A Simulation Study For Integrating Library Material Handling with Autonomous Mobile Robots

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Abstract. Libraries have served customer, so-called patrons, as a cultural and educational arena for many decades. Although there is a trace of attempts for incorporating advantageous technologies into the library environment, efficient operation of the library is still an underinvestigated topic which deserves scholarly efforts in the realm of material handling. Thus, this study seeks to contribute to the improvement of the library material handling by taking advantage of mobile robot solutions. A case study at the Trondheim Public Library of Norway is primary employed in order to capture the material flow of books within a library and to study the challenges of material handling in this context. The literature review assists in exploring the recent technologies that have contributed to the material handling. In pursuit of improving the moving processes, a simulation analysis is then considered to examine the utilization of autonomous mobile robot (AMR) under two layout configurations: centralized and decentralized. The simulation analysis is accomplished under the influence of two automation strategy, consisting semi-automated and fully-automated. Given the impact of two layout configurations, four scenarios were examined throughout the simulation, and the results demonstrate that an exhaustive technological upgrade of the material handling in the library does not necessarily yield the optimal performance. In this regard, the semi-automated approach in conjunction with the decentralized layout configuration demonstrated the highest performance with respect to two key performance indicators (KPIs), namely time in the machine and time for moving/emptying the bins.

Keywords: Library · Library Operations· Material Handling · Autonomous Mobile Robots· Simulation

1 Introduction

Library is a social entity that contributes to an array of public and intellectual services [1]. Although libraries have functioned as an axle of knowledge preservation, they have evolved into vibrant cultural centers providing an array of services, such as event organization. This forms the basis for acknowledging library as a service-oriented organization whose performance is determined by operations tied to the experience of library customers or visitors, known as patrons. In the same vein, previous studies, corroborate that library operations follow the 'input-transformation-output' model to ensure patron's satisfaction as the primary goal [2]. Experience with other service-oriented organizations demonstrates an improved patron's experience through integrating the fundamental operations with the digital technologies [3]. In fact, such digital transition within entities has contributed to better resource management, which in turn, has demonstrated positive impacts on the operational efficiency.

Following the fourth industrial revolution, service-oriented organizations have progressed to provide digital services [4]. Libraries are no exception in this realm, and digital technologies have enabled more personalized services and increased patrons' engagement in the library environment. Internet of Things (IoT) and Artificial Intelligence (AI) are only a few of the revolutionary technologies in this landscape [5]. The most common IoT-based approach established in the library environment refers to Radio Frequency Identification (RFID), whose adoption was evoked by improving operational efficiency [6–8], and ultimately, enhancing the patron's experience. Its deployment enabled an elevated degree of accuracy and agility associated with inventory management and book retrieval [9, 10], as well as better surveillance and control of the available items [11, 12]. The recent AI-based solutions have positively influenced demand forecasting by understanding the patrons' tastes, habits, and preferences. Deep learning [13], and collaborative filtering [14], just to name a few, are some of the main solutions used to establish personalized recommender systems. Solutions of this sort have been further extended by facial recognition [15, 16] and QR code [17] to augment the convenience and efficiency, allowing patrons to engage with services more independently. In corollary, previous efforts demonstrate that digital transition in the library positively contributes to resource management and patron interaction.

The empirical assessments of libraries indicate that material handling processes, i.e., sorting, controlling, moving, and storing, constitute the highest proportion of operational challenges [2]. These processes ensure the availability of items for patrons to meet the primary objective of libraries: patrons' satisfaction. Although some aspects of the library operations have taken advantage of digital technologies, less scholarly efforts have been put into material handling processes which are central in the library operations [2]. Hence, more research effort is required to enable libraries to address the major challenges attributed to the material handling processes, such as labor-intensive and manual processes. Needless to note these challenges become even more sophisticated given the incremental flow of books and the absence of automated material handling in the library. To that essence, librarians need to ensure the efficient execution of material handling processes by lifting the focus onto the manual processes which determine the patrons' satisfaction. Given the promising opportunities provided by the digital transition agenda, this study puts forward the idea of investigating the utilization of mobile robot solutions to improve material handling in the library. In this regard, the following research questions are developed:

1. What challenges influence the performance of material handling in the library?
2. How can mobile robot solutions contribute to addressing the challenges of material handling in the library?

