Journal Pre-proof

Performance indicator selection for operating room supply chains: An application of ANP

Karen Moons, Geert Waeyenbergh, Liliane Pintelon,
Paul Timmermans, Dirk De Ridder

PII: S2211-6923(17)30149-2
DOI: <https://doi.org/10.1016/j.orhc.2019.100229>
Reference: ORHC 100229

To appear in: *Operations Research for Health Care*

Received date : 3 October 2017
Accepted date : 6 November 2019

Please cite this article as: K. Moons, G. Waeyenbergh, L. Pintelon et al., Performance indicator selection for operating room supply chains: An application of ANP, *Operations Research for Health Care* (2019), doi: <https://doi.org/10.1016/j.orhc.2019.100229>.

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2019 Published by Elsevier Ltd.

Performance Indicator Selection for Operating Room Supply Chains: an Application of ANP

Karen Moons¹, Geert Waeyenbergh², Liliane Pintelon¹, Paul Timmermans³, Dirk De Ridder⁴

Contact: Karen.Moons@kuleuven.be, Celestijnenlaan 300 bus 2422, 3000 Leuven, Belgium

¹ KU Leuven, Centre for Industrial Management / Traffic & Infrastructure

² KU Leuven, Research Group Sustainable Engineering

³ UZ Leuven, Logistics & Supply Chain Management Department

⁴ UZ Leuven, Department of Development and Regeneration

Abstract

Manufacturing and maintenance processes significantly benefit from effective and integrated supply chain management. Recently, hospitals start to recognize the importance of these logistics initiatives to improve their operational performance while also maintaining high quality of patient care. Patient care processes are supported by a range of supply chain activities including inventory management and distribution of medical supplies to point-of-care locations. At the operating room for instance, the logistics staff's goal is managing materials and information flows to have the requested materials at the right operating room at the right time, in the most efficient way. However, poor inventory management, lack of standardization and lack of coordination between departments complicate healthcare logistics processes, and hence result in many waste. Opportunities for efficiency gains in these logistics processes can be identified by measuring the performance of the internal supply chain. This paper presents a rigorously defined logistics performance measurement framework to evaluate the efficiency of logistics processes in operating rooms. The Analytic Network Process (ANP) is utilized as a popular Multi-Criteria Decision-Making (MCDM) technique to provide effective decision-support models. The proposed ANP-based framework is a first step towards measuring the performance of operating room supply chain processes by selecting and prioritizing logistics objectives and associated key performance indicators. Further research is required to validate the ANP framework by including multiple stakeholders' preferences, as they may have conflicting views on performance definitions. The final goal of the framework is to support hospital logistics managers in making transparent and informed decisions to improve inventory and distribution policies in the operating room while considering all stakeholders' preferences.

Key words: operating room, supply chain management, performance measurement, multi-criteria decision-making, analytic network process

1. Introduction

The ultimate goal for healthcare services is to provide high-quality care and safety to patients. However, with increasing demand and expenditures, and a movement towards value-based payment models, healthcare managers are forced to pay more attention to the efficient and effective operation of their service delivery processes in order to reduce total costs of care and simultaneously improve patient quality, safety and personnel satisfaction. Although hospital managers recognize the impact of materials management practices on clinical, financial and

operational outcomes, many healthcare organizations struggle to implement efficient logistics programs. Typical problems are stock-outs, paper-based information exchange, lack of inventory visibility, hidden stocks or distribution problems [1]. The main cause of these problems is the universal complexity that characterizes the hospital supply chain, such as unpredictability, fragmented logistics responsibility or complex and dynamic relationships. As a consequence, hospital managers are challenged with standardizing processes and adopting process-oriented optimization approaches [2]. According to Camp et al. [3], the Operating Rooms (OR), in particular, are a costly burden to the hospital as the cost of surgical supplies accounts for 40-60% of total hospital supply expenditures. **These supply expenses include** all items directly linked to the care of patients (e.g. pharmaceuticals, medical consumables, food, laundry, sterile items, laboratory samples, etc.). And thus, the OR setting appears to be a primary target for material management improvement initiatives.

Rothstein et al. [4] and Fong et al. [5] focus on product standardization, surgeon engagement and Supply Chain Management (SCM) to improve OR logistics efficiency. Effective SCM strategies can aid OR logistics managers to achieve operational excellence in their operations “through the use of best inventory management and distribution systems, combined with continuous supply chain process improvements and better integration with the patient care process” [6]. Manufacturing and maintenance processes have successfully adopted process-oriented improvement techniques such as Just-In-Time (JIT), lean, six sigma, Total Quality Management (TQM), Business Process Reengineering (BPR) and benchmarking [7]. In a healthcare setting, process-oriented optimization requires aligning of materials, information and patient flows to improve costs, satisfaction and quality [8]. **Effective coordination of all entities involved in OR logistics processes** is fundamental to achieve a properly functioning OR supply chain, including medical, financial and resource decisions [9]. The approach by Broome et al. [10] focuses on streamlining processes, rationalizing supply utilization and standardizing clinical processes to increase operational efficiency and reduce clinical variability. However, achieving operational excellence in the OR context poses a major challenge to hospital managers as they lack systems for assessing performance of the current processes in order to set future goals according to the hospital’s strategy and objectives [11]. Performance measurement is a major research opportunity in healthcare SCM and Operations Management (OM) literature [12]. SCM measurement systems enable integration among multiple **departments** and aim to improve performance through the effective use of resources [13]. At present, hospitals cannot optimally benefit from reduced costs and improved quality service compared to other industrial sectors due to limited SCM understanding and lack of coordination among stakeholders which lead to poor supply chain performance [14],[15]. A sound methodological approach for measuring performance of healthcare logistics processes, while considering the healthcare sector uniqueness, is missing. Evaluating logistics performance allows hospitals to increase visibility of supply chain processes and hence reduce costs by eliminating waste. Moreover, there is a lack of strategic and operational performance indicators linked to the OR logistics processes and overall hospital strategy, which prevents the implementation of a holistic view [16]. **Hospitals using a performance measurement framework have a competitive advantage as they have control of their supply chain strategy, can implement continuous improvement programs, and have improved decision-making capabilities by focusing on relevant indicators [13].**

This paper contributes to the current literature by presenting a rigorously defined logistics performance measurement framework to evaluate the efficiency of logistics processes in the OR setting. Designing the framework requires a careful selection of objectives and performance indicators tailored to the specific context. Multi-Criteria Decision-Making (MCDM) techniques provide effective decision-support models to select the most relevant or Key Performance Indicators (KPIs) and to help logistics managers identifying improvement areas based on a ranking of KPIs. This KPI ranking indicates what is most important or contributes most to the process performance. However, the involvement of multiple stakeholders with possibly conflicting goals for efficiency management in hospital logistics processes further complicate the decision process. The Analytic Network Process (ANP) is a well-known MCDM method applied for performance measurement by taking into account the complexity of the problem, multiple and conflicting criteria, information availability, stakeholders' preferences and expertise in modeling and analysis [17]. Therefore, we propose a framework, based on ANP, as a first step towards measuring the performance of OR supply chain processes by aligning the overall hospital strategy, logistics objectives and KPIs. The final outcome will be a ranking or prioritization of KPIs, which serves as a useful input for hospital managers to gain managerial insights into tackling the trade-offs which are inherent to OR logistics processes. **The most important KPIs can be tracked to identify potential efficiency gaps in inventory and distribution systems. Moreover, the framework guides hospital managers in making transparent and informed decisions to adopt effective supply chain improvement initiatives while considering all stakeholders' perspectives.**

In this study, the internal logistics processes will be discussed including the storing of disposable surgical supplies close to the OR and the replenishment of decentral and central storage rooms within the OR environment. The remainder of the paper is organized as follows. The literature is reviewed in Section 2, discussing applications of MCDM in hospitals and the need for establishing performance measurement frameworks. This Section also discusses the objectives and performance indicators used in the framework. In Section 3, the ANP method is applied for the performance indicator selection and prioritization problem for OR logistics processes. The results are summarized and discussed in Section 4. Section 5 addresses a sensitivity analysis by varying the criteria weights of the ANP model to quantify potential trade-offs. The paper ends with a final conclusion in Section 6.

