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Abstract. Until recently, architects planned the layout for a new hospital based only on design aspects, experience, and legal regulations. Today, hospital logistics planners are included at an earlier stage in the project and support hospital layout planning with important logistics aspects. While methods supporting patient flow are prioritized in the layout planning, methods focusing on material flow are lacking. Therefore, this study is part of a project that aims to develop a decision support model for hospital layout planning that includes material flow. We develop a semi-open queuing network model of a hospital with multiple floors and compare it with agent-based simulation modeling. Simulation results show that a semi-open queuing network is a promising approach to support hospital planners in the decision-making process of hospital layout planning that includes planning material flow performed by autonomous mobile robots.

Keywords: Autonomous mobile robots, semi-open queuing network, hospital intralogistics, hospital layout.

1 Introduction

Until recently, architects planned the layout for a new hospital based only on design aspects, experience, and legal regulations [1]. Today, hospital logistics planners are included at an earlier stage in the project and support the hospital layout planning with important logistics aspects. Layout planning for hospitals differs from that in industry. While in industry, analyzing the material flow is the primary input to determine the layout, in hospitals, the flows of persons, including patients, family, and staff, are prioritized [2]. Unsurprisingly, the material flow aspect has received little attention in hospital layout planning, and methods supporting it are lacking [3].

However, material flow plays a crucial role in the daily operation of a hospital. Activities connected to material flow consume, on average, 25–30% of a hospital's budget [4]. One of these is material handling activities, which are still mainly performed manually, especially inside the departments, which represent excellent opportunities for automation [5].

Recent advances in technology have increased flexibility in indoor mobility and human-robot collaboration, opening new opportunities to perform material handling activities, particularly in narrow, dynamic environments. Sensing devices, powerful onboard computers, artificial intelligence, and collaborative equipment allow autonomous mobile robots (AMRs) to navigate freely within a predefined area and provide material handling services [6]. AMRs can be increasingly applied in the material flow activities within departments. In contrast, automated guided vehicles cannot enter departments and deliver only in front of them. These capabilities allow deliveries to the point-of-use, the patient, and so cover a wide service area. For many years, mobile robots were a virtually unimaginable and practically unacceptable solution in healthcare support, as people did not associate hospitals with a production environment. The increased acceptance of AMRs allows their integration into departments and wards [7,8].

The integration of AMRs as transporting, collaborating, or assisting robots can reduce humans' involvement and responsibilities in material handling activities. Including material flow and material handling activities to a stronger degree in layout planning may reduce costs. Small changes such as reducing the distance between departments with frequent material transportation or increasing elevator capacity have a strong impact on material handling performance. In a hospital layout's decision-making processes, hospital planners need to consider material flow and material handling activities.

This study is part of a project that aims to develop a decision support model for hospital layout planning, including material flow and material handling activities. Semi-open queuing network (SOQN) modeling is a promising solution for analyzing hospital layout design configurations while planning material flow performed by AMRs to achieve high performance. The present study investigates the applicability and suitability of this modeling approach and provides a basis for developing an analytical model at the next stage. To achieve this, we develop a SOQN model and compare it with agent-based simulation (ABS) modeling. Analyzing different scenarios helps identify the suitability and applicability of SOQN modeling in hospital layout planning, including material flow and material handling activities.

The rest of the paper is organized as follows. Section 2 reviews the literature on hospital layout planning, material flow and AMRs in hospitals, and SOQN modeling approaches. Section 3 provides a system description, and Section 4 introduces the modeling approach and assumptions. In Section 5, we present the results of simulations. Section 6 discusses insights related to design aspects. We conclude the study with recommendations for future research.

2　Literature review

Hospital layout planning is conducted according to a multi-level approach in which hospital layout planning problems are often differentiated into macro- and micro-levels [1]. While the macro level focuses on the arrangement of the different departments within a hospital, the micro-level focuses on organizing the rooms and

corridors within the different departments, such as the operating theater, wards, and emergency department. The approaches of quadratic assignment problems, mixed-integer programming, and discrete-event simulation have mainly been used to support the decision-making process [1]. Although quadratic assignment problems are more common in facility location planning, it has been frequently applied to support planning and optimize hospital layouts [3].

Patient flow and patient transportation are major issues in hospital planning and are often approached at the macro level. Several studies have investigated patient transportation in hospital layout planning with the objective of reducing distances to save time and resources [9-11]. However, the topic of material flow and material transportation in hospital layout planning is still lacking [3].

