Autonomous mobile robots in sterile instrument logistics

an evaluation of the material handling system for a strategic fit framework

Fragapane, Giuseppe; Hvolby, Hans Henrik; Sgarbossa, Fabio; Strandhagen, Jan Ola

Published in:
Production Planning and Control

DOI (link to publication from Publisher):
10.1080/09537287.2021.1884914

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Production Planning & Control
The Management of Operations

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tppc20

Autonomous mobile robots in sterile instrument logistics: an evaluation of the material handling system for a strategic fit framework

Giuseppe Fragapane, Hans-Henrik Hvolby, Fabio Sgarbossa & Jan Ola Strandhagen

To cite this article: Giuseppe Fragapane, Hans-Henrik Hvolby, Fabio Sgarbossa & Jan Ola Strandhagen (2023) Autonomous mobile robots in sterile instrument logistics: an evaluation of the material handling system for a strategic fit framework, Production Planning & Control, 34:1, 53-67, DOI: 10.1080/09537287.2021.1884914

To link to this article: https://doi.org/10.1080/09537287.2021.1884914

PRODUCTION PLANNING & CONTROL
2023, VOL. 34, NO. 1, 53–67
https://doi.org/10.1080/09537287.2021.1884914

Autonomous mobile robots in sterile instrument logistics: an evaluation of the material handling system for a strategic fit framework

Giuseppe Fragapane[a], Hans-Henrik Hvolby[b], Fabio Sgarbossa[a] and Jan Ola Strandhagen[a]

[a]Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Trondheim, Norway; [b]Department of Materials and Production, Centre for Logistics, Aalborg University, Denmark

ABSTRACT
The logistics activities of sterile instruments are both labour- and cost-intensive. Automating sterile instrument transportation offers an excellent opportunity to reduce staff members' responsibilities and time committed to that task. With recent technological advances in material handling, autonomous mobile robots offer an innovative solution for transporting sterile instruments, especially in dynamic environments such as hospitals. However, hospital planners need guidance in deciding when to apply which material handling systems to achieve optimal performance. This study uses a multiple case study to map sterile instrument logistics and evaluate the transportation performance of material handling systems in terms of flexibility, productivity, quality/service, and costs. Applying contingency theory and analysing the relationships between material handling systems and hospital characteristics, we contribute with a strategic fit framework showing the ideal states to achieve high performance.

ARTICLE HISTORY
Received 16 June 2020
Accepted 30 January 2021

KEYWORDS
autonomous mobile robots; sterile instrument logistics; material handling; strategic fit; multiple case study

1. Introduction

The well-being and recovery of patients seeking help depend heavily on hospitals' responsiveness in providing treatment in both emergency cases and elective procedures (Soremekun, Takayesu, and Bohan 2011; Siciliani, Moran, and Borowitz 2014; Nikolova, Harrison, and Sutton 2016). Ensuring a high level of responsiveness requires hospitals to manage – in addition to human and machine resources – the flow of materials, such as sterile instruments, to provide emergency and planned treatments or surgeries. Maintaining the high availability of sterile instruments requires efficient and reliable logistics (Volland et al. 2017). Many of these instruments are expensive and can only be used for a specific type of procedure. To keep costs low, hospitals circulate a wide range of instruments, often several times per day, between point-of-use stations – such as operating theatres and outpatient rooms – and their central sterile processing department (CSPD). All reusable instruments must be properly cleaned, disinfected and checked for functionality after each use. Since patient safety depends on medical instruments functioning properly with minimal contagion risk, hospitals must ensure that these instruments are always of high quality, sterile and available when needed (Chobin and Swanson 2012).

However, hospitals struggle to manage an efficient sterile instrument logistics system, which includes processing, storage, usage and transportation, to keep the balance between low costs and high availability of instruments. A recent study revealed that in hospitals, up to 46% of the delays in operation rooms (ORs) can be traced back to the unavailability of sterile instruments (Wubben et al. 2010). These delays not only cause longer working hours for doctors and staff – additional costs for the hospitals – but also negatively impact the quality of care, and so adverse effects can occur. The logistics of sterile instruments impact the hospital's overall performance in terms of flexibility, productivity, quality and costs (Di Mascolo and Gouin 2013).

Activities connected to the logistics of sterile instruments, such as cleaning, processing, inspecting, packaging, storing and transporting, are both labour- and cost-intensive and represent an opportunity to reduce costs for many hospitals (van de Klundert, Muls, and Schadd 2008; Di Mascolo and Gouin 2013). Previous studies have identified that transportation has a significant impact on the performance of sterile instrument logistics and is one of the major drivers of costs (Hammami et al. 2006; van de Klundert, Muls, and Schadd 2008; Tlahig et al. 2013). Transportation requests can vary considerably in frequency, distance and quantity, and the requested period from ordering to receiving sterile instruments can be very short because of, for instance, patients arriving unexpectedly and in need of emergency surgery (van de Klundert, Muls, and Schadd 2008). Furthermore, the number of carts used for the transportation of sterile instruments to the operating theatre varies. The same surgical procedure can require different or additional instruments depending on the patient's age, sex and physical condition

CONTACT Giuseppe Fragapane Giuseppe.fragapane@ntnu.no Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Trondheim, Norway

and the surgeon's preferences. Therefore, a great challenge lies in managing transportation resources of the material handling system to respond quickly in times of emergency and keeping regular transportation efficient at the same time.

Hospitals are continuously strategising about the automation of transporting hospital goods with the aim of reducing staff members' responsibilities and the amount of time required for transportation, hence increasing patient care and reducing costs (Pedan, Gregor, and Plinta 2017). Sterile instrument transportation has proven challenging to automate. Only one out of 39 hospitals in Norway uses an automated material handling system – in this case, automated guided vehicles (AGVs) – to transport sterile instruments (Ullrich 2015). The difficulty lies in finding the appropriate material handling system and level of automation for the physical and organisational needs of hospitals (Granlund and Wiktorsson 2014). The necessary level of flexibility in sterile instrument transportation has often been achieved by human labour, so manual transportation is the primary choice between a hospital's CSPD and its various point-of-use stations.

The growing logistics sector requires more highly tailored machines and could benefit from robotics (Hichri et al. 2019). Recent technological advances have had a positive impact on robots' indoor mobility. More powerful batteries, high-quality cameras for environmental recognition and increased onboard computational power enable greater autonomy of mobile robots' navigation. These changes have led to the introduction of autonomous mobile robots (AMRs) that can navigate freely within a predefined area and provide material handling services (Fragapane et al. 2021). Because of their obstacle avoidance, dynamic pathfinding and smaller vehicle dimensions, AMRs can be implemented in busy environments, such as areas with patients present and narrow hallways and doors, leading to a higher degree of integration in hospitals. Compared with an AGV, no physical reference points need to be preinstalled to guide an AMR through a hospital, and implementation time and costs can be greatly reduced. User-friendly controls enable employees to send, receive and track each transportation with ease. Technologies promoting the exchange of information have been identified as a key factor in streamlining material flow and improving collaboration in hospitals (Marques, Martins, and Araújo 2020). AMRs offer an opportunity to reduce the involvement and responsibilities of humans in material handling activities (Fragapane et al. 2020). Indeed, the implementation of AMRs may increase the responsiveness of a hospital's sterile instrument logistics while retaining the necessary level of flexibility to ensure that items are available and service levels maintained.

Most material handling systems originate and are operated in industrial settings, but to ensure long-term performance benefits, technologies must adapt to hospital characteristics – for instance, handling high levels of human interaction in a narrow and dynamic environment (Fragapane et al. 2019; Tortorella et al. 2020). Because of the variability in these traits, standards and best practices on how goods should be transported in hospitals are lacking (Volland et al. 2017). Hospital planners need guidance to achieve high performance when applying advanced technologies (Tortorella et al. 2020). The identification of the drivers of high performance and examination of the conditions under which specific practices, resources or setups are used are all vital for planning and controlling a logistics system (Ketokivi and Schroeder 2004; Böhme et al. 2016). The literature is still lacking in this regard (see Section 2). Material handling systems for sterile instrument logistics have not been investigated enough to provide hospital planners with enough support to achieve high performance in transportation while still considering crucial hospital characteristics. An approach to filling this gap is to analyse different material handling systems based on several key performance indicators (KPIs) and apply contingency theory to identify the impact of organisational characteristics with contingencies – in this case, hospital characteristics – to achieve high performance. The results and insights of this type of investigation can be used to develop a strategic fit framework for hospital planners, indicating the high performance of material handling systems and taking into consideration the hospital characteristics and contingencies.

Based on the information above, the present study's objectives are as follows:

1. Identify KPIs that are useful in evaluating the performance of sterile instrument transportation;
2. Apply contingency theory to describe and explain the impact of hospital characteristics and contingencies on the performance of the material handling systems; and
3. Based on the findings in objectives 1 and 2, align material handling systems, hospital characteristics and contingencies to achieve high performance, thus identifying the strategic fit.

To achieve these objectives, a multiple case study was conducted at three hospitals that each use different material handling systems to transport sterile instruments: manual transportation with dedicated elevators, a shared AGV system and a dedicated AMR system.

The remainder of the current paper is organised as follows: The next section reviews the related literature on sterile instrument logistics, the KPIs applied, contingency theory and strategic fit to frame the gap in existing research. Section 3 describes the multiple case study method and contingency theory employed, including case selection, data collection and analysis, while Section 4 describes the characteristics of the three case hospitals. Section 5 presents the KPI results for each case hospital, Section 6 explains the impact of hospital characteristics on material handling systems, and Section 7 explains the strategic fit between material handling systems and hospital characteristics. We conclude the study in Section 8 and offer recommendations for future research.