2. Literature review

The internal hospital supply chain processes are stated to be the weak link in process optimization and integration [18]. Coordination and integration positively contributes to the performance of the supply chain. The ultimate goal of healthcare SCM is to achieve a “well-coordinated system that delivers care with great efficiency and quality, at reasonable cost, matching the resources for care to where (and when) they are needed most” [19]. However, it is a major challenge for OR logistics managers to assess the performance of the logistics processes and to identify improvement opportunities [9],[20],[21],[22]. Few studies evaluate the impact of SCM strategies for healthcare logistics [23]-[24]. **A recent literature review by Volland et al. [12] focuses on materials logistics in hospitals. The authors identify interesting research possibilities such as integrated optimization across the supply chain in the hospital logistics context, transferring established logistics concepts**

from other industries while accounting for hospital specifics and adopting information technology systems and data standards as enablers for implementing logistics concepts in hospitals. In addition, a logistics performance measurement system is needed to measure and monitor logistics processes within the hospital setting. Although traditional models exist, little attempts have been made to adapt performance measurement models to the specificities of the hospital environment [23].

2.1 MCDM in hospital supply chain management

The Operations Research and Management Science (OR/MS) field provides optimization techniques, such as mathematical programming, computer simulation or queueing theory, for quantitative support and rationalization of planning and control decisions. Inspired on the successful applications of OR/MS methods in many industrial sectors, Hulshof et al. [25] classify planning and control decisions in a healthcare context. Typical examples include patient routing, staff and surgical case scheduling, or capacity allocation [25],[26],[27],[28],[29],[30]. Beck and Hofmann [31] focus on another prominent class of OR/MS problems, namely MCDM techniques used in SCM. MCDM is a quantitative approach to evaluate alternatives based on various, possibly conflicting, criteria by assigning relative weights in order to help decision makers to select the areas for improvement. MCDM methods can use multi-objective mathematical programming, multi-attributive utility theory, outranking or non-classical approaches to support model building, with respectively goal programming or Data Envelopment Analysis (DEA), Analytic Hierarchy Process (AHP) or Analytic Network Process (ANP), PROMETHEE and Fuzzy Set Theory as well-known MCDM approaches [31]. However, a detailed analysis of the theoretical foundations of MCDM is beyond the scope of this article. In the healthcare sector, the number of MCDM applications is increasing to support SCM decisions [30]. MCDM is appropriate because it utilizes quantitative and qualitative information, accounts for multiple conflicting objectives, and makes the decision process more explicit, rational and efficient [31],[32]. Moreover, it helps decision makers in determining performance metrics, eliciting preferences, and trading off between criteria in a consistent and transparent manner [33]. The literature review by Adunlin et al. [32] show increased awareness of MCDM as a sound and rigorous approach to support decision-making in a healthcare setting, especially due to the impact and complexity of healthcare decisions.

AHP and ANP are the most frequently used methods in healthcare because of the flexibility and ability to capture both subjective and objective aspects of decisions. Moreover, these methods are powerful tools for decision-making as they rely on managerial judgment and knowledge of healthcare practitioners [34]. The main issue with AHP is that it cannot model real-world complex problems since it does not consider interdependencies between elements. ANP is a generalization of AHP and goes beyond this problem by systematically dealing with all kinds of dependence and feedback in the system [35]. A number of AHP/ANP applications occur in healthcare problems concerning diagnosis and treatment, priority setting, health technology assessment or hospital location selection [34],[36],[37].

It should be noted that MCDM applications, such as AHP or ANP, have some problems which need to be overcome to achieve its potential. Typical challenges include dealing with uncertainty or incomplete data, aggregating individual judgments and defining whose preferences matter for

different decisions [33]. ANP is limited by its inability to deal with incomplete data or human subjective analysis during the pairwise comparison stage. This uncertainty issue can be addressed by incorporating a fuzzy extension to ANP or by conducting a sensitivity analysis [17],[37],[40]. In addition, decision makers' judgments may be biased. ANP accommodates a group decision-making approach by aggregating individual opinions to prevent a single decision-maker's bias [39]. In the literature, aggregation techniques such as consensus, vote, compromise, geometric mean of judgments are discussed [40],[41].

2.2 Performance measurement frameworks in a hospital context

Today more than ever, both healthcare and industrial sectors are improving supply chain processes to ensure efficient integration among all components. However, different levels of adoption of supply chain practices among hospitals exist which impacts their logistics performance, mainly due to different levels of logistics responsibility, lack of efficient distribution systems or hospital-vendor partnerships [42],[43],[44]. In a healthcare setting, logistics performance measurement frameworks should be developed to account for the unique and complex factors inherent in its supply chain [20]. According to Maestrini et al. [13], supply chain performance measurement systems are defined as “a set of metrics used to quantify the efficiency and effectiveness of supply chain processes and relationships, spanning multiple organizational functions and multiple firms and enabling supply chain orchestration”. Designing effective frameworks ensures a clear definition of performance and requires selecting meaningful performance indicators, which can be financial, non-financial, quantitative or qualitative, and are related to the organization's strategy [38],[45]. Van Horenbeek and Pintelon [39] develop a performance measurement system based on a ANP model to assist managers in defining and selecting relevant indicators in line with the company's objectives and strategy in a maintenance setting. A few studies in literature are concerned about performance measurement frameworks in healthcare logistics and they identify relevant indicators to consider when improving hospital supply chain processes. These are summarized in Table 1 and shortly discussed below.

Di Martinelly et al. [46] apply the Supply Chain Operations Reference (SCOR) model together with Porter's value chain modeling approach to the hospital supply chain and define reliability, responsiveness, flexibility, costs and assets to be five types of performance metrics. De Pourcq et al. [8] use a Balanced Score Card (BSC) model to develop a process-oriented performance measurement system to integrate business functions throughout supporting processes within the hospital. Carrus et al. [47] evaluate hospital logistics innovations, such as Kanban cards, RFID technology or Automated Guided Vehicles (AGVs) by developing a measurement framework based on four performance dimensions, namely costs, benefits, quality and safety. These performance dimensions are also used by Lega et al. [23] in their framework to analyze the impact of supply chain centralization on healthcare logistics performance. Longaray et al. [48] use the MACBETH method to establish a performance framework for measuring internal logistics processes, focusing on infrastructure, materials and people. Supeekit et al. [20] investigates relationships among operations in clinical care and supporting processes to develop a performance measurement framework based on a combination of DEMATEL and ANP. Kritchanchai et al. [49] use the ANP approach to develop a strategy for improving healthcare logistics performance at the

operational level by prioritization of the KPIs. Feibert et al. [7],[50] assume a process-oriented perspective and present a context-specific decision support tool for designing and benchmarking efficient healthcare logistics processes. They identify a set of performance indicators for assessing track-and-trace technologies in healthcare, including quality, resources, productivity, satisfaction and service delivery. El Mokrini et al. [51] propose a multi-criteria framework using AHP to select the appropriate distribution network by considering supply chain responsiveness and costs.

Table 1. Literature overview of performance indicators to measure healthcare logistics.

<i>Di Martinelly et al.</i> [46]	<i>De Pourcq et al.</i> [8]	<i>Feibert et al.</i> [50]	<i>Carrus et al.</i> [47]; <i>Lega et al.</i> [23]
Reliability Responsiveness Flexibility Costs Assets	Financial Customer Internal business Learning and growth	Quality Resources Productivity Satisfaction Service delivery	Costs Benefits Quality Safety
<i>Supeekit et al.</i> [20]	<i>Longaray et al.</i> [48]	<i>Kritchanchai et al.</i> [49]	<i>El Mokrini et al.</i> [51]
Clinical care process efficiency Supporting process efficiency Patient safety	Infrastructure Materials People	Purchasing Warehousing Inventory management Transportation and distribution Information and technology management	Responsiveness Costs

In this study, ANP is chosen to construct a performance measurement framework in the hospital logistics context, and more specifically for the OR. Supeekit et al. [20] combines DEMATEL and ANP to evaluate the internal hospital supply chain performance. Their framework mainly focuses on the interaction between clinical care processes, supporting processes and patient safety while considering the main performance aspects of cost, reliability, time and productivity. However, a more complete and detailed framework is required to further link the performance aspects to business processes of the hospital supply chain and to obtain KPIs for each process in order to improve overall hospital supply chain performance. Kritchanchai et al. [49] develop a logistics performance framework based on ANP to develop a set of KPIs to assess the operational performance. Their results show that inventory management and information and technology management are the most important strategies for improving logistics performance in hospitals, with inventory visibility and availability as the key strategic KPIs. In this work, we will further elaborate on operational indicators covering all aspects of inventory management and distribution to improve overall supply chain performance. The research by Van Horenbeek and Pintelon [39] serves as an interesting opportunity to transfer the knowledge to develop a performance measurement framework in a maintenance setting to a hospital setting. In their framework, relevant KPIs for specific business processes are selected in relation with the company's objectives. However, it will be a challenge in healthcare to adapt it to the specificities, such as taking into account multiple stakeholders with conflicting opinions for hospital performance. Moreover, measuring KPIs in healthcare is not straightforward due to lack of data.