Material flow in hospitals focuses on providing materials to departments and medical services at the right time and quantity, facilitating patient care. Most studies have focused on procurement and inventory management, and only a few have investigated modeling and optimizing approaches for material handling activities such as material transportation in hospitals [12]. Those that have been done have mainly focused on flows of sterile instruments, food, linen, medical supplies, beds, and pharmaceuticals. Analytical models combined with mixed-integer linear programming and simulation modeling are the preferred methodologies for providing the necessary decision support to optimize work routes, workloads, and costs.

To transport materials, various manual, semi-automated, and automated material handling equipment and systems are currently used in hospitals. Many small and short deliveries of medical equipment, medicine, etc., are performed manually by nurses, physicians, porters, etc. Therefore, manual transportation is widely applied throughout the hospital, especially inside departments close to the patient [5]. The few automated material handling systems in departments, such as pneumatic tube systems, are stationary and allow low flexibility. Automated guided vehicles cannot enter departments because of their size. However, they can transport high-volume materials to many pickup and delivery locations and travel long distances within hospitals. To plan and control material handling systems, hospital planners rely mainly on discrete-event and ABS, with the main objectives of minimizing transportation time, total throughput time, and costs. These methods help to determine vehicle size, the number of vehicles, transportation schedule [13-15]. Further, simulating different scenarios such as increasing demand helps in analyzing the system's behavior and develop countermeasures to face the current challenges in hospitals [13, 16]. However, few methods are available to provide decision-making support for material transportation performed by AMRs.

Based on a recent literature review, SOQN has been identified as the most promising method to support the decision-making process for planning and controlling AMRs in hospital logistics [6]. SOQN modeling has been applied to manufacturing [17, 18], warehousing [19-22], container terminals [23, 24], and other logistics environments [24] to improve waiting and throughput time. To the best of our knowledge, the existing literature lacks modeling and proposed solutions to support hospital planners in the hospital layout planning, including material flow and material activities such as determining AMR fleet size to achieve high performance.

3　Method

To analyze the applicability and suitability of SOQN modeling for hospital layout and material flow, this study follows a three-step approach.

First, the hospital layout and AMR transportation are modeled as SOQN. SOQN modeling combines the advantages of open queuing networks (external queues to accommodate jobs whose entrances are delayed) and closed queuing networks (inner networks with a population constraint). Using a synchronization station, incoming customers waiting in an external queue can be paired with available resources in the resource queue. This modeling approach can capture external wait times and precisely estimate throughput times. [25].

Second, to evaluate the SOQN model, an ABS model is developed to serve as a benchmark. ABS has recently received more interest among practitioners because it can model stochastic processes. At its core, ABS is built by autonomous resource units that follow a series of predefined rules to achieve their objectives while interacting with each other and their environment [26]. These attributes are especially salient for modeling AMRs in hospitals.

Finally, different scenarios are simulated with SOQN and ABS models to compare them and analyze the applicability and suitability of SOQN modeling for hospital layout and material flow.

4　System Description

In high-density areas, such as big cities, where area costs are high, hospital layouts can be characterized as tall and compact. The hospital layout includes few buildings with many floors and elevators. Each floor consists of several departments. At the department level, the layout is often divided into single or double corridors with treatment, operating, office, or patient rooms at each side [27].

Material flow and material handling activities are performed by AMRs, which can access the entire hospital. Communicating with the hospital infrastructure equipment, such as doors or elevators, AMRs can move to different floors and enter rooms, thereby performing the material handling activities of material transportation, which include the following steps between hospital staff and AMRs:

1. *Ordering:* A hospital staff communicates information about the job (material, pickup, and delivery points) to the AMRs.
2. *Synchronization:* The job is communicated to the AMRs, and idle AMRs receive the job after negotiating with other AMRs.
3. *Pickup:* The AMR navigates autonomously through the hospital layout to the pickup point and loads the material.
4. *Delivery:* The AMR navigates autonomously through the hospital layout to the delivery point and unloads the material. When the material arrives at its final destination, the AMR sends an arrival message to the department. A staff member receives the materials, and the AMR returns to idle.

5 Modeling Approach and Assumptions

For this study, we assume that the hospital layout is rectangular, including one building with six floors, four elevators, and 42 rooms with pickup and delivery points. The AMR can move autonomously within one floor and can enter rooms. The dwell and so the parking position of the AMR is on the first floor.