2. Literature review

2.1. Sterile instrument logistics

Instrument sterilisation in hospitals has evolved from a decentralised service performed by nurses in an operating room annexe to a centralised activity in which large-scale sterilisation is performed in a separate department by specialised technicians. Centralising the sterilisation process has made it possible to apply operations management techniques and optimise reverse, closed-loop logistics with the operational activities of sterile processing, storage, usage and transportation.

Regarding sterile processing, Di Mascolo and Gouin (2013) propose a generic simulation model for hospital planners to design the CSPD (e.g. determine the number of machines or loading machines policies) and evaluate the different sterile processing activities in the utilisation or throughput times. Ozturk, Begen, and Zaric (2014) propose that a typical bottleneck in sterile processing is the washing step. The arrival patterns of contaminated sterile instruments often result in significant accumulation throughout the CSPD (Lin et al. 2008). Ozturk, Begen, and Zaric (2014) introduce a branch-and bound-based heuristic to optimise the washing machine schedule, minimising the makespan of parallel job batches.

To reduce costs and increase the efficiency of CSPD, several studies have investigated decentralising and outsourcing the sterilisation process in hospitals. van de Klundert, Muls, and Schadd (2008) investigate the optimisation problems that must be resolved when redesigning the supply processes of the decentralised CSPD to improve the availability of materials and reduce costs; the introduced lot-sizing and transportation model aims to find the minimal inventory and transportation costs by using dynamic programming for different replenishment methods. Outsourcing implies keeping safety stocks on site at the hospital. The study by van de Klundert, Muls, and Schadd (2008) highlights the difficulty of setting the safety stock for keeping inventory and transportations low and availability high at the same time. Rather than the number of instruments, it is their immense variety that is challenging for the outsourcing process of the CSPD. Information technology is identified as a valuable opportunity for improvement. Therefore, the model has been extended to a dynamic, nondeterministic setting to highlight the value-added of real-time information availability. In two different scenarios and sterilisation service structures, a recent study by Tlahig et al. (2013) compares the in-house sterilisation and outsourced sterilisation services supplying a network of several hospitals. The introduced model aims to find the optimal setup, location and capacity with the objective function of minimising the total costs, which consist of transportation, sterilisation, resource transfer and acquisition.

Studies about sterile processing have included the constraint of transportation to a larger extent than storage and point-of-use. However, for storage activities, Landry and Beaulieu (2010) present and describe the most common inventory control methods applied in sterile logistics, and Ahmadi et al. (2019) provide an overview of the optimisation approaches to reduce inventory levels, space requirements and costs. Lean tools have mainly supported reducing waste and improving process efficiency at the point-of-use (Costa and Godinho Filho 2016; Villarreal et al. 2018; Fogliatto et al. 2020).

To plan transportation and design material handling systems in hospitals, discrete-event simulations have been the most appropriate approach, especially for AGVs (Čerić 1990; Chikul, Maw, and Soong 2017). Le-Anh and De Koster (2006) provide an overview of the strategic, tactical and operational decisions for planning and controlling AGVs. Fragapane et al. (2019) apply an agent-based simulation model to assess the AGV system in hospitals, investigating the different transportation scenarios to improve delivery time and resource utilisation. A case study by Benzidia et al. (2019) investigates the different goods flows in hospitals and highlights the complexity of the distribution networks performed by AGVs; the study points out that hospitals are more likely to decide to keep manual transportation in case the demand is less predictable and the variety of a single category of goods is high.

In summary, studies in sterile instrument logistics apply significantly higher quantitative methods than qualitative or mixed methods. Mathematical modelling and simulation have been the preferred approaches for planning and optimising the activities of sterile processing, storage, use and transportation of sterile logistics. Furthermore, decision support systems for planning transportation or the material handling system mainly focus on the tactical and operational levels, such as scheduling, routing, battery and traffic management.

2.2. Key performance indicators for sterile instrument transportation

Measuring performance can provide information about optimal status or deficiencies in sterile instrument transportation and can serve as the basis for planning, optimisation, improvement, control or evaluation purposes. According to Behn (2003), an evaluation is the most common reason for measuring performance because it tries to answer the following question: How do the operations and practices of this organisation compare with the ones that are known to be most effective and efficient? To compare the actual performance of an organisation against the performance criteria, a variety of outcome measures combined with some input measures should be defined (Behn 2003).

The literature review on sterile instrument logistics allows for identifying the different KPIs applied in previous studies and grouping them in terms of their flexibility, productivity, quality, service and costs. Benzidia et al. (2019) and Fragapane et al. (2019) investigate how well the material handling system in hospitals can adapt to transportation demand changes and how well it can handle different flows of goods. Automating the material flows can reduce the degree of personnel involved in deliveries (Volland et al. 2017). Thereby, measuring and comparing the value-added time supports a comparison of the productivity of an automated material handling system with a manual one. To assess the quality of deliveries, Čerić (1990) uses lead time as a KPI to optimise the transportation schedule of AGVs. Moons, Waeyenbergh, and Pintelon (2019) argue that measuring the response time to urgent requests and reliability of timely and correct deliveries can improve transportation quality. Investigating the reliability and robustness of AGV transportation in hospitals, Fragapane et al. (2019) analyse the number of errors and their effects on transportation performance.

Unsurprisingly, measuring cost performance has received the most attention in hospital logistics (Moons, Waeyenbergh, and Pintelon 2019). For the evaluation of automated material handling systems, the implementation and adjustment costs are especially important to consider because these costs can be quite high and make the automation of material flows unprofitable in hospitals (Chikul, Maw, and Soong 2017). The operational costs of transportation are not to be underestimated; these costs can be crucial when deciding on outsourcing a sterile processing department from the hospital (van de Klundert, Muls, and Schadd 2008).

Overall, in sterile instrument transportation, the defining performance indicators and performance measurements are for planning, optimisation and improvement purposes. Thereby, only a single material handling system has been assessed in these studies. The introduced KPIs allow only for reflection and discussion on a small aspect of sterile instrument transportation, limiting the comparison of different material handling systems. There is a need for a broader variety of KPIs to evaluate the material handling systems in sterile instrument logistics and to support the analysis of the impact of hospital characteristics on these material handling systems.

2.3. Contingency theory and strategic fit

Contingency theory is a major theoretical lens used to view organisations and support organisations to see the relation between organisational characteristics and contingencies, such as the environment, size and strategy for reaching high performance (Donaldson 2001). This theory provides a substantial basis for investigating fit (Acur, Destan, and Boer 2012) because the concept of strategic fit builds on contingent views of strategy and resources (Venkatraman 1989). Strategic fit describes a situation in which elements both internal and external to the organisation are aligned (Scholz 1987), and this fit between a firm and its environment is crucial to yield desirable performance implications (Zott 2003; Fainshmidt et al. 2019). Therefore, strategic fit has been a powerful tool for managers to match the demand and supply characteristics on a strategic level (Fisher 1997; Christopher, Peck, and Towill 2006; Gligor, Esmark, and Holcomb 2015) because it helps reveal the ideal state towards which a logistics system should be continually directed (Zajac, Kraatz, and Bresser 2000). This concept can be used on a supply chain level (Cannas et al. 2020) and for areas within the supply chain, such as production (Buer et al. 2016) or, as in our study, transportation.

2.4. Research gap

The introduction of AMRs has opened new possibilities for performing services and activities and addressing some current challenges in hospital logistics. Since AMRs have only recently been introduced to hospitals, studies analysing the impact of AMRs on hospital logistics and how to deploy them at the strategic level are lacking. No study has yet evaluated the transportation performance of different material handling systems in sterile instrument logistics. The KPIs for the transportation of sterile instruments and crucial hospital characteristics necessary for such an investigation have not yet been sufficiently detailed. Identifying the ideal states of material handling systems on the strategic level – especially the application of AMRs to achieve high performance in sterile instrument transportation – has also not been sufficiently addressed. Contingency theory can provide support in such investigations to identify hospital characteristics and align them to develop strategic fit. To the best of our knowledge, the existing literature is entirely lacking in this regard.

3. Methods

Case research was conducted to achieve the current study's aims and fill the gap in the literature. This research approach is suitable for investigating a real-life phenomenon when the associated variables and complexity are not sufficiently understood (Creswell John 2012). The case study research method has been highly recommended by many researchers as an excellent tool for improving the conceptual and descriptive understanding of phenomena (McCutcheon and Meredith 1993; Barratt, Choi, and Li 2011; Yin 2017). The growing frequency and magnitude of changes in technology and managerial methods in operations management require researchers to apply field-based methods (Lewis 1998), and a case study is among the most powerful research methods in operations management (Fynes et al. 2015). The multiple case study approach allows for a more direct comparison of the similarities and differences between implementation practices in different contexts than other approaches (Dinwoodie and Xu 2008), increases external validity and protects against observer bias (Voss 2010). Since the present study aims to compare different material handling systems regarding performance and understand the impact of contextual factors – in this case, hospital characteristics – contingency theory was chosen as the theoretical lens. The contingency theory focuses on achieving high performance in technology and practice by including and adapting to the organisational context (Donaldson 2001; Sousa and Voss 2008). To do so, three sets of variables should be considered: use of practice, performance and contingency factors.

For the use of practice, the theoretical framework by Tanchoco (1994), which specifies the crucial parts when designing and operating a material handling system in a logistics system, has been applied. KPIs were defined to compare the different material handling systems that involve sterile instrument logistics. Selecting suitable and relevant performance measures is critical when analysing any system precisely. According to Gunasekaran and Kobu (2007), intangibles, such as resource utilisation and flexibility, are difficult to measure but play a major role in the effective management of logistics. Therefore, they advise that KPIs and metrics should be discussed with and tailored to the individual organisations.