2.2.1 Performance metrics in a hospital logistics context

Operational efficiency can be measured via a broad range of indicators. Selecting meaningful performance metrics is a challenging task for decision makers, as different organizations use different metrics based on company goals, strategies or policies [52]. In order to design a flexible performance measurement model applicable to various healthcare supply chains, the purpose is to find a generalized list of logistics performance metrics, which can be customized according to the specific context or situation needs [39],[51]. In this study, the set of KPIs impacting the OR logistics supply chain is selected based on a comprehensive literature review by Moons et al. [53] and **expertise of the OR logistics manager**. Moons et al. [53] discuss internal hospital supply chain performance measurement systems for inventory management and distribution systems, and define a set of performance indicators categorized according to four objectives: quality, time, financial and productivity/organization. Based on the literature and the experience of the authors, the objectives and a set of indicators for measuring performance of inventory and distribution in ORs are summarized in Table 2. The Appendix A.1 and A.2 contain definitions for each indicator, and sub-indicators are proposed.

Table 2. Objectives and indicators to measure OR logistics performance.

Objectives	Definition	Inventory indicators	Distribution indicators
Quality	Quality specifies how well a specific activity has been performed, ensuring that patients receive care service in a safe manner and that problems such as medical errors are minimized	Inventory service level (ISL) Inventory visibility (IV) Inventory accuracy (IA) Inventory criticality (ICr)	Distribution service level (DSL) Centralization impact (CI) Delivery accuracy (DA)
Time	Time involves the time to complete the logistics operations to ensure that the right items are at the right place and time		Replenishment lead time (RLT) Response time (RT) Clinical staff involvement (CSI)
Financial	Financial indicators identify supply chain cost drivers, such as expenses incurred by departments for providing services, including direct and overhead costs for inventory and internal distribution	Inventory cost (ICo) Value of inventory (VoI)	Distribution cost (DCo) Personnel cost (PCo)
Productivity/ Organization	Productivity/Organization involves operational control metrics for logistics departments used for streamlining processes, reducing costs, facilitating information flow and enhancing provided care services	Inventory turnover (IT) Inventory usage (IU) Product standardization (PS)	Case cart efficiency (CCE) Delivery frequency (DF) Process standardization (S) Personnel management (PM)

Improvement initiatives on inventory management systems are a promising research area for achieving significant efficiency gains while satisfying the desired patient care service levels [12],[54]. However, missing data on inventory levels, consumption or surgery costs complicate

inventory control in the OR. Moreover, these data are relevant information to convince stakeholders of the financial, clinical and operational impact of efficient supply chain practices [3]. The biggest challenge presented to hospital logistics managers is balancing costs with the right inventory levels to sustain quality and timely patient care [55]. Many elements such as costs, service levels, storage space, expiration or obsolescence are taken into account when controlling stock levels in central warehouses and point-of-use locations. The performance of inventory management systems can be measured using indicators such as inventory visibility, availability, accuracy and cost [49]. Poor visibility and uncoordinated processes can result in high inventory costs. Gebicki et al. [56] consider criticality levels and consequences of stock-outs when developing replenishment policies within hospitals. Consequences of stock-outs in hospitals are more severe as it might endanger a patient's life compared to industrial sectors [57]. Short expiration products further increase the risk of a stock-out. Lega et al. [23] measure the value of stock, the value of expired products, the inventory turnover rate and the coverage ratio to efficiently manage supplies. Supeekit et al. [20] and Aronovich et al. [58] assess supporting process efficiency, which consists of costs (inventory cost, obsolete stock cost, overstocking cost), time (response time), reliability (perfect order fulfilment, on-time in-full delivery, stock discrepancy, stock-out rate), and productivity (resource utilization, inventory turnover and availability of resources). Carrus et al. [47] evaluate hospital logistics innovations by considering inventory levels, turnover rate, responsiveness, delivery frequency, errors, workload distribution, information and traceability. They also consider product and process standardization as relevant indicators.

A second hospital supply chain activity is related to internal distribution to ensure the provision of medical supplies by efficiently moving goods from storage to point-of-use locations. Little and Coughlan [59] combine logistics and inventory decisions by incorporating delivery resources and routing information. Coordination of healthcare resources, effective delivery strategies and measurement of delivery services are crucial for creating high-value outcomes for the overall healthcare system [60]. This paragraph focuses on the internal distribution processes in the ORs, aiming at improving delivery processes in terms of costs, quality, time and productivity/organization. The distribution process is complicated by the large amount of ORs, the daily replenishment of items at various point-of-use locations, the number of staff affected and the cost of the items [6]. KPIs related to internal supply distribution include factors such as delivery accuracy, delivery perfect condition, order delivery in full, on-time order delivery and urgent delivery [49]. El Mokrini et al. [51] select the appropriate distribution network related to the pharmaceutical supply chain by considering supply chain reactivity criteria, such as response time, product availability, customer or staff satisfaction, and cost criteria including inventory, transportation, facilities, handling and information system cost. Augusto and Xie [61] combine supply and transportation planning in order to balance staff workload and simultaneously respecting the availability constraint of medical supplies. In addition, centralization of OR logistics processes will lower costs and inventory levels due to more frequent deliveries, balanced workload and a higher service level [62]. Lega et al. [23] measure organizational and process benefits through the percentage of urgent orders, use of common lists of products throughout the organization and errors. They measure quality using the following indicators: delivery

performance, time to delivery, flexibility, distribution of workload, and accuracy and timeliness of information. Another indicator to measure healthcare performance is clinical staff involvement.

The frameworks and performance metrics described above make the foundation for establishing a logistics performance measurement framework for internal supply chain processes in a healthcare setting. This paper focuses on investigating specific healthcare logistics processes, such as inventory and distribution processes within the ORs. Current literature lacks methodological approaches to measure performance of internal OR logistics. The purpose of this study is to define a general list of performance metrics for evaluating internal logistics processes in accordance with the goals of the hospital supply chain process under study. The proposed performance measurement framework ensures a clear performance definition and aligns logistics objectives with KPIs providing an integrated view of the OR logistics performance. In the framework, relationships among performance indicators are established and trade-offs are defined to inform decision makers on how different indicators impact the supply chain performance and to identify opportunities for improvements while considering different stakeholders' views.

3. Logistics performance measurement framework in OR setting

KPI selection and prioritization problems can be solved as a MCDM problem [38]. The KPIs do not equally contribute to the overall performance of OR logistics processes, so ANP is recommended for prioritization via pairwise comparisons. ANP is a popular MCDM technique used to form a network structure of the criteria and it captures interdependencies among these criteria [49]. Considering this interrelationship property of the ANP methodology is particularly important when addressing topics related to performance measurement due to the existence of feedback relationships between indicators. For example, Supeekit et al. [20] show that a change in supporting process efficiency results in a change in clinical care process efficiency. This makes ANP a perfect methodology for developing a comprehensive decision-support framework for hospital logistics managers, accommodating multiple criteria and stakeholder perspectives. This section presents an overview of the ANP methodology to select and prioritize indicators that could be of any importance for measuring the efficiency of the OR supply chain processes at the University Hospital in Leuven. For more detailed information on the ANP method, the interested reader is referred to the work of Saaty [63].

3.1 ANP-based logistics performance measurement framework

Step 1 – Model construction

In the first step of the ANP methodology, the model is constructed based on the problem formulation. ANP structures decision problems into a network of clusters, nodes and dependency relations among the network elements. Figure 1 displays the generic network structure for inventory management and distribution priority setting in the OR. The clusters and nodes refer to the objectives and indicators respectively, which are mainly based on the literature review by Moons et al. [53]. At the top level, the goal is defined as ranking KPIs to measure efficiency of OR logistics processes. A distinction is made between inventory management and distribution activities, where the former represents the process of storing disposable medical supplies and the latter refers to replenishment policies and getting materials at the right place and time for surgical

procedures. The framework will guide hospital managers to find improvement opportunities for both activities that will enhance overall OR logistics performance. At the second level, the clusters contain the objectives for inventory and distribution processes. The definitions of the objectives can be found in Table 2. This table slightly deviates from the tables presented in Moons et al. [53]. First, the 'Time' objective is important for determining replenishment or distribution policies, but it is not considered as an objective for inventory management. There are also some adaptations at the third level, representing all indicators in every cluster. 'Patient safety' is included in 'Inventory criticality', which considers the impact of errors, delays of supplies on the surgical procedure (see Appendix A.1). 'Clinical staff involvement' is re-categorized to distribution activities since it refers to the amount of time clinical staff is busy with logistics tasks, such as retrieving additional materials for surgical procedures (see Appendix A.2). Furthermore, the indicator 'Preparation time' is divided into 'Replenishment lead time' and 'Response time'. Finally, 'Personnel management' is categorized under productivity/organization, measuring for example the workload distribution, which was categorized under distribution time in Moons et al. [53]. Finally ANP considers inner dependencies (i.e. elements of a cluster depend on each other) or outer dependencies (i.e. feedback between clusters from different levels) among the network elements [39]. For example, higher inventory service level requires increasing inventory levels in order to decrease the stock-out rate, and thus larger inventory cost. **This relationship is described by link A and B in Figure 1.**

Figure 1. A generic hospital logistics performance measurement framework.

