the advantages of the non-financial measures, the framework is an alternative for decision-makers to select the replenishment policy in a blood centre or hospitals.

6. Discussion and conclusion

This research considered inventory management for perishable health products. The perishable and substitutable nature of these products causes complexities in balancing

Table 2.
The weights along with the change of each measure and the original weight

Scenario	Testing measure	AI (21.7%)	FR (71.7%)	ORVR (6.6%)
1	AI	10.0%	82.4%	7.6%
2	AI	90.0%	9.2%	0.8%
3	FR	69.0%	10.0%	21.0%
4	FR	7.7%	90.0%	2.3%
5	ORVR	20.9%	69.1%	10.0%
6	ORVR	2.3%	7.7%	90.0%

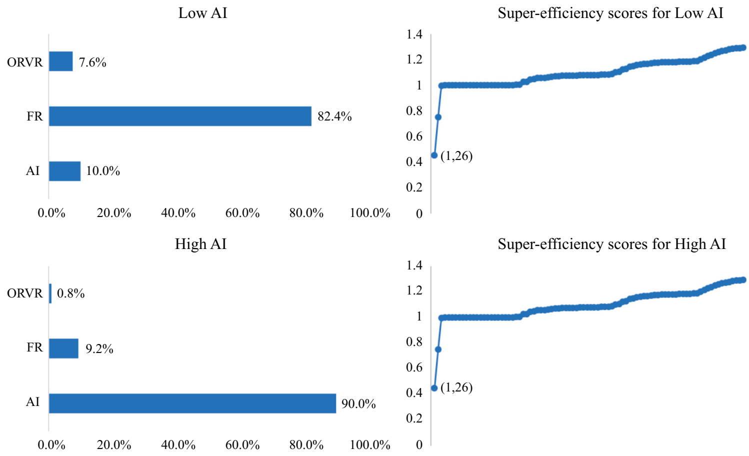

Figure 2.
Sensitivity analysis of AI influencing the super-efficiency scores

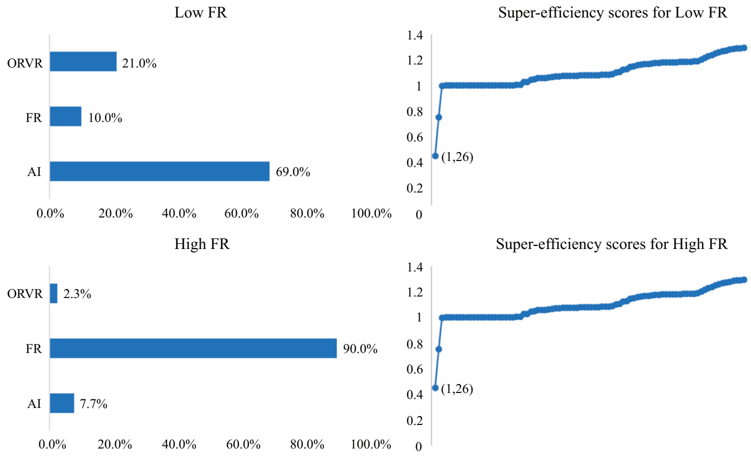

Figure 3.
Sensitivity analysis of FR influencing the super-efficiency scores

objectives and identifying a suitable replenishment policy. This research argued that non-financial measures reflect the multi-dimensional nature of supply chain management. This research, to our knowledge, is the first work to develop a framework that balances non-financial measures to define a replenishment policy for perishable and substitutable products. It provides a way to effectively reduce the loss of quality and quantity and an alternate approach to manage inventory and improve hospital performance.