For the contingency factors, the current study included hospital characteristics of the general, environmental and operational aspects reflecting the common contingencies of environment, size and strategy. This selection is based on a review of the literature in the field of hospital logistics (Granlund and Wiktorsson 2014; Böhme et al. 2016; Volland et al. 2017; Moons, Waeyenbergh, and Pintelon 2019).

The multiple case study format allowed for building a comprehensive understanding of the findings from different sites and combining them to create a total knowledge area of the critical aspects that helped develop the strategic fit between the case hospitals' characteristics and material handling systems.

3.1. Case selection

Case selection is a vital element in the current type of research. When using the traditional approach, a sample of cases is built by selecting cases according to different criteria (Eisenhardt and Graebner 2007). However, for multiple cases that resemble multiple experiments, it is crucial to focus on the replication logic rather than the sampling logic (Yin 2017). Our strategy is based on achieving theoretical replication using information-rich cases that produce diverse results and maximum variation, although for predictable reasons (Bazeley 2013; Voss 2010). The three hospitals selected have implemented three distinct material handling systems – each with different degrees of automation – to supply their CSPDs and point-of-use locations. A material handling system using manual transportation and dedicated elevators, a shared AGV system and a dedicated AMR system both using elevators represent the different degrees of automation in the transportation of sterile instruments. The three hospitals are located in Norway and Denmark and share similarities in how they are structured as organisations and how they provide healthcare.

3.2. Data collection and analysis

In case research, triangulation is an essential factor in increasing the research validity: it is the process of corroborating evidence from different individuals and types of data, such as theory, interviews, observations, documents and field notes, to reflect the same phenomenon (Creswell John 2012; Carter et al. 2014). In the current study, multiple semistructured interviews were conducted. The purpose was to interview key personnel who could provide useful information regarding their hospitals' CSPD processes, logistics loops and material handling systems. The interviews were conducted with each hospital's managers, leaders, operators, coordinators and other personnel involved in the day-to-day transportation of sterile instruments to obtain information about decision-making at the operational, tactical and strategic levels. Personnel from different departments were interviewed to ensure the representation of several central stakeholders in the logistics loop (Table 1).

In preparation for the interviews, an interview guide was developed based on the literature review and was adapted to match the subjects' backgrounds and levels of education (Appendix A). This guide supported the discussion with the hospital personnel, leading them to both describe the sterile instrument logistics and express their points of view about applied material handling systems in the case hospitals. Semistructured interviews proved an effective way to collect data, and the interviews were analysed using the recommendations by Mayring (2004) for a content analysis. Several visits were made to conduct observations in different departments (CSPD, ORs, points-of-use, etc.) at all three hospitals. Here, observations were crucial because many occurrences concerning the transportation of goods, such as delays, often go unrecorded. Complex processes inside and outside the CSPD could be observed in their natural setting, allowing the researchers to study actual behaviour. Relevant information was also obtained through the documents, illustrations and reports provided by the participants during the visits and interviews.

Table 1. List of interviews conducted.

Hospital	Interview	Duration
A	Logistics Manager	90 min
	CSPD Department Manager	45 min
	CSPD Quality Coordinator	45 min
	Operation Room Coordinator	30 min
	Maintenance Operator	90 min
B	CSPD Department Manager	45 min
	CSPD Quality Coordinator	45 min
	Logistics Manager	45 min
	Inventory Control Manager	90 min
	Maintenance Operator	90 min
C	Hospital Director	30 min
	Hospital Planner	45 min
	Logistics Manager	45 min
	CSPD Department Manager	30 min
	Material Handling Supplier	90 min

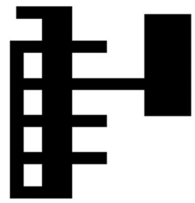
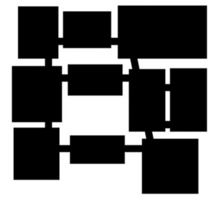
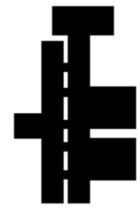
4. The case hospitals' sterile instrument logistics and applied material handling systems

The following three subsections provide a detailed description of each case hospital's sterile instrument logistics and applied material handling systems, followed by a description of its closed-loop sterile instrument logistics control model. The general, environmental and operational characteristics of the hospitals are summarised in Table 2.

4.1. Hospital A

This hospital's layout follows the principle of serving patients who come for brief visits on the lower floors and patients requiring longer visits on the higher floors. Therefore, outpatient clinics and the emergency department are located on the lower floors and inpatient services on the higher ones. ORs and treatment rooms are located in the left wing and wards in the right wing. The CSPD is located in the basement of the left wing below the ORs and processes reusable instruments for ORs and outpatient clinics. Thus, the surgical department, which uses the largest share (90%) of reusable instruments, is located near the CSPD.

Table 2: Case hospitals' key characteristics.

Hospital characteristics	Hospital A	Hospital B	Hospital C
General			
Size	700 beds	750 beds	300 beds
Type	University hospital	University hospital	Regional hospital
Construction year (Last major renovation or addition)	1961 (2008)	1902 (2005)	1988 (expected to be finished in 2024)
Environmental			
Building layout			
Building layout	(add the attached figure here)	(add the attached figure here)	(add the attached figure here)
Buildings floors	Up to 6 floors	Up to 7 floors	Up to 4 floors
Ratio of vertical to horizontal transportation	Vertical 70%, horizontal 30%	Vertical 20%, horizontal 80%	Vertical 30%, horizontal 70%
Operational			
Sterile processing Location	Centralised, in-house	Centralised, in-house	Centralised, in-house
Sterile processing Planning horizon	Week	Day	Week
Sterile processing Throughput time	6 h maximum	24 h maximum	6 h maximum
Inventory Location	Centralised	Decentralised	Centralised
Inventory Replenishment method	Kanban	Reorder point policy with periodic review	Kanban
Delivery Principle	Just-in-time deliveries with low time buffer	Scheduled deliveries with high time buffer	Just-in-time deliveries with low time buffer
Control model	Figure 1	Figure 2	Figure 3
Material handling system			
Method, type	Manual transportation using dedicated elevators	Shared AGV system using shared elevators	AMR using shared elevators
Size (length, width, height)	Cart: 860 × 710 × 1500 mm	AGV with cart: 1700 × 860 × 1600 mm	AMR with cart: 890 × 780 × 1600 mm
Navigation	Autonomous	Path-guided	Autonomous
Transported material types	One – Sterile instruments	Six – Sterile instruments, food, pharmaceuticals, medical supplies, laundry, and waste	One – Sterile instruments

Since Hospital A is a large university hospital, its CSPD operates 24 h a day, although staffing levels are lower on the weekends. The CSPD's workload is heaviest between 11:00 am and 7:30 pm each weekday, mainly because of the scheduling of surgeries. After the contaminated instruments are returned to the CSPD, the hospital's goal is to wash, inspect, pack, sterilise and return the instruments to storage within 6 h. The carts are washed at the same time in a cart washing machine. Most sterile instruments are stored centrally within the CSPD, which means that it is responsible for cleaning, storing and distributing the hospital's sterile instruments.

The available information technology (IT) system allows sharing information about planned surgeries among all departments involved in the hospital's sterile instrument logistics. The hospital provides information regarding planned surgeries on a weekly basis, allowing the CSPD to plan a week ahead and be quickly updated on changes in surgery schedules. Detailed information about the instruments needed for surgeries can be extracted from the IT system, and the delivery of sterile instruments follows the just-in-time principle. CSPD staff members prepare carts with the instruments needed for a given operation or treatment from central storage. The carts are picked up by porters and delivered to their destinations using elevators and corridors. The CSPD has dedicated clean and soiled elevators. The delivery and return of carts with sterile instruments are both performed manually. After surgery, soiled materials are brought directly to the CSPD's decontamination area. A high level of coordination is required among CSPD personnel, the OR and porters. The control model of the sterile instrument logistics for Hospital A is shown in Figure 1.

4.2. Hospital B

This hospital's specialised healthcare services are spread across nine buildings, each containing up to seven floors. The CSPD is in the basement of one of the western buildings. It processes reusable instruments for ORs, the emergency department, outpatient clinics and wards. The orthopaedic clinic and ORs are the CSPD's primary clients. On weekdays, it is staffed 24 h a day, but staffing levels are lower on the weekends. Some equipment and instruments are kept in storage at the CSPD, but the largest share of such items is placed in decentralised storage areas in the hospital's various department levels and ORs. For inventory control, the hospital uses a reorder point policy with periodic review. In every review cycle, if the inventory level is equal to or less than the reorder point, replenishment is triggered to increase inventory to a predefined maximum level. The amount ordered is not constant and depends on the current inventory. All departments use manual requisition forms to indicate their requirements for the next day and, preferably, the specific time at which the items will be needed. These forms are sent electronically to the CSPD each day. The emergency department can order supplies and receive them on the same working day, but departments cannot automatically order what they need for several reasons. Some types of surgery and hospital departments have additional instrument requirements, and some instruments cannot be traced back to their original storage area when they arrive at the CSPD. The instruments are processed according to their priority status: rush orders (as soon as possible), priority orders (within 14 h) and regular orders (within 24 h). Because surgery schedules change frequently, the hospital has decided not to permit placing orders for sterile instruments for more than 24 h in advance. The hospital uses an IT system that can track the flow of sterile reusable instruments in the logistics loop. The items must be scanned manually after they are received, cleaned, inspected, delivered and stored. In some departments, information regarding inventory levels is available.