Step 2 – Building pairwise comparison matrices

After customizing the network structure to the context-specific problem, pairwise comparison matrices are constructed for each relationship between clusters and/or nodes in the network. The pairwise comparison approach is based on Saaty's nine-point **absolute** scale to derive decision makers' preferences [63],[64],[65]. Next, the priorities or weights of all criteria can be derived using the principal eigenvector method. The local priority vector or principal eigenvector is computed representing the weight of each element in the pairwise comparison matrices, while always considering the control or goal criterion in the network. As an illustrative example, Table 3 present pairwise comparison matrices for the inventory problem, indicating the preferences of the OR logistics manager at UZ Leuven, namely how much an indicator in a row is preferred to indicators in the columns. For example, Table 3 illustrates that, with respect to the 'Quality' objective, 'Inventory service level' is five times more important or preferred than 'Inventory visibility'. The column 'Priorities' contains the local priority vector for each element in the pairwise comparison matrix.

However, performing pairwise comparisons in a consistent way is almost never the case. Therefore, Saaty [63] recommends calculating a Consistency Ratio (CR) with a threshold of 10

per cent for all judgments of the decision makers. If this ratio exceeds the threshold, judgments must be revised or the weighted consistency method by Jarek [67] can be used to reduce inconsistency without changing decision makers' judgments. CR is included in the final column of Table 3. It is important to note that other challenges can be encountered in this step, such as uncertainty or vagueness of preferences, gaps in knowledge or lack of problem understanding, or conflicts between different decision makers, which may lead to wrong decisions based on the framework.

Table 3. Pairwise comparisons of indicators with respect to 'Quality' objective.

Wrt Quality	ISL	IV	IA	ICr	Priorities	CR
Inventory service level	1	5	5	1/3	0,30508	0,0579
Inventory visibility	1/5	1	1	1/5	0,07829	
Inventory accuracy	1/5	1	1	1/5	0,07829	
Inventory criticality	3	5	5	1	0,53833	

Step 3 – Supermatrix formation and overall priority calculation

The third step of the ANP methodology consists of composing a supermatrix including all interactions between clusters and/or nodes in the network. The local priority vectors obtained in step 2 form the segments of the supermatrix. Three types of supermatrices can be distinguished, namely the unweighted, weighted and limit supermatrix. The unweighted supermatrix (see Table 4) contains the local priority vectors obtained by the preferences of the logistics manager.

Table 4. Unweighted supermatrix for inventory management network.

	Goal	ISL	IV	IA	ICr	ICo	Vol	IT	IU	PS
Goal	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Inventory service level	0,305	0,000	0,750	0,800	0,614	0,625	0,540	0,429	0,439	0,594
Inventory visibility	0,078	0,088	0,000	0,200	0,117	0,136	0,163	0,429	0,265	0,249
Inventory accuracy	0,078	0,195	0,250	0,000	0,268	0,238	0,297	0,143	0,110	0,157
Inventory criticality	0,538	0,717	0,000	0,000	0,000	0,000	0,000	0,000	0,187	0,000
Inventory cost	0,750	0,000	0,200	0,500	0,000	0,000	1,000	0,800	0,000	0,750
Value of inventory	0,250	0,000	0,800	0,500	0,000	1,000	0,000	0,200	0,000	0,250
Inventory turnover	0,167	1,000	0,655	0,750	0,000	0,648	0,540	0,000	0,167	0,125
Inventory usage	0,667	0,000	0,250	0,000	0,750	0,230	0,297	0,500	0,000	0,875
Product standardization	0,167	0,000	0,095	0,250	0,250	0,122	0,163	0,500	0,833	0,000

The clusters are not equally important as the objectives differ in how they contribute to the overall performance of OR logistics processes. Therefore, clusters are also pairwise compared to establish their relative importance by deriving cluster weights. Interpretation of the weights indicates that quality has the most impact on both financial and productivity. Link C in Figure 1 represents the inner dependence loop in the clusters. These cluster weights are used to weight the unweighted supermatrix. After normalization, the weighted supermatrix has been formed. Finally, the weighted supermatrix is raised to large powers in order to reach convergence or stability. This matrix with

equal scores in all rows is called the limit supermatrix, and the scores denote the overall or global priorities of each element in the network.

Step 4 – Prioritization and selection of KPIs

The limit supermatrix contains the overall priorities of the indicators, representing the impact of each element on every other element in the network with which it interacts. Table 5 presents the global priorities of the objectives and indicators, together with a ranking of performance indicators for measuring the efficiency of the OR supply chain operations. The highest-ranked indicators represent the most important indicators with the greatest contribution to improving inventory management and distribution systems.

Table 5. Ranking of inventory and distribution KPIs based on ANP weights.

Inventory objectives	Weights	Indicators	Weights	Ranking	Cumulative weights
Quality	0,68	Inventory service level	0,289	1	0,289
		Inventory visibility	0,106	5	0,802
		Inventory accuracy	0,123	3	0,576
		Inventory criticality	0,164	2	0,453
Financial	0,06	Inventory cost	0,032	8	0,972
		Value of inventory	0,027	9	1,000
Productivity/organization	0,26	Inventory turnover	0,120	4	0,696
		Inventory usage	0,075	6	0,877
		Product standardization	0,063	7	0,940
Distribution objectives	Weights	Indicators	Weights	Ranking	Cumulative weights
Quality	0,32	Delivery accuracy	0,092	5	0,630
		Centralization	0,091	6	0,721
		Distribution service level	0,136	2	0,296
Time	0,15	Replenishment lead time	0,057	8	0,851
		Response time	0,053	9	0,904
		Clinical staff involvement	0,036	10	0,940
Financial	0,06	Distribution cost	0,035	11	0,975
		Personnel cost	0,025	12	1,000
Productivity/organization	0,48	Case cart efficiency	0,073	7	0,794
		Delivery frequency	0,121	4	0,538
		Process standardization	0,160	1	0,160
		Personnel management	0,121	3	0,417

4. Results and Discussion

4.1 Results

The example described in Section 3.1 illustrates a methodological approach for ranking logistics objectives and selecting KPIs that contribute most to improving OR supply chain processes, such as inventory and distribution. The network in Figure 1 is established based on literature and interviews with hospital logistics experts. In this first study, one stakeholder, namely the OR logistics manager at UZ Leuven, has judged the pairwise comparison questions. According to this stakeholder's preferences, the following preliminary results are found.

For improving inventory management systems, quality is the first-ranked objective with a weight of 68% (see Table 5) and thus the greatest contributor to efficiency improvements. Also note the low weight for the financial objective, i.e. 6%, which is surprising as the logistics manager's goal is to reduce costs while maintaining high service levels. **The final column in Table 5 computes the cumulative weights, considering the indicators in a descending order according to their weight-based ranking.** When exploring the results into detail, the cumulative percentage shows that the four **highest ranked** indicators account for almost 70% **of the total weight assigned to all indicators.** These four indicators are inventory service level, inventory criticality, inventory accuracy and inventory turnover. Inventory service level is the most important indicator in the OR setting, representing the ability to fulfill orders from stock on-hand. At the operational level, inventory service level can be measured using sub-indicators inventory availability or stock-out rate. The second most important indicator is inventory criticality, measuring the impact of errors, delays of supplies or adverse effects on the surgical procedure or the patient. Inventory criticality is related to patient safety, which is the ultimate goal in any healthcare process. Third, having accurate inventory is important to eliminate overstocking or hoarding behaviour of clinical staff who hold many items in stock as a response to the high variability encountered in the OR. Furthermore, product standardization and the cost indicators appear to be less important compared to the quality objective indicators. However, improving product standardization and introducing appropriate product/location identification standards is crucial to reduce variability due to physician preferences, and hence improve inventory control and reduce inventory costs.