Based on the system description and assumptions, a closed queuing network (CQN) model of the hospital floor (Fig. 1) and SOQN model of a hospital with multiple floors were developed (Fig. 2).
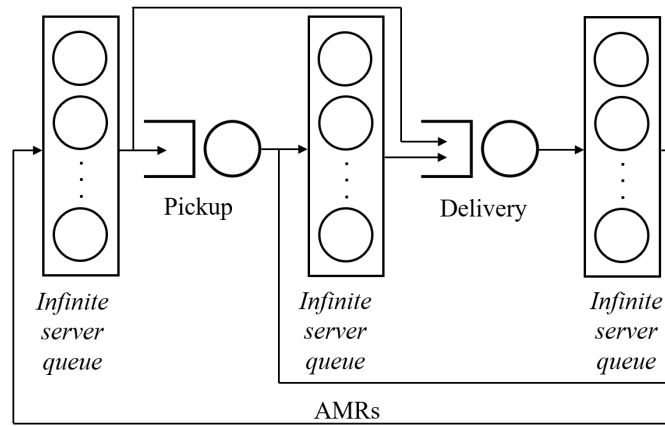

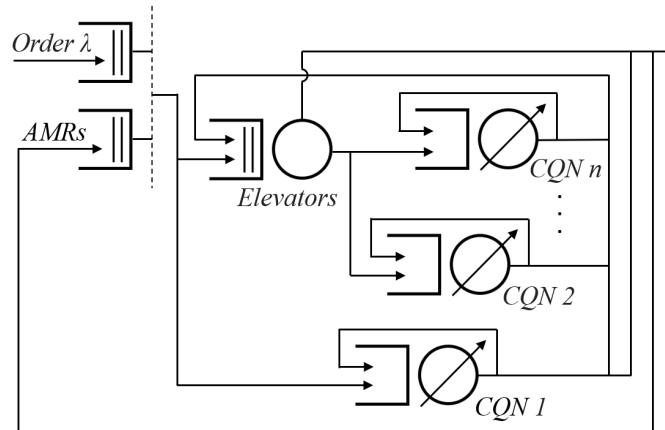**Fig. 1.** CQN model of the hospital floor

Fig. 2. SOQN model of a hospital with multiple floors

While the CQN model represents the processes within one floor, the SOQN model synchronizes the orders in the open queue with the AMRs in the closed queue. Pickup and delivery can be either on the same or at a different floor and so be grouped to several main transportation routes: a) both pickup and delivery on the first floor, b) pickup on the first floor and delivery on a different floor, c) pickup not on the first floor and delivery on the same floor, d) pickup not on the first floor and delivery on a different floor. The elevators connect the different CQN models of the hospital floor and allow to move AMRs from floor to floor to fulfill the orders. There are multiple types of orders: pickup within one CQN, delivery within one CQN, both pickup and delivery within one CQN, and pickup from one CQN and delivery in another CQN. These transaction types distinguish especially from previous studies.

To identify the mean throughput time and waiting time, we calculate the mean process times for pickup and delivery. Next, we identify the processing time for the CQN model with simulation. Varying the remaining process times in the SOQN model and conducting simulations allows identifying the transportation performance (Tab. 1). Seven different scenarios are developed to analyze AMR fleet size (scenarios 1, 2, and 3), the elevator response time (scenarios 1, 4, and 5), and delivery routes (scenarios 1, 6, and 7) on the transportation performance.

Table 1. Investigated scenarios

Notation	1	2	3	4	5	6	7
$L_{in\,m}$	**100**	100	100	100	100	100	100
$W_{in\,m}$	**100**	100	100	100	100	100	100
AMR	**4**	5	6	4	4	4	4
Elevator	**4**	4	4	4	4	4	4
$\lambda_{per\,min}$*	**1, 3.6**	1, 3.6	1, 3.6	1, 3.6	1, 3.6	1, 3.6	1, 3.6
$\mu_{Pickup\,in\,min}$*	**2,1, 3.6**	2,1, 3.6	2,1, 3.6	2,1, 3.6	2,1, 3.6	2,1, 3.6	2,1, 3.6
$\mu_{Delivery\,in\,min}$*	**2,1, 3.6**	2,1, 3.6	2,1, 3.6	2,1, 3.6	2,1, 3.6	2,1, 3.6	2,1, 3.6
$\mu_{CQN\,in\,min}$*	**2,22, 3.6**	2,22, 3.6	2,22, 3.6	2,22, 3.6	2,22, 3.6	2,22, 3.6	2,22, 3.6
$\mu_{Elevator\,in\,sec}$*	**35, 3.6**	35, 3.6	35, 3.6	**30, 3.6**	**40, 3.6**	35, 3.6	35, 3.6
a	**0,25**	0,25	0,25	0,25	0,25	**0,5**	0,25
b	**0,25**	0,25	0,25	0,25	0,25	**0,125**	**0,125**
c	**0,25**	0,25	0,25	0,25	0,25	**0,125**	**0,125**
d	**0,25**	0,25	0,25	0,25	0,25	**0,25**	**0,5**