The AGV system covers the hospital's transportation services to and from the CSPD and other departments. In total, there are 25 AGV pickup and delivery points connected to the sterile instrument logistics (in front of the CSPD and at various point-of-use departments). Personnel must place wagons containing sterile instruments in dedicated areas for pickup by an AGV. When the wagons are delivered to the appropriate department, the hospital personnel are informed via the IT system that the wagons have arrived. In some critical cases and on weekends, manual transportation is used to supply and return sterile instruments. Hospital B's sterile instrument logistics mode is illustrated in Figure 2.

The hospital's AGV system consists of 21 laser-guided AGVs and transports, in addition to sterile instruments, food, linen and clothing, medical supplies, pharmaceutical products and waste. Different priorities and time slots are defined for each group of goods. The AGVs can lift and move wagons within the 4500-m guide-path and access tunnels and elevators, thus reaching many areas of the hospital. The AGVs can communicate with doors and elevators via ultra-wideband. On average, the AGVs transport approximately 50–70 tonnes of goods every week between a total of 114 pickup and delivery points. The remaining 89 points are positioned at goods arrival, kitchen, pharmacy, waste disposal and various departments. The AGVs are cleaned on a regular basis, and each one can operate for 3 h before needing to be charged for an hour.

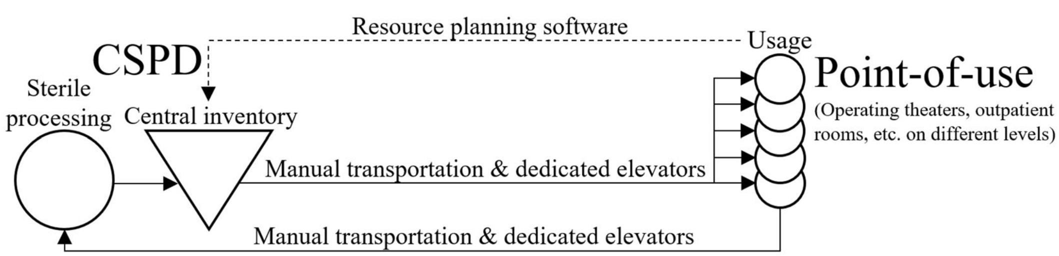


Figure 1. Control model of sterile instrument logistics in Hospital A.

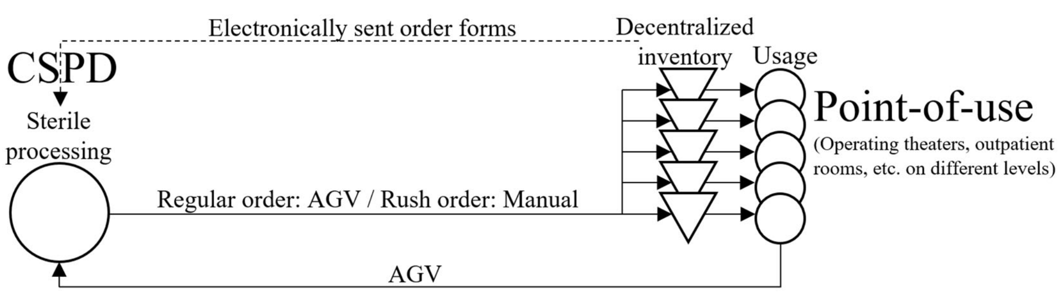


Figure 2. Control model of sterile instrument logistics in Hospital B.

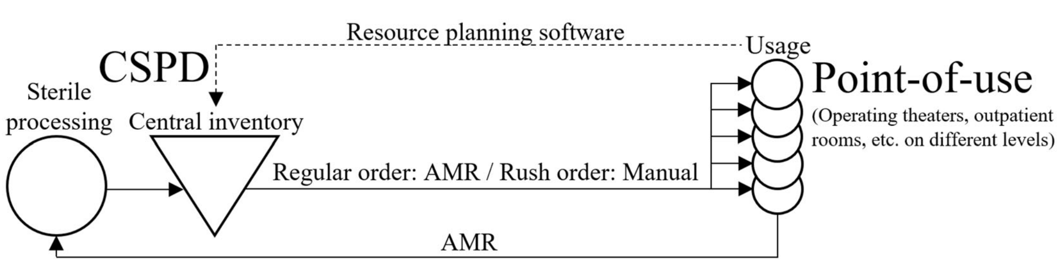


Figure 3. Control model of sterile instrument logistics in Hospital C.

4.3. Hospital C

This hospital's healthcare services are spread throughout the building and are arranged by type of patient visit. Outpatient clinics are mainly on the first floor, whereas inpatient wards are on the second. The CSPD is currently in the basement and serves the hospital's operating rooms, outpatient clinics and wards. Elevators and corridors must be used to reach the different departments from the CSPD. Because the hospital has only two floors, more horizontal than vertical transportation is required.

The CSPD is not staffed 24 h a day; it operates from 7:00 am to 10:00 pm on weekdays and 7:00 am to 3:00 pm on weekends. During these hours, it is responsible for washing, maintaining, packing, sterilising and distributing instruments to the hospital's various departments. After a short processing and throughput time of a maximum of 6 h, the instruments are sent to central storage at the CSPD, which is in charge of distributing the instruments and supplies required for surgeries and other treatments. The IT system allows for extracting the information needed to prepare the required sterile goods. The instruments are picked up at the storage area and packed onto a wagon. CSPD staff members send the wagons, with the help of the AMR, from the CSPD to the hospital's various departments (Figure 3). Thus, instruments are delivered according to the just-in-time principle, reducing the need for local storage. Some departments have small local depots with low inventory for special and critical situations. The number and contents in the wagons in operation must be kept up-to-date by the end users in each department. In the past, service assistants delivered the disposable equipment supplies to the departments, which required heavy lifting and considerable physical activity. Today, CSPD personnel can control, monitor and track transports using a tablet computer. There are 10 different pickup and delivery points within the logistics loop. After registering a delivery, the AMR picks up the wagon and delivers it to its destination. It does not have to follow a strict guide-path and, thus, can avoid obstacles and people by autonomously finding alternative paths. This attribute supports the AMR's usefulness in dynamic environments involving human interaction. CSPD personnel can monitor the AMR's path remotely and see if something unusual or wrong is occurring. Communicating via ultra-wideband, the AMR can use elevators and doors; hence, it can access all parts of Hospital C. Because no physical references must be implemented to guide it through the hospital, the costs and implementation time are reduced significantly. The AMR travels 15 km and delivers approximately 60 wagons per day. It can remain in operation for 10 h or travel 20 km before needing to be charged. To prevent and control infection, the AMR is cleaned regularly.

5. Performance measures of sterile instrument transportation

Previous studies on material handling systems in sterile instrument logistics have focussed on a few KPIs. The current study identified KPIs that allow for the evaluation of material handling systems not only from the common aspects of costs and productivity, but also flexibility, quality and service.

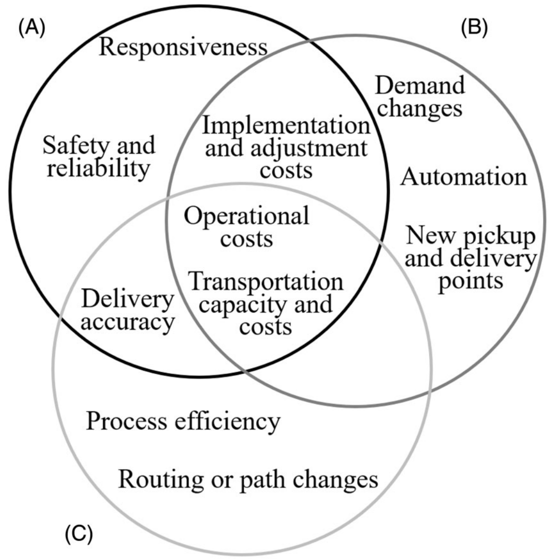


Figure 4. Identified KPIs for sterile instrument transportation in the three case hospitals.

To assess the adequacy and select the appropriate KPIs for sterile instrument transportation, we first determined the main performance areas based on the literature on sterile instrument transportation, as discussed in Section 2. Second, we identified the applied KPIs at each hospital (see Figure 4).

Finally, we selected relevant KPIs and discussed how to evaluate and rate the transportation performance of the hospitals' material handling systems through whole-day workshops at each hospital with hospital planners. Table 3 describes the selected KPIs for sterile instrument transportation.

Three different types of material handling systems – manual transportation with dedicated elevators, a shared AGV system and a dedicated AMR system – that transport sterile instruments in hospitals were analysed by measuring and comparing their performance using several KPIs to assess their applicability in hospitals.

Manual transportation with dedicated elevators was found to be highly flexible, agile and easy to maintain. The level of human involvement, however, reveals its productivity efficiency to be low and that it is an expensive transportation solution because of issues with communication, time management and transportation inefficiency. Since manual transportation is logged less often, it is also difficult to recall errors, delays or miscommunications.

The shared AGV system has standardised processes that enable a high degree of automation. Due to its ability to handle different material flows and heavy loads, the AGV system has been demonstrated to be very efficient and productive. Since the communication system and its interfaces are clearly defined between the personnel and AGVs, the AGV system can immediately register when a wagon must be delivered or returned. However, these positive attributes have drawbacks: there is limited flexibility for making changes and working with large buffers. For example, when changing the pickup and delivery points, the hospital must implement physical reference points, set up new readers for the wagons, establish the new infrastructure information and adapt the guide-path of the AGV's controls. These efforts are

Table 3: KPIs for sterile instrument transportation.