6.1 Theoretical contributions

This research has two important contributions to the inventory management theory. First, it enhances the perishable inventory theory by proposing three non-financial measures for identifying replenishment policies. Non-financial measures transform and convey a company's strategies and visions to communicate strategic objectives and motivate performance (Kaplan and Norton, 2005; Senot *et al.*, 2016). Thus, researchers (e.g. Dreyfuss and Giat, 2019; Dweekat *et al.*, 2017; Vidalis *et al.*, 2014) have called for using non-financial

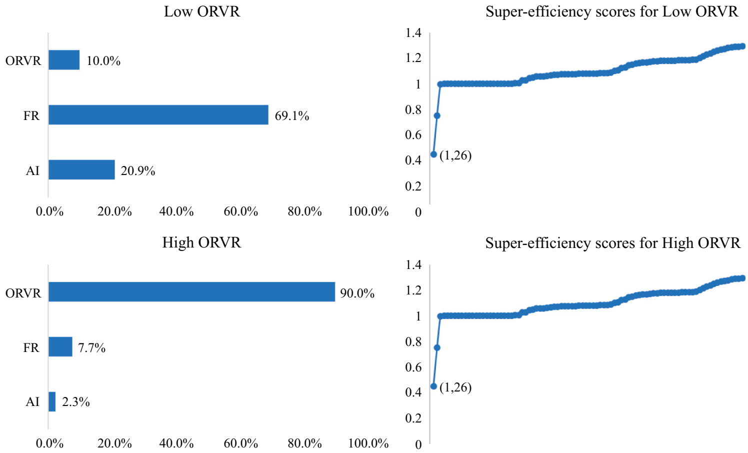

Figure 4.
Sensitivity analysis of ORVR influencing the super-efficiency scores

measures in inventory management. This research, in response to that call, considers common factors in a total cost function in perishable inventory management, specifically: holding cost, purchase cost, lost sales cost, and outdated cost (Kouki *et al.*, 2014). Applying the definition from Cannella *et al.* (2013), these costs are translated into non-financial measures including AI, FR, and ORVR, which are used to select a replenishment policy that is the best trade-off in all three non-financial measures (i.e. AI, FR, and ORVR).

For hospital inventory management, this is a significant contribution. Inventory management is a crucial driver for efficiency improvement (e.g. cost reduction) while sustaining the healthcare service level (Moons *et al.*, 2019). In hospitals, several uncertain factors (e.g. products' lifetime or demand) create more complexity in selecting a suitable replenishment policy. Traditional methods of using financial measures may be inappropriate under some contexts, e.g. the annual-dollar-usage ranking method may under-emphasise low annual cost items that are important or vice versa (Dreyfuss and Giat, 2019). Other issues are poor inventory practices as it is difficult to quantify ordering costs or holding costs in hospitals (Abdallah *et al.*, 2017). Using non-financial measures overcomes these difficulties and improves hospital inventory performance (Ahmadi *et al.*, 2019).

This research extends the work of Vila-Parrish *et al.* (2012) to consider situations where blood groups could be substituted from internal or external sources. It is aligned with the call for attention on service levels and uncertainties such as patient conditions, demand, or product quality (Ahmadi *et al.*, 2019). By using non-financial measures, our model has the ability to consider patient safety issues and service levels (with fill rate) and deal with uncertainties (with average inventory and order rate variance ratio). It extends the recent works of Dillon *et al.* (2017) and Hamdan and Diabat (2019) by only considering non-financial measures. Thus, this research avoids difficulties with financial measures and improves the performance of perishable inventory management.