* Weilbull = α is the scale parameter, β is the shape parameter

We developed an ABS model for comparison with the SOQN model (Fig. 3). The ABS modelling approach follows the recommendations from a previous study on mobile robots in hospital intralogistics [16]. For the ABS, the AMR must be further specified. The AMR speed is 1 m/s, and it can move autonomously in 'free space,' which is framed by the walls. It chooses the shortest path to move between points and maintains a safe distance of 30 cm from all obstacles. The AMR size is 100 cm in length and 60 cm in width. The elevators can only transport one AMR at a time.
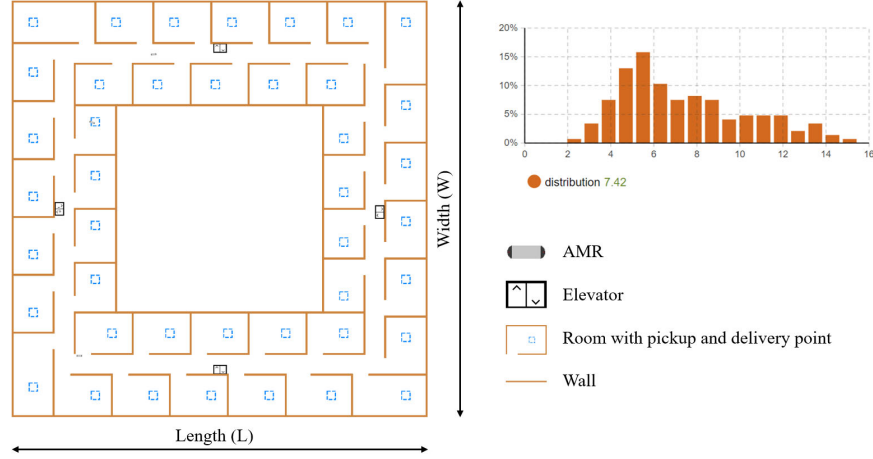
Fig. 3. Top view of ABS model for material transportation performed by AMRs in hospitals

6 Results

The simulation software Anylogic was used to simulate the SOQN and ABS models with the different scenarios (Table 2). Each scenario was conducted several times, with at least 10,000 transportation trips representing ca. 14,000 min in the simulation. On a PC with Processor Intel core i9-8950HK CPU@2.90GHz and 32GB installed memory RAM, the SOQN models lasted 5 s, while the ABS models took 4.75 min.

Table 2. Simulation results of the different scenarios after 10,000 transportation trips

Model	Performance	1	2	3	4	5	6	7
SOQN	Mean throughput time in min	9.88	5.73	5.19	8.68	12.17	7.5	12.43
	Mean waiting time in min	4.03	0.44	0.11	3.04	6.09	2.09	6.33
ABS	Mean throughput time in min	9.43	5.45	4.89	8.34	10.7	8.62	11.28
	Mean waiting time in min	4.95	1.09	0.57	3.97	6.11	4.17	6.75

7 Discussion and Conclusion

The SOQN and ABS models provide very close results for analyzing the AMR fleet (scenario 1,2, and 3), while the remaining results (scenario 4, 5, 6, and 7) provide similar tendencies. Thus, either model can support hospital planners in decision-making for hospital layouts, including material flow and material handling activities. Depending on the required transportation performance, hospital planners have different alternatives to satisfy the requirements. They can either adapt the AMR fleet size (scenarios 1, 2, and 3), the elevator response time (scenarios 1, 4, and 5), or

delivery routes (scenarios 1, 6, and 7). Increasing fleet size can help provide a robust transportation system but affects traffic and costs. The elevators play a crucial role in transportation between different floors. A few seconds' difference in response time has a significant effect. This can be observed in the ABS model and simulation since the elevator can only transport one AMR at a time. Waiting time can quickly increase for the next one to use it. Analyzing different transportation routes helps hospital planners to decide where to allocate departments in a hospital. Thereby, it can support finding the optimal mix of delivery routes for a hospital. Allocating departments with frequent transportation on the same floor can significantly reduce transportation time.

A significant difference can be observed between the time used to model and simulate a scenario. SOQN modeling and simulation can provide quick results, which is especially useful at an early stage of a project. It allows to investigate many different layouts in a short time and so decide which is the most appropriate for material transportation.

SOQN modeling has been demonstrated to be applicable and suitable for hospital layout and material flow, enabling hospital planners to support the decision-making process to achieve high performance. Future research should focus on extending the model to connect different buildings and investigate different hospital layouts. Further, analytical approaches to solve SOQN models should be investigated and the statistical analysis should be extended to make a solid conclusion.

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