Performance dimensions	KPI	Description
Flexibility	Demand changes	The degree of adaptation to changes in demand
	Routing or path changes	The degree of adaptation to new paths
	Add new pickup and delivery points	The degree of time and effort required to include and integrate new buildings, departments and areas
Productivity	Transportation capacity	The number of transported items per delivery
	Automation	The ratio of machines to personnel time involved in deliveries
	Process efficiency	The ratio of value-added time to non-value-added time
Quality/Service	Delivery accuracy	The proportion of correct and on-time deliveries
	Responsiveness	The time period for total transportation, including ordering, pickup, and delivery
	Safety and reliability	The number of system failures and errors
Costs	Implementation and adjustment costs	The costs of setting up and modifying the material handling system
	Transportation costs	The costs of single transport run
	Operational costs	The costs of operating and maintaining the material handling system

time-consuming and expensive for hospitals because they require planning the changes and involving all the implementation's external partners.

Due to the low level of effort required for its implementation, the minimal human involvement in its transportation and its modest need for maintenance, the AMR is an affordable material handling system for a single material flow. It facilitates a high degree of responsiveness and the capability of applying lean principles to the supply task, with many small, just-in-time transportations instead of fewer transportations with heavier loads. Reducing the batch sizes and performing on-demand transportation can improve both forward and return logistics. For instance, the washing process performed at the CSPD can form a bottleneck within logistics systems. Supplying the CSPD with soiled instruments in small batches facilitates faster response times, as it allows the washing process to begin earlier, and thus reducing the amount of work in process. Table 4 presents the results of the performance measurements, rated in the ranges of low, middle and high, to differentiate the results.

6. Impact of hospital characteristics on material handling systems

6.1. Impact of general and environmental hospital characteristics on material handling systems

Whether small or large, regional or university, hospitals have demonstrated favourable productivity, quality, service and cost performance outcomes after applying an automated material handling system for sterile instrument logistics. Even a small regional hospital can implement and use an automated material handling system. In Hospital C, the AMR substituted one full-time employee and amortised costs within two years. It is not the size that is important, but rather the environmental variables, such as the hospital layout and distribution of the pickup and delivery points.

Hospitals have attempted to concentrate their many departments within the sterile instruments loop to reduce transportation times and, thus, costs. Locating the units involved in sterile instrument logistics above one another and using elevators have helped reduce transport times. Therefore, hospital planners aim for a higher ratio of vertical to horizontal transportation when designing a hospital. According to the logistics managers of the case hospitals, this ratio is being challenged by two major identified trends. First, several polyclinical departments increasingly use more complex and reusable instruments and want to be connected to the CSPD. These departments are located throughout hospitals, so relocating them close to the CSPD is nearly impossible in an operating hospital. Second, hospitals are expanding and erecting new buildings, and new departments must be incorporated into the existing sterile instrument logistics. Restructuring and expanding major hospitals while smaller ones are closed has been reported in many Western countries (Giancotti, Guglielmo, and Mauro 2017). The layout of hospitals is changing, and the ratio of vertical to horizontal transportation is decreasing, trending towards a more horizontal approach. Changing the ratio of vertical to horizontal transportation especially affects the productivity and cost performance of the material handling system. As horizontal transportation increases, the economic suitability of AGVs and AMRs also increases because manual transportation reduces the value-added time of hospital personnel, which is associated with higher costs.

6.2. Impact of operational characteristics of sterile instrument logistics on material handling systems

In the current study, two logistics system strategies that are typically applied in hospitals were investigated: an efficient one with centralised sterile processing, decentralised storage and scheduled deliveries with a high time buffer and a responsive one with centralised sterile processing, centralised storage and just-in-time deliveries. Both can fulfil the central objective of ensuring the availability of sterile instruments for planned and emergency surgeries, and each one is associated with different trade-offs.

The first strategy relies on decentralised storage areas with high inventory levels in the departments at the point of care responding quickly in critical situations. This allows for longer replenishment lead times, thus reducing the pressure on delivery accuracy. The material handling system can perform deliveries with a high time buffer and low responsiveness. This strategy is convenient for transporting sterile instruments and several other material flows, such as linen, food, waste and so forth with one material handling system, thus reducing the overall transportation costs. The suitable solution for this strategy has been the implementation of AGVs.

Table 4. Results of performance measurements conducted in the three case hospitals.

KPI	Hospital A	Hospital B	Hospital C
Flexibility			
Demand changes	*High* – Personnel schedules can be adapted easily	*Low* – The AGV system can adapt to changes, but this may result in longer wait times	*Medium* – The AMR can adapt to changes
Routing or path changes	*High* – Personnel can easily make routing or path changes	*Low* – Technical staff must invest many hours adjusting AGV guide paths, sensors, etc.	*High* – The AMR can autonomously find alternatives
Add new pickup and delivery points	*High* – New areas can be added easily	*Low* – Technical staff must invest many hours adjusting AGV guide paths, sensors, etc.	*Medium* – New areas can be scanned easily with the AMR to increase the transportation area
Productivity			
Transportation capacity	*Low* – Personnel can only move small carts for a single operation	*High* – AGVs can transport several heavy wagons	*Low* – AMRs can transport a single large wagon
Automation	*Low* – Personnel are involved throughout the delivery process	*High* – Personnel only prepare and unload the wagons	*High* – Personnel only prepare and unload the wagons
Process efficiency	*Low* – Difficult to combine forward and reverse transportation; many idle periods for personnel without goods transportation	*High* – The AGV system transports many other goods and has a very low number of empty transportations	*Medium* – The AMR can transport both sterile and dirty instruments; nevertheless, some empty transportations are unavoidable
Quality/Service			
Delivery accuracy	High – Applies the just-in-time principle	High – Large time buffers allow the AGVs to make deliveries on time	High – Applies the just-in-time principle
Responsiveness	*Medium* – While outgoing instruments are delivered quickly, the return of instruments takes a long time	*Low* – The AGV system must manage several material flows at the same time; ordering and pickup times can both occur during the hospital's core operating hours	*High* – Manages one material flow; the AMR has short wait times and moves rapidly
Safety and reliability	*High* – Personnel can make quick decisions and adapt to new challenges	*Low* – AGVs cannot bypass obstacles or errors and depend on technical staff to fix failures and errors	*Medium* – AMRs can handle dynamic areas and bypass obstacles; however, complicated errors must be resolved by personnel
Cost			
Implementation and adjustment costs	Low – Minor costs for equipment and setup; manual transportation can be changed easily at a low cost	High – Physical reference points, the IT structure that must be installed, and high vehicle prices result in high implementation costs; additional adjustments increase costs	*Medium* – Short implementation time, low cost of vehicles and equipment, adjustments can be implemented easily
Transportation costs	*High* – High personnel involvement and low transportation capacity result in high transportation costs	*Low* – Electricity and manual preparation of the wagons are incidental costs	*Low* – Electricity and manual preparation of the wagons are incidental costs
Operational costs	*High* – High labour costs and low transportation efficiency	*Medium* – Technical staff must maintain the AGVs on a regular basis and are needed during AGV operation to fix problems like removing obstacles from the guide-path	*Low* – Technical staff must maintain the AMRs on a regular basis

The planner must justify the high implementation costs of incorporating an AGV system into a hospital's design. Including many material flows in the AGV system enables the conversion of a hospital personnel's time from goods transportation to healthcare and value-added activities, as seen in Hospital B's case. This reduces the transportation costs and the hospital's overall operating costs.

This strategy and its corresponding material handling systems are challenged by increased hospital admissions and commensurate material consumption. The rise in material consumption requires increasing either the inventory levels in the decentralised storage areas or transportation frequency to enable shorter reprocessing and replenishment cycles. Increasing inventory levels – thus using more of the hospital's storage area – is costly because the additional space could be used for patient care.

However, increasing the transportation frequency and changing the transportation pattern of AGVs could have a significant impact on the overall material flow in a hospital. The operation or production schedules of ORs, the CSPD, kitchen and other departments must be considered when making even minor changes to an AGV system. Hospital logistics planners are struggling to determine which changes should be made to the AGV system to handle the complexity of several types of material flows (Benzidia et al. 2019). The decentralised planning of the different units complicates the decision-making process when the goal is to improve transportation performance. Therefore, the AGV allows for only minimal adjustments and results in low flexibility.

In contrast, the second strategy aims to achieve high performance regarding flexibility and the provision of high-quality service in deliveries. The inventory is centralised with the purpose of sharing all sterile instruments among different departments. Applying the kanban system allows for keeping inventory levels and costs low. This improves the quality of the services in hospital supply chains, moving away from a push with a high buffer towards a pull with just-in-time deliveries (Papalexi, Bamford, and Dehe 2016).

This strategy requires a material handling system that can easily adapt to changes and be responsive to deliver sterile instruments just in time to the many point-of-use locations throughout the hospital. In the past, it was difficult to find an automated material handling system that could meet these needs, so many hospitals relied on manual transportation. Thanks to recent technological advances, it has been possible to successfully implement AMRs as a material handling system for this strategy.

AMRs can find the shortest path and handle dynamic areas by passing obstacles. This guarantees a high delivery accuracy. Serving only one material flow allows for a high degree of adaptation to the demand changes caused, for instance, by increased surgical operations and responsiveness in the case of an emergency. Furthermore, the AMR can find ideal spots to idle and reduce pickup time. This improves both the outgoing and return logistics of sterile instruments. However, high responsiveness comes with the downside of low utilisation. Therefore, the material handling system results in poor productivity.

7. Strategic fit of material handling systems in sterile instrument transportation

A framework can be established for the strategic fit to achieve high performance thanks to the mapping of sterile instrument logistics, the performance measures of sterile instrument transportation and the identification of hospital characteristics impacting the material handling system. The environmental and operational characteristics set the framework dimensions. Thereby, the environmental characteristics are represented by two sets: concentrated pickup and delivery points and a high ratio of vertical to horizontal transportation (E1) and widespread pickup and delivery points and a low ratio of vertical to horizontal transportation (E2). The operational characteristics are represented by the two strategies described in the previous section: centralised sterile processing, decentralised storage and scheduled deliveries with a high time buffer (O1) and centralised sterile processing, centralised storage and just-in-time deliveries (O2).