The framework can also be adapted to guide hospital management in selecting and prioritizing objectives and KPIs related to internal distribution or replenishment policies, ensuring that the right materials are at the right place and time. Table 5 shows that productivity/organization (48%) and quality (32%) are the main objectives when evaluating distribution processes. It is remarkable that productivity is higher ranked than quality. A plausible explanation is that the logistics manager emphasizes process standardization, personnel management and delivery frequency as the relevant KPIs to simplify the workflow and increase staff satisfaction. Together with distribution service level, these four indicators make up more than 50% of all indicators. Notice that the time indicators have lower weights, although the logistics manager aims to provide all materials for surgical procedures in time.

The findings show that different objectives and KPIs are selected for different processes in order to adequately measure the performance of the OR logistics supply chain. **This paper contributes to literature in proposing a methodological and transparent approach, integrating multiple indicators considered by traditional operations management techniques to guide hospital management**

decision-making based on context-specific objectives. The framework is based on ANP to calculate global priority weights, which allows to select and identify relevant KPIs to improve inventory and distribution systems. Moreover, KPI prioritization allows to quantify trade-offs between different objectives. Thus, the OR logistics manager uses evidence-based decision-making when specifying service levels in order to reduce costs or reduce number of stock-outs.

4.2 Discussion

This paper presents a generic performance measurement framework for evaluating OR logistics operations by using ANP. A complex MCDM problem is simplified by using the ANP methodology, which takes into account both quantitative and qualitative judgments to evaluate a set of criteria, as well as interdependencies among the criteria. The customizable framework serves as a reference model providing logistics managers with a better understanding of KPIs that are most important for a specific problem, or in other words, the ‘best’ set of KPIs for assessing the performance of OR inventory and distribution systems.

The increased pressure to reduce costs forces hospital managers to develop new management and decision support tools to ensure efficient and effective operations of their care delivery systems [68]. OR logistics processes are an important contributor to the overall performance of the hospital due to the criticality and costs associated to surgical operations. The proposed framework contains a set of KPIs to support managerial decision-making and guides hospital managers in identifying performance gaps or deficient areas. Moons et al. [53] provide a generic list of criteria for evaluating internal logistics processes in hospitals. Section 3.1 (Step 1) discusses the inclusion or exclusion of criteria compared to Moons et al. [53]. Some indicators are combined or eliminated due to overlap or too broad interpretation. The proposed methodology can be used with any set of criteria, and thus is generic enough to evaluate other healthcare supply chains by customizing it to specific contexts. In this case, the framework is adapted to the OR setting to evaluate internal logistics processes such as inventory and distribution activities. Logistics-oriented KPIs in the OR setting are similar to any industrial setting, but the weights attached to the KPIs can differ significantly between sectors. Indicators such as inventory service level, inventory turnover or inventory cost assess traditional logistics management concepts, but the consequence of having a stock-out is far more severe in a healthcare setting than in a manufacturing process and thus requires a higher weight. In addition, hospitals have poor inventory management, lack of data and lack of standardization due to physician preference cards, which complicates KPI monitoring and results in costly and ineffective systems [3]. Therefore, this KPI ranking problem contributes to supporting evidence-based decision-making in healthcare environments. Quantitative methods, such as AHP or ANP, can be applied to prioritize this list of indicators. ANP is preferred over AHP because logistics related objectives are often interdependent, like for example quality and cost (Link C in Figure 1). ANP enables simplifying complex decision problems while taking into account all interdependencies. Moreover, ANP allows for balancing opposing influences, such as different performance perspectives between logistics and clinical stakeholders. The network structure in Figure 1 shows all interdependencies. For example, an inner dependence loop exists between inventory service level and patient safety in the quality cluster (Link A). The priorities of the indicators depend on the available inventory systems. Assume two systems achieve high

service levels, then inventory criticality (e.g. patient safety) would have higher priority than in a hierarchy.

The framework currently covers two major logistics activities performed in the OR: inventory and internal distribution. Both activities interact since distribution ensures that material stocks are replenished in time such that stock-outs can be minimized. However, the framework considers one activity at a time, as the goal is to understand which decision criteria are important when selecting respectively inventory or distribution policies in the OR. The results show that different objectives are considered to evaluate inventory or distribution policies, with respectively quality and productivity/organization being the most important objectives. By obtaining efficient inventory and distribution processes, the overall performance of the OR supply chain can be improved which in turn will improve clinical processes. Hoeur and Kritchanchai [54] and Kritchanchai et al. [49] show the significant impact of inventory management to the overall performance of healthcare logistics. For this reason, we develop a more detailed framework to **translate logistics objectives into relevant indicators and to prioritize between indicators to identify opportunities for efficiency gains**. The results of the **case study** show that **the four highest-ranked KPIs contribute most to the overall performance of the inventory system**. In further research, **improvement initiatives will be evaluated by tracking these KPIs and appropriate inventory control policies will be proposed based on the KPIs**. Moreover, the findings also confirm the dominance of patient safety, which is represented by the indicator ‘inventory criticality’, as being the ultimate goal in healthcare [53]. Although product standardization proves to be a significant enabler to reduce costs and variability and improve healthcare supply chain performance [3],[48],[65], its importance has not yet been emphasized by the logistics manager. Inventory costs are ranked in the last position, however the main goal of the logistics flow is to hold inventory to guarantee availability while reducing costs [47]. Besides proper inventory management, the logistics flow should also ensure timely provision of medical supplies at the right place in the most efficient way. Therefore, the framework also covers KPIs measuring the performance of internal distribution systems. It is remarkable that productivity has a higher weight than quality. This is mainly due to the high importance attached to simplifying the logistics flow for logistics personnel. Carrus et al. [47], Pinna et al. [62] and Robinson et al. [70] also show the importance of balanced workload distribution and process standardization in their work. Furthermore, the impact of centralization on costs, service level and the workflow is also considered important, which is confirmed by Pinna et al. [62], Iannone et al. [71] and Landry et al. [6].

The OR logistics manager recognizes the potential of the framework to be highly relevant in optimizing the logistics flow. The outcome is a ranking of indicators used as a guideline for optimizing inventory systems and distribution activities within the OR in order to provide patient care quality in the most efficient manner. **The KPI ranking stimulates evidence-based decision-making, reflecting the contribution of logistics supporting activities to value-based healthcare**. For example, **the OR logistics manager can justify decisions to hold items in stock close to the OR and to define a standardized workflow to increase staff satisfaction**. Other advantages of the framework are its transparency and **its systematic approach**. **It enables stakeholders to track the impact of new logistics practices**, which improves managerial communication significantly.

As this paper is a first step towards a logistics performance measurement system, a few limitations should be considered. Section 2.1 already discussed challenges that occur in ANP studies, such as inconsistency, uncertainty, knowledge gaps, or conflicting views [33]. **We propose to use complementary methods to ANP in order to overcome these challenges.** During the questionnaires, the decision maker may lose focus which result in inconsistent judgments. **In this work,** the weighted consistency method by Jarek [67] performed well to reduce inconsistency without significantly changing the priority vectors. **Second, the uncertainty issue can be overcome by incorporating a fuzzy logic into ANP or by conducting a sensitivity analysis [17], [37], [40].** Another limitation is related to the sample size of the case study. This case study presents preliminary results of the application of the framework since only one stakeholder, namely the OR logistics manager at UZ Leuven, expressed his preferences for a specified set of performance criteria. However, the attitude of a single decision maker can be biased. Therefore, in further research, a team of stakeholders representing different departments (e.g. nursing department, surgery, logistics) will be composed to avoid biased judgments. The big challenge will be to deal with **possibly** conflicting views **among** different stakeholders. Literature discusses some techniques for aggregating group member judgments, such as consensus, vote or compromise, geometric mean of individual judgments and a separate model [41],[72]. **In further work, we will apply the cluster similarity approach, proposed by Song and Hu [73], to combine stakeholders' conflicting views into an overall stakeholder group. Finally, we assume in this study that all the proposed KPIs can be measured. However, a general limitation of implementing performance systems is the lack of information systems, lack of product identification and lack of data standardization, which leads to poor performance of the hospital supply chain [49]. Different types of technologies, such as RFID or cloud-based platforms are potential enablers for a successful implementation, and hence system efficiency.**

5. Sensitivity analysis

A final sensitivity or 'what-if' analysis is performed to validate the robustness of the decision support framework. In addition, it helps in understanding which criteria drive changes in the results and to what extent the ranking is valid when changing the importance or influence of criteria [17], [45]. Typical what-if questions can be: what if all stakeholders have equal importance in their judgments, what if all criteria are equally important, what if one criterion is given more importance. Since the model is heavily dependent on qualitative judgments of the decision makers to derive the weights of the criteria, the accuracy of these judgments is crucial. To perform a sensitivity check, the ANP network should be extended with alternatives. These alternatives represent potential strategies for controlling inventory or distribution activities in the OR setting. For inventory management, three alternative inventory control policies are included based on the objectives of cost minimization, service level maximization or inventory standardization. Similarly for distribution, four objective-related alternative strategies can be added, such as centralization, time/distance ratio, distribution cost minimization and balanced workload.