Second, this research develops a decision framework that integrates DES, AHP, and DEA to select the most favourable replenishment policy. In contrast to other studies that use mathematical algorithms (Lin *et al.*, forthcoming), the proposed integration of simulation, AHP, and DEA enables the investigation of relationships between problem's characteristics (e.g. product lifetime or decision-makers' opinions) (Bonney and Jaber, 2014; Moktadir *et al.*, 2019). While mathematical algorithms have been widely used to select the best trade-off among conflicting objectives for perishable inventory management problems, they require a large amount of enumeration memory, complex calculations, and have high sensitivity to input values (Zhang *et al.*, 2014). In contrast, we developed a framework that includes three steps that alleviate these problems. A simulation model of the perishable inventory model, developed by the DES method, is run for each scenario or replenishment policy that is a pair of the review period and order-up-to level. The performance of each replenishment policy is measured by three non-financial measures (i.e. AI, FR, and ORVR). As these measures conflict with each other, it is impossible to optimise all of them simultaneously (Choi *et al.*, 2016). We, therefore, integrate AHP and DEA to the simulation model. While there is a large body of literature on various combinations of simulation, AHP, and DEA (Choi *et al.*, 2016; Ho and Ma, 2018; Moktadir *et al.*, 2018), few studies integrate these three methods in a comparable framework to analyse the challenges associated with perishable inventory management. This research considers a trade-off solution between three measures; thus, the use of simulation with AHP and DEA is reasonable. The importance of each performance measure, calculated by AHP, is multiplied by the values received from the simulation model to identify the relative value of each measure. After that, the DEA, Cook's super-efficiency method (Cook *et al.*, 2009) is performed to evaluate and rank the performance of each replenishment policy. The most favourable replenishment policy was selected from the policy having the lowest DEA supper-efficiency score.

6.2 Practical contribution

This research allows consideration of multiple measures and encourages greater participation from more departments or managerial roles. In contrast to Duan and Liao (2014), who considered only the outdated level to select the most favourable replenishment policy with a given fill rate level, this research considered multiple measures without predetermining the constraint level of any measure. This research used the AHP method, which enables decision-makers to use business objectives and reference to the business environment to negotiate and define the importance of each measure (Moktadir *et al.*, 2019).

Inventory management has been highlighted as one of the challenges to the global healthcare sector (Privett and Gonsalvez, 2014). Fundamental approaches should be taken to increase the collaboration among supply chain partners, which improves inventory management and overall efficiency (Moktadir *et al.*, 2018). For example, sharing information on the remaining lifetime of blood units could reduce the number of outdated units and improve inventory performance. However, one of the main barriers to developing collaboration in hospital inventory management remains objective incongruence, as different supply chain partners (e.g. departments or hospitals) have different business objectives (Duijzer *et al.*, 2018). For example, while donors want to trace impact for each health product, the efforts to provide traceability usually require time, labour, and cost, which lower efficiency in hospitals (Feibert and Jacobsen, 2019; Kraiselburd and Yadav, 2013).

In summary, while there are several conflicting objectives for inventory management in the healthcare sector, we have been missing an approach for selecting relevant performance measures in this sector (Moons *et al.*, 2019). This research proposes a framework for using non-financial measures for inventory management. The integration framework is in line with the call to apply supply chain collaboration in practice (Senot *et al.*, 2016). It reduces the bullwhip effect, enhances the sharing of information and creates a transparent demand pattern for enhancing the entire supply chain performance (Cannella *et al.*, 2013). It also provides performance targets and correlated information for related departments (Senot *et al.*, 2016). Managers could communicate business objectives easily and motivate people and departments concerning their performance that positively impacts employee satisfaction and the achievement of company objectives (Elgazzar *et al.*, 2019).

Our research offers opportunities to provide incentives to reduce waste. For instance, by providing a financial bonus and encouraging doctors to notify the inventory department before providers supply surgical items, a California hospital reduced inventory costs by 7.5% (White, 2017). Thus, it is beneficial to get staff involved in the process of reducing waste. With the use of non-financial measures, our research makes communication easier and gets staff involved in programmes to improve inventory at hospitals.

6.3 Future research

Findings from this research suggest several research directions. While three non-financial measures were considered, the identification of other non-financial measures may depend on research contexts. Further, the AHP-based model may be biased as it depends on expert opinions and a fuzzy-based AHP method might reduce human bias (Moktadir *et al.*, 2018). The decision framework in this research could be applied to a supply chain model having more than two echelons or more than three substitutable products. Alternatively, future research could relax the assumption of periodic review policy (T, S) with a fixed lead-time. Other types of replenishment policies or substitution ratios may be adapted to extend this research. Our research can be applied to other types of perishable products (e.g. foods). It can also be extended to directions towards the reduction of unused supplies, waste and potential pollution.

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