Although the analysis of sterile instrument transportation positions the material handling systems, the performance measures (low, medium and high) reveal the fit of the material handling systems for sterile instrument transportation (see Figure 5).

The strategic fit framework shows both the advantages and disadvantages of the material handling systems in sterile instrument transportation, thus exposing several interesting trade-offs. High productivity can be achieved with high automation. However, these achievements come with high flexibility and a drop in quality. Furthermore, the logistical setup must be adapted to handle the long delivery times.

Hospitals with concentrated pickup and delivery points and a high ratio of vertical to horizontal transportation can mainly rely on a manual material handling system with low automation (e.g. person elevators) or high automation (e.g. industrial paternoster) support. The investment in automation must be foremost in vertical support systems. Low investment in elevators can form bottlenecks, leading to long waiting times, thus reducing performance quality and flexibility.

However, it is difficult to achieve high productivity with manual material handling systems. Keeping the communication level high with all departments to enable scheduling the personnel responsible for sending and receiving goods requires a highly advanced IT system, which hospitals often do not have. Without the support of such a system, the personnel must make decisions regarding transportation scheduling and routing on their own. Human involvement in this decision-making process can lead to inefficient routing, poor sequencing of transportation, excess transportation and other problems. Some of these transportation inefficiencies have been identified in previous studies (Benzidia et al. 2019;

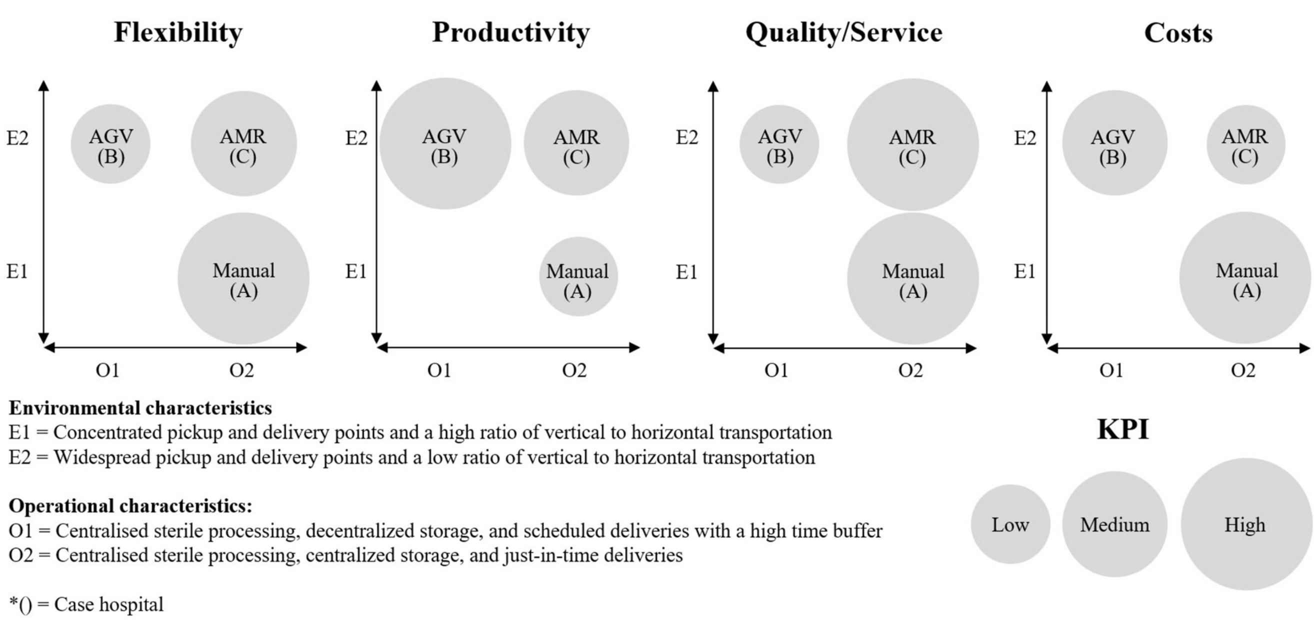


Figure 5. Strategic fit framework of the material handling systems for sterile instrument transportation.

Moons, Waeyenbergh, and Pintelon 2019) and are confirmed in the present one.

Implementing an AGV system in a hospital merely for the sake of automating the material flow will not necessarily bring a positive return on investment or achieve better performance than a manual approach (Chikul, Maw, and Soong 2017). The high implementation costs of an AGV system can only be financially justified when they cover as many material movements in a hospital as possible and reduce overall manual transportation. Achieving high utilisation of AGVs leads to large buffers to handle the different material flows in hospitals. Prioritising single material flows can improve the responsiveness of the system, hence the quality of transportation as well. However, just-in-time deliveries are still rarely feasible. Furthermore, the transportation performance of AGVs in hospitals is vulnerable because of the dynamic environment. Interacting with people and obstacles in narrow hallways can hinder AGVs' performance, as they cannot avoid obstacles and depend on support personnel to address these failures. A recent study confirms that failures caused by dynamic environments result in long queues of AGVs, impairing their transportation performance in hospitals (Fragapane et al. 2019).

One of the strengths of AMRs is their ability to navigate dynamic environments, enabling high flexibility and quality in transportation. Their intelligent navigation system supports maintaining a high level of accuracy when delivering sterile instruments by bypassing obstacles and finding the fastest route. AMRs can be a useful automation alternative to the AGV system. They offer a low-cost solution and just-in-time deliveries. However, in the future, AMRs should improve their decentralised decision-making process to handle several material flows and just-in-time deliveries. This will allow for the achievement of high productivity in transportation and close the gap with AGVs.

Finally, the introduced framework can be especially supportive in the decision-making process on a strategic level. In the planning phase of a new hospital, balancing the previously mentioned trade-offs allows for making better decisions regarding the layout, logistics system setup and the material handling system to achieve high performance. Furthermore, it can support the decision-making process of automating sterile instrument transportation in existing hospitals by indicating which material handling systems are most suitable for the hospitals' characteristics and logistical setup.

8. Conclusions

In the present study, the transportation of sterile instruments in three case hospitals was investigated and compared using KPIs to identify the strategic fit between material handling systems and hospital characteristics. AMRs have been shown to be a suitable alternative by providing highly flexible and cost-efficient transportation. The forward and reverse logistics in the closed loop of sterile instrument transportation can produce powerful benefits from such a material handling system. Sterile instruments can be delivered just in time to point-of-use areas while centralising inventory. The rapid return of goods can enable CSPDs to distribute duties more evenly across the workday while avoiding bottlenecks during washing. AMRs might also help reduce throughput times by returning instruments to the CSPD's storage area more quickly, thus reducing inventory levels and providing a buffer against increasing demand.

Due to their size, AGVs are often unable to enter departments, instead delivering only to a predetermined nearby area. However, AMRs can enter departments and deliver materials closer to the point of use because of their intelligent navigation system and smaller size. Integrating AMRs more deeply into the departments, as seen in Hospital C, can help hospitals increase efficiency and meet demand. Currently, the last 50 m, which refers to the innermost area of a hospital department, have not undergone automation. The AMRs' ability to work in dynamic environments alongside patients, nurses, doctors and visitors can lower the need for manual transportation not only in the last 50 m, but also in the entire hospital. The present study and recent study by Fragapane et al. (2020) show that mobile robots have been widely accepted in hospitals and can collaborate with hospital personnel.

The current study contributes to the development of theory by defining the adequate KPIs for assessing sterile instrument transportation. Furthermore, it demonstrates the strengths and weaknesses of different material handling systems, explaining how AMRs can support logistics in hospitals. The strategic fit framework will support practitioners in managing sterile instrument logistics, especially indicating how to automate transportation.

One of the present study's limitations is its exclusive focus on European hospitals. Each facility's layout and its personnel's degree of acceptance of robots have a significant impact on decisions regarding material handling systems in hospitals. Future research should investigate how this innovative AMR technology should be planned and controlled in different types of hospitals and for different material flows. In addition, future research could determine the most suitable ratio of vertical to horizontal transportation for automated material handling systems.

Acknowledgements

The authors would like to express their gratitude to the Regional Development Fund in Denmark for supporting the project 'Reference architecture and open standards'.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research received funding from the strategic research area of NTNU Health in 2020 at NTNU, the Norwegian University of Science and Technology.

Notes on contributors

Giuseppe Fragapane is a PhD candidate in the Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology (NTNU). He holds an M.Sc. in Business Administration and Engineering from Beuth University of Applied Sciences in Berlin, Germany, and a B.Eng. in Mechanical Engineering from the Pforzheim University of Applied Sciences, Germany. His main research interests are in the area of logistics and material handling, about which he has published research articles in peer-reviewed international conferences and journals. In addition to research activities, he is also assisting in lecturing, configuring layouts, warehousing, scheduling and conducting experimental research with autonomous mobile robots in the Logistics 4.0 Lab.

Hans-Henrik Hvolby is a Full Professor at the Centre for Logistics, Aalborg University in Denmark and a visiting professor at the Norwegian University of Science and Technology and at the University of Tasmania, Australia. For seven years, he was a visiting professor at the University of South Australia. He holds a PhD in Manufacturing Information Systems, has published more than 150 peer-reviewed papers and serves as an editorial board member of several international journals. For over two decades, he has been the project manager or partner in larger research projects raising national and European research funding. His research areas include manufacturing information systems (MRP, ERP, APS and VMI), logistics, supply chain planning, supply chain integration, value chain management and order management (BPR).