In a single-factor sensitivity analysis, the priority vector or weight of a criterion is varied, one at a time, while keeping the remaining weights relatively unchanged, to examine the effect on the alternative rankings [74]. The Super Decisions software is utilized to conduct the sensitivity analysis by varying the sensitivity parameter, α , which provides a measure for comparative judgments of adjustments in the priority vectors with respect to a specific node [75]. The original ANP values of the alternatives are displayed when α equals 0,5. Adjusting this parameter α with respect to a specific node can lead to changes in the ranking of alternative solutions. For example, when the parameter value of inventory service level is adjusted from 0,0001 to 0,9999 (see left plot in Figure 2), cost minimization (green line) is found to be the best strategy for inventory control with a weight of 0,423, followed by service level maximization (red line) and standardization (blue line) with a weight of 0,306 and 0,271 respectively. However, beyond a parameter value α of 0,274, service level maximization raises to 0,751, whereas for cost minimization the weight decreases to 0,103 and standardization to 0,146 at $\alpha = 0,9999$. Similarly, the right plot of Figure 2 shows how the ranking of alternatives changes by adjusting the parameter α for the inventory cost indicator. At $\alpha = 0,578$ or in other words, an increase of 15 per cent in the inventory cost weight, cost minimization policies are preferred above service level. At smaller parameter values, service level maximization is the recommended strategy. This analysis guides hospital management in selecting appropriate inventory control policies by quantifying the trade-off between costs and service level. The plots provide insights into the stakeholders' preferences to maximize service levels, which comes at the expense of increasing inventory costs. Strategies for inventory standardization in order to improve productivity are dominated by the main trade-off between balancing inventory levels and costs. However, improving product standardization will reduce costs and simplify inventory control, and thus is important when tackling the trade-off between cost and service level.

Figure 2. Sensitivity analysis of Inventory service level (left plot) and Inventory cost (right plot) ranging from 0,0001 to 0,9999.

In addition, when conducting the single-factor sensitivity analysis for identifying distribution strategies, no clear trade-offs appear in the plot. The strategy to centralize distribution activities, by moving away activities from the ORs, is found to be the dominant policy to implement followed by time/distance ratio, balanced workload and cost minimization.

6. Conclusion

ANP is a valuable, analytical tool for supporting managerial decision-making related to performance measurement. This method allows for priority setting of all performance indicators considering multiple stakeholders perspectives in a consistent and organized way. Moreover, the approach gives insights in understanding the complex relationships in the decision problem and thus, improves the reliability of the corresponding decisions. Therefore, this paper presents a ANP-based methodology to guide hospital logistics managers in translating logistics objectives to relevant KPIs measuring the overall performance of the hospital supply chain. A generic logistics performance measurement framework is developed, customized to the OR setting, to evaluate inventory and internal distribution systems based on quality, time, financial and productivity/organization objectives. A set of indicators has been identified from literature to be considered when assessing performance. The outcome emphasizes quality and productivity indicators for inventory management and distribution respectively as the most contributing factors to OR logistics performance, by improving inventory service level, inventory criticality and process standardization. **Hence, multiple objectives and indicators have impact on the logistics flow. Therefore, multiple improvement initiatives can be identified to increase overall supply chain performance in hospitals.** Moreover, the framework is a useful tool to help hospital managers in understanding and quantifying trade-offs between objectives and KPIs that affect overall performance. The “what-if” analysis shows the changes in the ranking of inventory control policies when the goal is minimizing costs compared to maximizing service levels.

This study is a first step towards measuring performance of OR logistics processes. The findings of this work are relevant for stakeholders involved within the hospital logistics flow to gain insights into priorities and trade-offs among indicators to focus the decision maker’s attention to the most promising improvement areas. As surgical supply costs take up more than 40% of the hospital operating budget, a well-defined supply chain strategy is needed to align internal logistics processes and reduce costs. Based on the defined performance indicators, the performance of potential logistics concepts or policies can be measured, monitored and controlled. Although this case study deals with the OR logistics flow, the decision support framework can also be customized according to specific objectives and process-related KPIs of other hospital logistics processes. **Further work will address the extension of the methodology to other healthcare supply chains to ensure a generic framework, suitable to most healthcare logistics contexts.** Moreover, the development of the framework contributes significantly to existing literature as it provides a transparent and methodological approach for demonstrating the impact of supply chain strategies on the overall performance of the **internal hospital logistics** system, and more particularly in the OR setting.

Several directions for future research can be addressed. This application is limited to a single case study of the flow of disposable supplies in ORs at UZ Leuven hospital, but in a further study it

will be extended to other hospital logistics processes (e.g. intensive care units, nursing wards), stakeholders or other hospitals. The proposed logistics framework can be elaborated by linking performance aspects to particular hospital processes to obtain process-specific KPIs, reflecting the overall hospital supply chain performance. This extension will be relevant for validating the generic framework and it contributes to the adoption of – or overcoming possible obstacles to adopt – SCM practices within hospitals. In addition, diverse MCDM methods can be compared to test the robustness and validity of the model results. Second, this study is a first step towards measuring performance of OR logistics processes. Based on the framework, a questionnaire will be used to obtain the overall performance of each KPI by combining the ANP weight of the KPI and the performance score related to that KPI [49]. It might be interesting to investigate how the overall performance differs for high-cost and low-cost items and how the trade-offs differ for various material types. In practical terms for hospital management, this means that the outcomes of the framework, being KPI prioritization and the performance scores, act as a useful visualization tool for revealing wasteful processes. Third, the outcome can be used to implement a strategy for improving the logistics performance in ORs or other hospital departments. Finally, the proposed framework enables benchmarking between different logistics processes in hospitals to evaluate SCM strategies and to improve process performance [7].

References

- [1] C. Machado Guimarães, J. Crespo de Carvalho, and A. Maia, "Vendor managed inventory (VMI): evidences from lean deployment in healthcare," *Strategic Outsourcing: An International Journal*, vol. 6, no. 1, pp. 8–24, 2013.
- [2] H. Aronsson, M. Abrahamsson, and K. Spens, "Developing lean and agile health care supply chains," *Supply Chain Management*, 2011.
- [3] M. Camp, J. Pfister, D. Reeves, and J. Kneeder, "Effective Operating Room Inventory Management," *Pfiedler Enterprises*, p. 26, 2014.
- [4] D. H. Rothstein and M. V. Raval, "Operating room efficiency," *Seminars in Pediatric Surgery*, 2018.
- [5] A. J. Fong, M. Smith, and A. Langerman, "Efficiency improvement in the operating room," *Journal of Surgical Research*, vol. 204, no. 2, pp. 371–383, 2016.
- [6] S. Landry and M. Beaulieu, "The challenges of hospital supply chain management, from central stores to nursing units," in *International Series in Operations Research and Management Science*, vol. 184, 2013, pp. 465–482.
- [7] D. C. Feibert, B. Andersen, and P. Jacobsen, "Benchmarking healthcare logistics processes – a comparative case study of Danish and US hospitals," *Total Quality Management and Business Excellence*, vol. 3363, no. June, pp. 1–27, 2017.
- [8] K. De Pourcq, P. Gemmel, and J. Trybou, "Measuring process performance in hospitals," *EurOMA Conference 2015*, pp. 1–10, 2015.
- [9] K. Lenin, "Science Journal of Business and Management," vol. 2, no. 5, pp. 136–142, 2014.
- [10] B. Broome, K. Grote, J. Scott, S. Sutaria, and P. Urban, "Clinical operations excellence: Unlocking a hospital's true potential," *The post-reform health system: Meeting the challenges ahead*, no. May, pp. 1–10, 2013.
- [11] R. Anupindi, S. Chopra, S. Deshmukh, J. Van Mieghem, and E. Zemel, *Managing business process flows: Principles of operations management*. 2012.