Fabio Sgarbossa has been a Full Professor of Industrial Logistics at the Department of Mechanical and Industrial Engineering at NTNU, Norway, since October 2018. He was an Associate Professor at the University of Padova (Italy), where he also received his PhD in Industrial Engineering in 2010. He is working in the Production Management Group at MTP and is responsible for the Logistics 4.0 Lab at NTNU. He has been involved in several Europeans and national projects and is the author and co-author of about 90 publications in relevant international journals on industrial logistics, material handling, materials management and supply chain. He is a member of the organising and scientific committees of several international conferences and served as a guest editor of several special issues of relevant international journals, such as Omega.

Jan Ola Strandhagen is a Full Professor of Production Management in the Department of Mechanical and Industrial Engineering at NTNU, Norway. He holds a PhD in Manufacturing Logistics. For three decades, he has been working with the research organisation SINTEF as a researcher and research manager. He now holds a full professorship at NTNU doing research in and teaching manufacturing strategy, production planning and control, and logistics and sustainability and has supervised 10 PhD students.

ORCID

Giuseppe Fragapane http://orcid.org/0000-0001-8915-509X
Hans-Henrik Hvolby http://orcid.org/0000-0002-5574-5216
Fabio Sgarbossa http://orcid.org/0000-0002-9541-3515
Jan Ola Strandhagen http://orcid.org/0000-0003-3741-9000

References

Acur, Nuran, Kandemir Destan, and Harry Boer. 2012. "Strategic Alignment and New Product Development: Drivers and Performance Effects." *Journal of Product Innovation Management* 29 (2): 304–318. doi:10.1111/j.1540-5885.2011.00897.x.

Ahmadi, Ehsan, Dale T. Masel, Ashley Y. Metcalf, and Kristin Schuller. 2019. "Inventory Management of Surgical Supplies and Sterile Instruments in Hospitals: A Literature Review." *Health Systems (Basingstoke, England)* 8 (2): 134–151. doi:10.1080/20476965.2018.1496875.

Barratt, Mark, Thomas Y. Choi, and Mei Li. 2011. "Qualitative Case Studies in Operations Management: Trends, Research Outcomes, and Future Research Implications." *Journal of Operations Management* 29 (4): 329–342. doi:10.1016/j.jom.2010.06.002.

Bazeley, Patricia. 2013. *Qualitative Data Analysis: Practical Strategies*. London: Sage Publications.

Behn, Robert D. 2003. "Why Measure Performance? Different Purposes Require Different Measures." *Public Administration Review* 63 (5): 586–606. doi:10.1111/1540-6210.00322.

Benzidia, Smail, Blandine Ageron, Omar Bentahar, and Julien Husson. 2019. "Investigating Automation and AGV in Healthcare Logistics: A Case Study Based Approach." *International Journal of Logistics Research and Applications* 22 (3): 273–293. doi:10.1080/13675567.2018.1518414.

Böhme, Tillmann, Sharon J. Williams, Paul Childerhouse, Eric Deakins, and Denis Towill. 2016. "Causes, Effects and Mitigation of Unreliable Healthcare Supplies." *Production Planning & Control* 27 (4): 249–262. doi:10.1080/09537287.2015.1105396.

Buer, Sven-Vegard, Jo Wessel Strandhagen, Jan Ola Strandhagen, and Erlend Alfnes. 2016. "Strategic Fit of Planning Environments: Towards an Integrated Framework." International Conference on Information Systems, Logistics and Supply Chain, 77–92. Cham: Springer.

Cannas, Violetta G., Jonathan Gosling, Margherita Pero, and Tommaso Rossi. 2020. "Determinants for Order-Fulfilment Strategies in Engineer-to-Order Companies: Insights from the Machinery Industry." *International Journal of Production Economics* 228: 107743. doi:10.1016/j.ijpe.2020.107743.

Carter, Nancy, Denise Bryant-Lukosius, Alba DiCenso, Jennifer Blythe, and Alan J. Neville. 2014. "The Use of Triangulation in Qualitative Research." *Oncology Nursing Forum* 41 (5): 545–547. doi:10.1188/14.ONF.545-547.

Čerić, Vlatko. 1990. "Simulation Study of an Automated Guided-Vehicle System in a Yugoslav Hospital." *Journal of the Operational Research Society* 41 (4): 299–310. doi:10.1057/jors.1990.51.

Chikul, Mittal, Hsann Yin Maw, and Yang Kok Soong. 2017. "Technology in Healthcare: A Case Study of Healthcare Supply Chain Management Models in a General Hospital in Singapore." *Journal of Hospital Administration* 6 (6): 63–70. doi:10.5430/jha.v6n6p63.

Chobin, Nancy, and Karen Swanson. 2012. "Putting Patient Safety First: The Sterile Processing Department and Healthcare Technology Management." *Biomedical Instrumentation & Technology* 46 (sp12): 27–31. doi:10.2345/0899-8205-12.1.27.

Christopher, Martin, Helen Peck, and Denis Towill. 2006. "A Taxonomy for Selecting Global Supply Chain Strategies." *The International Journal of Logistics Management* 17 (2): 277–287. doi:10.1108/09574090610689998.

Costa, Luana Bonome Message, and Moacir Godinho Filho. 2016. "Lean Healthcare: Review, Classification and Analysis of Literature." *Production Planning & Control* 27 (10): 823–836. doi:10.1080/09537287.2016.1143131.

Creswell John, W. 2012. *Educational Research: Planning, Conducting, and Evaluating Quantitative and Qualitative Research*. 4th ed. Boston: Pearson.

Di Mascolo, Maria, and Alexia Gouin. 2013. "A Generic Simulation Model to Assess the Performance of Sterilization Services in Health

Establishments." *Health Care Management Science* 16 (1): 45–61. doi:10.1007/s10729-012-9210-2.

Dinwoodie, John, and Jingjing Xu. 2008. "Case Studies in Logistics: A Review and Tentative Taxonomy." *International Journal of Logistics Research and Applications* 11 (5): 393–408. doi:10.1080/13675560802389130.

Donaldson, Lex. 2001. *The Contingency Theory of Organizations*. Thousand Oaks, CA: Sage Publications.

Eisenhardt, Kathleen M., and Melissa E. Graebner. 2007. "Theory Building from Cases: Opportunities and Challenges." *Academy of Management Journal* 50 (1): 25–32. doi:10.5465/amj.2007.24160888.

Fainshmidt, Stav, Lucas Wenger, Amir Pezeshkan, and Mark R. Mallon. 2019. "When Do Dynamic Capabilities Lead to Competitive Advantage? The Importance of Strategic Fit." *Journal of Management Studies* 56 (4): 758–787. doi:10.1111/joms.12415.

Fisher, Marshall L. 1997. "What is the Right Supply Chain for Your Product?" *Harvard Business Review* 75: 105–117.

Fogliatto, Flavio S., Michel J. Anzanello, Leandro M. Tonetto, Daniela S. S. Schneider, and Ana Maria Muller Magalhães. 2020. "Lean-Healthcare Approach to Reduce Costs in a Sterilization Plant Based on Surgical Tray Rationalization." *Production Planning & Control* 31 (6): 483–495. doi:10.1080/09537287.2019.1647366.

Fragapane, Giuseppe, Hans-Henrik Hvolby, Fabio Sgarbossa, and Jan Ola Strandhagen. 2020. "Autonomous Mobile Robots in Hospital Logistics." IFIP International Conference on Advances in Production Management System. Cham: Springer.

Fragapane, Giuseppe, Cevin Zhang, Fabio Sgarbossa, and Jan Ola Strandhagen. 2019. "An Agent-Based Simulation Approach to Model Hospital Logistics." *International Journal of Simulation Modelling* 18 (4): 654–665. doi:10.2507/IJSIMM18(4)497.

Fragapane, Giuseppe, René de Koster, Fabio Sgarbossa, and Jan Ola Strandhagen. 2021. "Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda." *European Journal of Operational Research*. doi:10.1016/j.ejor.2021.01.019.

Fynes, Brian, Paul Coughlan, Harry Boer, Matthias Holweg, Martin Kilduff, Mark Pagell, Roger Schmenner, and Chris Voss. 2015. "Making a Meaningful Contribution to Theory." *International Journal of Operations & Production Management* 35 (9): 1231–1252. doi:10.1108/IJOPM-03-2015-0119.

Giancotti, Monica, Annamaria Guglielmo, and Marianna Mauro. 2017. "Efficiency and Optimal Size of Hospitals: Results of a Systematic Search." *PLoS One* 12 (3): e0174533 doi:10.1371/journal.pone.0174533.

Gligor, David M., Carol L. Esmark, and Mary C. Holcomb. 2015. "Performance Outcomes of Supply Chain Agility: When Should You Be Agile?" *Journal of Operations Management* 33-34 (1): 71–82. doi:10.1016/j.jom.2014.10.008.

Granlund, Anna, and Magnus Wiktorsson. 2014. "Automation in Internal Logistics: Strategic and Operational Challenges." *International Journal of Logistics Systems and Management* 18 (4): 538–558. doi:10.1504/IJLSM.2014.063984.

Gunasekaran, Angappa, and Bulent Kobu. 2007. "Performance Measures and Metrics in Logistics and Supply Chain Management: A Review of Recent Literature (1995–2004) for Research and Applications." *International Journal of Production Research* 45 (12): 2819–2840. doi:10.1080/00207540600806513.

Hammami, Sondes, Ruiz Angel, Pierre Ladet, and Atidel B. Hadj Alouane. 2006. "Supplying the Operating Theatre: Cyclic and Supply Chain Approaches." *IFAC Proceedings Volumes* 39 (3): 713–718. doi:10.3182/20060517-3-FR-2903.00361.

Hichri, B., J. C. Fauroux, L. Adouane, I. Doroftei, and Y. Mezouar. 2019. "Design of Cooperative Mobile Robots for Co-Manipulation and Transportation Tasks." *Robotics and Computer-Integrated Manufacturing* 57: 412–421. doi:10.1016/j.rcim.2019.01.002.

Ketokivi, Mikko, and Roger Schroeder. 2004. "Manufacturing Practices, Strategic Fit and Performance." *International Journal of Operations & Production Management* 24 (2): 171–191. doi:10.1108/01443570410514876.

Landry, Sylvain, and Martin Beaulieu. 2010. "Achieving Lean Healthcare by Combining the Two-Bin Kanban Replenishment System with RFID Technology." *International Journal of Health Management and Information* 1 (1): 85–98.

Le-Anh, Tuan, and M. B. M. De Koster. 2006. "A Review of Design and Control of Automated Guided Vehicle Systems." *European Journal of Operational Research* 171 (1): 1–23. doi:10.1016/j.ejor.2005.01.036.

Lewis, Marianne W. 1998. "Iterative Triangulation: A Theory Development Process Using Existing Case Studies." *Journal of Operations Management* 16 (4): 455–469. doi:10.1016/S0272-6963(98)00024-2.

Lin, Feng, Mark Lawley, Charlie Spry, Kelly McCarthy, Patricia G. Coyle-Rogers, and Yuehwern Yih. 2008. "Using Simulation to Design a Central Sterilization Department." *AORN Journal* 88 (4): 555–567. doi:10.1016/j.aorn.2008.03.015.

Marques, Leonardo, Marina Martins, and Cláudia Araújo. 2020. "The Healthcare Supply Network: Current State of the Literature and Research Opportunities." *Production Planning & Control* 31 (7): 590–609. doi:10.1080/09537287.2019.1663451.

Mayring, Philipp. 2004. "Qualitative Content Analysis." In *A Companion to Qualitative Research*, edited by Uwe Flick, Ernst von Kardorff, and Ines Steinke, 159–176. London: Sage Publications.

McCutcheon, David M., and Jack R. Meredith. 1993. "Conducting Case Study Research in Operations Management." *Journal of Operations Management* 11 (3): 239–256. doi:10.1016/0272-6963(93)90002-7.

Moons, Karen, Geert Waeyenbergh, and Liliane Pintelon. 2019. "Measuring the Logistics Performance of Internal Hospital Supply Chains–A Literature Study." *Omega* 82: 205–217. doi:10.1016/j.omega.2018.01.007.

Nikolova, Silviya, Mark Harrison, and Matt Sutton. 2016. "The Impact of Waiting Time on Health Gains from Surgery: Evidence from a National Patient-reported Outcome Dataset." *Health Econ* 25 (8): 955–968. doi:10.1002/hec.3195.

Ozturk, Onur, Mehmet A. Begen, and Gregory S. Zaric. 2014. "A Branch and Bound Based Heuristic for Makespan Minimization of Washing Operations in Hospital Sterilization Services." *European Journal of Operational Research* 239 (1): 214–226. doi:10.1016/j.ejor.2014.05.014.

Papalexi, Marina, David Bamford, and Benjamin Dehe. 2016. "A Case Study of Kanban Implementation within the Pharmaceutical Supply Chain." *International Journal of Logistics Research and Applications* 19 (4): 239–255. doi:10.1080/13675567.2015.1075478.

Pedan, Marko, Milan Gregor, and Dariusz Plinta. 2017. "Implementation of Automated Guided Vehicle System in Healthcare Facility." *Procedia Engineering* 192: 665–670. doi:10.1016/j.proeng.2017.06.115.

Scholz, Christian. 1987. "Corporate Culture and Strategy—The Problem of Strategic Fit." *Long Range Planning* 20 (4): 78–87. doi:10.1016/0024-6301(87)90158-0.

Siciliani, Luigi, Valerie Moran, and Michael Borowitz. 2014. "Measuring and Comparing Health Care Waiting Times in OECD Countries." *Health Policy* 118 (3): 292–303. doi:10.1016/j.healthpol.2014.08.011.

Soremekun, Olanrewaju A., James K. Takayesu, and Stephen J. Bohan. 2011. "Framework for Analyzing Wait Times and Other Factors That Impact Patient Satisfaction in the Emergency Department." *The Journal of Emergency Medicine* 41 (6): 686–692. doi:10.1016/j.jemermed.2011.01.018.

Sousa, Rui, and Christopher A. Voss. 2008. "Contingency Research in Operations Management Practices." *Journal of Operations Management* 26 (6): 697–713. doi:10.1016/j.jom.2008.06.001.

Tanchoco, Jose Mario Azaña. 1994. *Material Flow Systems in Manufacturing*. Boston: Springer.

Tlahig, Houda, Aida Jebali, Hanen Bouchriha, and Pierre Ladet. 2013. "Centralized versus Distributed Sterilization Service: A Location–Allocation Decision Model." *Operations Research for Health Care* 2 (4): 75–85. doi:10.1016/j.orhc.2013.05.001.

Tortorella, Guilherme Luz., Flávio Sanson Fogliatto, Alejandro Mac Cawley Vergara, Roberto Vassolo, and Rapinder Sawhney. 2020. "Healthcare 4.0: Trends, Challenges and Research Directions." *Production Planning & Control* 31 (15): 1245–1216. doi:10.1080/09537287.2019.1702226.

Ullrich, Günter. 2015. *Automated Guided Vehicle Systems*. Heidelberg: Springer.

van de Klundert, Joris, Philippe Muls, and Maarten Schadd. 2008. "Optimizing Sterilization Logistics in Hospitals." *Health Care Management Science* 11 (1): 23–33. doi:10.1007/s10729-007-9037-4.

Venkatraman, Nenkat. 1989. "The Concept of Fit in Strategy Research: Toward Verbal and Statistical Correspondence." *Academy of Management Review* 14 (3): 423–444. doi:10.5465/amr.1989.4279078.

Villarreal, Bernardo, Jose Arturo Garza-Reyes, Edgar Granda-Gutiérrez, Vikas Kumar, and Samantha Lankenau-Delgado. 2018. "A Lean Transportation Approach for Improving Emergency Medical Operations." *Production Planning & Control* 29 (11): 928–942. doi:10.1080/09537287.2018.1494343.

Volland, Jonas, Andreas Fügener, Jan Schoenfelder, and Jens O. Brunner. 2017. "Material Logistics in Hospitals: A Literature Review." *Omega* 69: 82–101. doi:10.1016/j.omega.2016.08.004.

Voss, C. 2010. *Case Research in Operations Management. Researching Operations Management*. London: Routledge.

Wubben, I., Jeanette Gabrielle van Manen, B. J. Van den Akker, S. R. Vaartjes, and Willem H. van Harten. 2010. "Equipment-Related Incidents in the Operating Room: An Analysis of Occurrence, Underlying Causes and Consequences for the Clinical Process." *Quality and Safety in Health Care* 19 (6): e64–e64.

Yin, Robert K. 2017. *Case Study Research and Applications: Design and Methods*. Beverly Hills, CA: Sage Publications.

Zajac, Edward J., Matthew S. Kraatz, and Rudi K. F. Bresser. 2000. "Modeling the Dynamics of Strategic Fit: A Normative Approach to Strategic Change." *Strategic Management Journal* 21 (4): 429–453. doi:10.1002/(SICI)1097-0266(200004)21:4<429::AID-SMJ81>3.0.CO;2-#.

Zott, Christoph. 2003. "Dynamic Capabilities and the Emergence of Intraindustry Differential Firm Performance: Insights from a Simulation Study." *Strategic Management Journal* 24 (2): 97–125. doi:10.1002/smj.288.

Appendix A

Semistructured interview guide:

A. Background
- Please introduce yourself (position and responsibilities, career background and years of employment)

B. **General and environmental information about the hospital**
- When was the hospital built, and what main changes have been made until now?
- What kind of hospital is it, and what does it specialise in?
- How many beds does the hospital have?
- How are the departments distributed in the hospital?

C. **Sterile processing**
- Where is the sterile processing department located?
- How are the resources for washing, inspection, packaging and sterilisation planned?
- What are the minimum, maximum and average process times for washing, inspection, packaging and sterilisation?
- How are the carts and material handling equipment washed and checked?

D. **Inventory**
- Is the storage centralised or decentralised?
- Where is the storage area located?
- Describe the inventory control and refill process.
- Describe the process from receiving an order until sending the cart.

E. **Material handling and transportation**
- What type of material handling system and equipment is used in the hospital?
- When was the material handling system implemented?
- How many pickups and delivery points are there in the hospital? How are they distributed?
- Explain the pickup and delivery process.
- Who is responsible for the loading and unloading activities? How are the employees informed when the carts arrive at the department?
- How is the communication carried out between the material handling system and employees, doors, elevators, etc.?
- How is the human interaction with the material handling equipment? How is the collaboration and acceptance between employees and the automated material handling system?
- Are elevator bottlenecks in the hospital?
- What problems or disturbances have occurred regarding the material handling system and transportation of sterile instruments?
- Describe the maintenance of the material handling equipment.
- What is the infection control process of the material handling equipment? How do you clean the material handling equipment?

F. **Point of use**
- Describe the ordering process of sterile instruments.
- How many people are involved from the pickup and delivery points at the department level to the point of use?
- Who is responsible for picking up the carts at the department level, preparing the return of soiled instruments and sending carts back?
- How are the sterile instruments received and checked for completeness or right of order?