- [12] J. Volland, A. Fügener, J. Schoenfelder, and J. O. Brunner, "Material logistics in hospitals: A literature review," *Omega (United Kingdom)*, vol. 69, pp. 82–101, 2017.
- [13] V. Maestrini, D. Luzzini, P. Maccarrone, and F. Caniato, "Supply chain performance measurement systems: A systematic review and research agenda," *International Journal of Production Economics*. 2017.
- [14] R. Yanamandra, "Development of an integrated healthcare supply chain model," *Supply Chain Forum*. 2018.
- [15] J. de Vries and R. Huijsman, "Supply chain management in health services: an overview," *Supply Chain Management: An International Journal*, vol. 16, no. 3, pp. 159–165, 2011.
- [16] P. Gemmel, D. Vandaele, and W. Tambeur, "Hospital Process Orientation (HPO): The development of a measurement tool," in *Total Quality Management and Business Excellence*, 2008.
- [17] K. L. Poh and Y. Liang, "Multiple-Criteria Decision Support for a Sustainable Supply Chain: Applications to the Fashion Industry," *Informatics*, 2017.
- [18] H. Rivard-Royer, S. Landry, and M. Beaulieu, "Hybrid stockless: a case study," *International Journal of Operations & Production Management*, vol. 22, no. 4, pp. 412–424, 2002.
- [19] R. Hall, *Handbook of healthcare system scheduling*. 2012.
- [20] T. Supeekit, T. Somboonwiwat, and D. Kritchanchai, "DEMATEL-modified ANP to evaluate internal hospital supply chain performance," *Computers and Industrial Engineering*, 2016.
- [21] R. Cuthbertson and W. Piotrowicz, "Performance measurement systems in supply chains: A framework for contextual analysis," *International Journal of Productivity and Performance Management*, 2011.
- [22] P. D. Heather Nachtmann, Edward A. Pohl, "The State of Healthcare Logistics," *Center for Innovation in Healthcare Logistics, University of Arkansas*, 2009.
- [23] F. Lega, M. Marsilio, and S. Villa, "An evaluation framework for measuring supply chain performance in the public healthcare sector: evidence from the Italian NHS," *Production Planning & Control*, vol. 24, no. 10–11, pp. 931–947, 2013.
- [24] D. Dobrzykowski, V. Saboori Deilami, P. Hong, and S. C. Kim, "A structured analysis of operations and supply chain management research in healthcare (1982-2011)," *International Journal of Production Economics*, vol. 147, no. PART B, pp. 514–530, 2014.
- [25] P. J. H. Hulshof, N. Kortbeek, R. J. Boucherie, E. W. Hans, and P. J. M. Bakker, "Taxonomic classification of planning decisions in health care: a structured review of the state of the art in OR/MS," *Health Systems*, vol. 1, no. 2, pp. 129–175, 2012.
- [26] B. Cardoen, E. Demeulemeester, and J. Beliën, "Operating room planning and scheduling: A literature review," *European Journal of Operational Research*, 2010.
- [27] F. Guerriero and R. Guido, "Operational research in the management of the operating theatre: A survey," *Health Care Management Science*. 2011.
- [28] D. Gupta, "Surgical suites' operations management," *Production and Operations Management*, 2007.
- [29] B. G. Sobolev, V. Sanchez, and C. Vasilakis, "Systematic review of the use of computer simulation modeling of patient flow in surgical care," *Journal of Medical Systems*. 2011.
- [30] A. Rais and A. Vianaa, "Operations research in healthcare: A survey," *International Transactions in Operational Research*, 2011.

- [31] P. Beck and E. Hofmann, "Multiple criteria decision making in supply chain management : Currently available methods and possibilities for future research," *Die Unternehmung*, vol. 66, no. 2, p. 2012, 2014.
- [32] G. Adunlin, V. Diaby, and H. Xiao, "Application of multicriteria decision analysis in health care: A systematic review and bibliometric analysis," *Health Expectations*, vol. 18, no. 6, pp. 1894–1905, 2015.
- [33] K. Marsh, M. Goetghebeur, P. Thokala, and R. Baltussen, *Multi-criteria decision analysis to support healthcare decisions*. 2017.
- [34] M. J. M. Hummel *et al.*, "Using the analytic hierarchy process to elicit patient preferences: Prioritizing multiple outcome measures of antidepressant drug treatment," *Patient*, 2012.
- [35] M.-C. Lee, "The analytic hierarchy and the network process in multicriteria decision making: performance evaluation and selecting key performance indicators based on ANP model," in *Convergence and Hybrid Information Technologies*, 2010, p. 426.
- [36] S. Sipahi and M. Timor, "The analytic hierarchy process and analytic network process: An overview of applications," *Management Decision*. 2010.
- [37] V. Diaby, K. Campbell, and R. Goeree, "Multi-criteria decision analysis (MCDA) in health care: A bibliometric analysis," *Operations Research for Health Care*, vol. 2, no. 1–2, pp. 20–24, 2013.
- [38] D. Carlucci, "Evaluating and selecting key performance indicators: An ANP-based model," *Measuring Business Excellence*, 2010.
- [39] A. Van Horenbeek and L. Pintelon, "Development of a maintenance performance measurement framework-using the analytic network process (ANP) for maintenance performance indicator selection," *Omega (United Kingdom)*, vol. 42, no. 1, pp. 33–46, 2014.
- [40] S. Jharkharia and R. Shankar, "Selection of logistics service provider: An analytic network process (ANP) approach," *Omega*, 2007.
- [41] R. F. Dyer and E. H. Forman, "Group decision support with the Analytic Hierarchy Process," *Decision Support Systems*, 1992.
- [42] O. Aptel and H. Pourjalali, "Improving activities and decreasing costs of logistics in hospitals: A comparison of U.S. and French hospitals," *International Journal of Accounting*, vol. 36, no. 1, pp. 65–90, 2001.
- [43] S. Landry and R. Philippe, "How Logistics Can Service Healthcare," *Supply Chain Forum: An International Journal*, 2004.
- [44] M. A. Rakovska and S. V. Stratieva, "A taxonomy of healthcare supply chain management practices," *Supply Chain Forum*, 2018.
- [45] L. Piratelli, Claudio, M. Belderrain, A. Junior, Walther, and J. L. Hermosilla, "Using the analytic network process to rank performance indicators for a undergraduate course," in *XVI International Conference on Industrial Engineering and Operations Management*, 2010.
- [46] C. Di Martinelly, F. Riane, and A. Guinet, "A Porter-SCOR modelling approach for the hospital supply chain," *International Journal of Logistics Systems and Management*, vol. 5, no. 3, pp. 436–456, 2009.
- [47] P. P. Carrus, F. Marras, and R. Pinna, "The Performance Measurement of Changes in the Logistics of Health Goods: A Theoretical Model," *Proceedings of the 18th Toulon-Verona International Conference*, pp. 85–100, 2015.
- [48] A. Longaray, L. Ensslin, S. Ensslin, G. Alves, A. Dutra, and P. Munhoz, "Using MCDA

- to evaluate the performance of the logistics process in public hospitals: the case of a Brazilian teaching hospital,” *International Transactions in Operational Research*, 2018.
- [49] D. Kritchanchai, S. Hoer, and P. Engelseth, “Develop a strategy for improving healthcare logistics performance,” *Supply Chain Forum: An International Journal*, 2018.
 - [50] D. C. Feibert and P. Jacobsen, “Measuring process performance within healthcare logistics - a decision tool for selecting track and trace technologies,” *Academy of Strategic Management Journal*, 2015.
 - [51] A. El Mokrini, L. Bennabbou, and A. Berrado, “Multi-criteria distribution network redesign - case of the public sector pharmaceutical supply chain in Morocco,” *Supply Chain Forum: An International Journal*, vol. 19, no. 1, pp. 42–54, 2018.
 - [52] S. M. Ordoobadi, “Application of ANP methodology in evaluation of advanced technologies,” *Journal of Manufacturing Technology Management*, 2012.
 - [53] K. Moons, G. Waeyenbergh, and L. Pintelon, “Measuring the logistics performance of internal hospital supply chains - a literature study,” *Omega (United Kingdom)*, 2018.
 - [54] Soriya Hoer and Duangpun Kritchanchai, “Key Performance Indicator Framework for Measuring Healthcare Logistics in ASEAN,” *Toward Sustainable Operations of Supply Chain and Logistics System*, 2015.
 - [55] E. Abukhousa, J. Al-jaroodi, S. Lazarova-molnar, and N. Mohamed, “Simulation and Modeling Efforts to Support Decision Making in Healthcare Supply Chain Management,” *The ScientificWorld Journal*, vol. 2014, p. 16, 2014.
 - [56] M. Gebicki, E. Mooney, S. J. (Gary) Chen, and L. M. Mazur, “Evaluation of hospital medication inventory policies,” *Health Care Management Science*, vol. 17, no. 3, pp. 215–229, 2014.
 - [57] S. Toba, M. Tomasini, and H. Yang, “Supply chain management in hospital: a case study,” *California Journal of Operations Management*, vol. 6, no. 1, pp. 49–55, 2008.
 - [58] D. Aronovich, M. Tien, E. Collins, A. Sommerlatte, and L. Allain, “Measuring Supply Chain Performance: Guide to Key Performance Indicators for Public Health Managers,” *U.S. Agency for International Development*, no. May, p. 62, 2010.
 - [59] J. Little and B. Coughlan, “Optimal inventory policy within hospital space constraints,” *Health Care Management Science*, vol. 11, no. 2, pp. 177–183, 2008.
 - [60] T. Rohleder *et al.*, “Improving a patient appointment call center at Mayo Clinic,” *International Journal of Health Care Quality Assurance*, vol. 26, no. 8, pp. 714–728, 2013.
 - [61] V. Augusto and X. Xie, “Redesigning pharmacy delivery processes of a health care complex,” *Health Care Management Science*, vol. 12, no. 2, pp. 166–178, 2009.
 - [62] R. Pinna, P. P. Carrus, and F. Marras, “Emerging trends in healthcare supply chain management - an Italian experience,” in *Applications of Contemporary Management Approaches in Supply Chains*, 2015.
 - [63] T. L. Saaty, “Decision making with the analytic hierarchy process,” *International Journal of Services Sciences*, vol. 1, no. 1, p. 83, 2008.
 - [64] T. L. Saaty, *Mathematical principles of decision making*. Pittsburgh, PA, 2010.
 - [65] B. Karpak, “REFLECTIONS: MATHEMATICAL PRINCIPLES OF DECISION MAKING,” *International Journal of the Analytic Hierarchy Process*, 2017.
 - [66] T. Saaty, *Theory and applications of the analytic network process: Decision making with benefits, opportunities, costs and risks*. 2005.
 - [67] S. Jarek, “Removing inconsistency in pairwise comparison matrix in the AHP,” *Multiple*

- Criteria Decision Making*, vol. 11, pp. 63–76, 2016.
- [68] D. Serrou and A. Abouabdellah, “Logistics in the hospital: Methodology for measuring performance,” *ARPN Journal of Engineering and Applied Sciences*, vol. 11, no. 5, pp. 2950–2956, 2016.
 - [69] M. Bijvank and I. F. A. Vis, “Inventory control for point-of-use locations in hospitals,” *Journal of the Operational Research Society*, vol. 63, no. 4, pp. 497–510, 2012.
 - [70] S. T. Robinson and J. R. Kirsch, “Lean Strategies in the Operating Room,” *Anesthesiology Clinics*, vol. 33, no. 4, pp. 713–730, 2015.
 - [71] R. Iannone, A. Lambiase, S. Miranda, S. Riemma, and D. Sarno, “Pulling drugs along the supply chain: Centralization of hospitals’ inventory,” *International Journal of Engineering Business Management*, vol. 6, no. 1, pp. 1–11, 2014.
 - [72] T. L. Saaty and L. G. Vargas, “Decision Making with the Analytic Network Process. Economic, Political, Social and Technological Applications with Benefits, Opportunities, Costs and Risks,” *International Series in Operations Research Management Science*, 2006.
 - [73] Y. Song and Y. Hu, “Group decision-making method in the field of coal mine safety management based on AHP with clustering,” *6th International Conference on Information Systems for Crisis Response and Management (ISCRAM 2009)*. 2009.
 - [74] M. Modak, K. K. Ghosh, and K. Pathak, “A BSC-ANP approach to organizational outsourcing decision support-A case study,” *Journal of Business Research*, 2018.
 - [75] R. C. Dobrea, G. Molănescu, and C. Busu, “Food sustainable model development: An ANP approach to prioritize sustainable factors in the romanian natural soft drinks industry context,” *Sustainability (Switzerland)*, 2015.

Appendix

A.1 Inventory performance metrics

Quality	Quality specifies how well a specific activity has been performed, ensuring that patients receive care service in a safe manner and that problems such as medical errors are minimized	
Indicators	Definition	Sub-indicators
Inventory service level	The ability to fulfill incoming orders from stock on-hand	-Inventory availability -Stock-out rate
Inventory visibility	The ability to monitor the amount of stock on-hand in the central storage and point-of-use locations	-Inventory level -Safety stock -Inventory classification -Supply location (central or decentral)
Inventory accuracy	The ability to compare stock records and actual stock on-hand	-Inventory discrepancy -Stocked according to plan -Items in overstock -Items in understock
Inventory criticality	The impact of errors or delays of supplies on the surgical procedure	-Availability of substitute supplies -% of errors (wrong item or quantity of items) -Delays of surgical procedures

Financial	Financial indicators identify supply chain cost drivers, such as expenses incurred by departments for providing services, including direct and overhead costs for inventory and internal distribution	
Indicators	Definition	Sub-indicators
Inventory cost	The annual cost of holding inventory at a specific storage room	-Ordering cost -Holding cost -Shortage cost -Overstocking cost -Storage space cost
Value of inventory	The determination of the cost of unsold inventory at the end of a period	-Value of inventory per storage room -Value of expired inventory -Value of damaged items

Productivity/ Organization	Productivity/Organization involves operational control metrics for logistics departments used for streamlining processes, reducing costs, facilitating information flow and enhancing provided care services	
Indicators	Definition	Sub-indicators

Inventory turnover	A measure of how fast inventory is used in the storage room	-Inventory days on-hand -Stock rotation: no-, slow-, fast-moving items
Inventory usage	The amount of inventory units consumed during a certain time period	-Consumption rate -Physician preference card usage rate -% of returned items -Storage space utilization
Product standardization	The ability to reduce variation of medical supplies in order to increase time spent at core activities	-Product duplication (multiple locations, multiple reference numbers) -Uniform/standardized workflows between ORs -Product/location identification standards

A.2 Distribution performance metrics

Quality	Quality specifies how well a specific activity has been performed, ensuring that patients receive care service in a safe manner and that problems such as medical errors are minimized	
Indicators	Definition	Sub-indicators
Delivery accuracy	The ability to pick and deliver the correct items and quantities from storage to point-of-use location	-Delivery/picking accuracy rate -Perfect order fulfillment -On-time delivery
Centralization	The ability to pick items at a central storage room, away from the operating rooms	-Material movements to decentral locations -Number of trips to storage rooms -Logistics activities close to OR
Distribution service level	The availability of logistics services to support clinical care processes	-Number of additional items needed -Number of returned/wasted items -Urgent delivery rate -Urgent material requests by nurses

Time	Time involves the time to complete the logistics operations to ensure that the right items are at the right place and time	
Indicators	Definition	Sub-indicators

Replenishment lead time	The total amount of time that elapses from the moment an item is ordered until the item is back on the shelf	-Order + picking + transportation + unloading time
Response time	The ability to deliver items on time, preventing delays in surgical procedures	-Average delivery time -Ratio of delivery time to distance travelled -Response time to urgent orders
Clinical staff involvement	The amount of time clinical staff is busy with logistics tasks, rather than their core activities	-Time spent at logistics activities -Time spent to request/retrieve stock-out items -Frequency and time of leaving OR

Financial	Financial indicators identify supply chain cost drivers, such as expenses incurred by departments for providing services, including direct and overhead costs for inventory and internal distribution	
Indicators	Definition	Sub-indicators
Distribution cost	Total cost of handling and transporting to move supplies from storage rooms to point-of-care locations	-Handling cost -Transportation cost -Ratio of transportation cost to value of items
Personnel cost	The cost related to the time personnel is involved with logistics activities	-Personnel time

Productivity/ Organization	Productivity/Organization involves operational control metrics for logistics departments used for streamlining processes, reducing costs, facilitating information flow and enhancing provided care services	
Indicators	Definition	Sub-indicators
Case cart efficiency	The availability and utilization of case carts to provide surgeons with the required supplies	-Case cart availability -Case cart utilization
Delivery frequency	The number of visits to decentral storage locations to deliver or replenish items in these locations	-% of items replenished -Scanning frequency -Review cycle length
Process standardization	The ability to simplify workflows between operating rooms and improve working conditions	-Uniform/standardized workflows and picking lists -% of scannable items for replenishment

Personnel management	A measure of how to obtain, use and maintain a satisfied workforce	<ul style="list-style-type: none">-Personnel's satisfaction-Workload distribution-Personnel flexibility (ability to do all tasks)-Personnel utilization-Ergonomics friendliness
----------------------	--	---