The first research question is approached by conducting a case study in the Trondheim Public Library, Norway, where the empirical assessments are directed to explore the status quo and challenges of material handling in the library, denoted as the 'AS-IS' scenario. According to the concern of automating material handling raised by the second research question, we study the use of autonomous mobile robots under the influence of two layout configurations and two forms of automation, constituting four distinct scenarios.

2 Research Methods

2.1 Case Study

In this research, a case study was conducted at Trondheim Public Library (TPL), Norway, and the core aim was to investigate the main operational challenges corresponding to material handling in the library. The underlying rationale for choosing TPL is primarily justified by the fact that it is situated in one of Norway's largest cities, and as claimed by the librarians, TPL has been encountering challenges that are attributed to the material handling processes. In this context, the initial objective is to capture the material flow within TPL and classify the accomplished tasks with respect to the material handling processes. Furthermore, a meticulous assessment of the means and forms of conducting the material handling processes was performed to illustrate the factors that limit the performance of material handling. This evaluation procedure, combined with group meetings between librarians and authors, led to discovering that the moving process constitutes the majority of material handling challenges compared to the other processes of material handling, i.e., sorting, controlling, and storing, which mainly emanates from lack of automation. As observed, manual moving not only reduces the efficiency of librarians, but also influences the accomplishment of other material handling processes. Thus, according to the insights gained from the on-site observations, we direct this research toward benchmarking the utilization of digital technologies in favor of better performing the moving process. The case study is further elaborated in Section 4.

2.2 Literature Review

To ensure a rigorous literature review the explicitness and reproducibility of the literature search are of importance [18]. To that end, the initial decision is made upon selecting a reliable database, for which we opt for using the Scopus online database to collect research papers surrounding the recent technological advancement in material handling. This is followed by narrowing down the list according to the compliance of the technologies with the library application. The search procedure commences with searching the relevant documents using the following combination of keywords: “Material Handling” AND logistics AND Technology. It is noteworthy that the ‘AND’ operator is used to combine distinct topics and the double quotations ("") is used for exact search associated with the phrases. The initial search, conducted in December 2023, yielded 431 documents. This initial list is narrowed down using relevant filters provided by Scopus as follows: (a) the language is set to English to focus on the international context, (b) the publication period is adjusted to 2009-2023 given the incremental agenda of using technologies in the material handling studies in this period, (c) the subject area is selected as ‘engineering’ to disregard papers with weak thematic correlation to the topic, (d) the document type is set to journal and proceeding papers to ensure the high quality and a broad range of articles, (e) the keywords suggested by Scopus is refined to ("Robotics", "Robots”, “Mobile Robots", "Fleet Operations", "Drones", "Conveyors”, "Autonomous Robots", "Autonomous Vehicle”, “Autonomous Vehicles", "Autonomous Operations", "Automatic Guided Vehicles", "Automated Guided Vehicles") to ensure accessing the research works that have a major focus on technologies tied to the moving process. Applying the corresponding filters reduced the list of papers to 28. The process continues with an appraisal process where the aim is to eliminate the papers whose content is unable to provide knowledge surrounding the moving process. This begins with scanning the title, abstracts, and keywords, followed by reading the full content of the papers that were accepted in the preceding round. Not to mention that we excluded papers with limited access which were not possible to retrieve. The quality appraisal procedure reduced the number of papers to nine. This list was ultimately extended to 14, given the fact that five papers were identified as relevant during the review process. Ultimately, the analysis procedure seeks to explore and study the application of material handling technologies contributing to the moving process and the results are presented in Section 3.

2.3 Simulation

The simulation approach in this study assists in analyzing the impacts of using AMR–concluded as a promising solution through the literature review–in contribution to the moving process in the library material handling. The simulation primarily seeks to identify the optimal configuration for using AMR in the environment of TPL. This implies that both layout properties and technological possibilities are essential to be considered. To that end, four scenarios are generated based on two layout configurations and two forms of automation. In this regard, we put forward to perform a discrete event simulation (DES) which is a suitable technique for analyzing complex and dynamic environments [19, 20]. Throughout the simulation experiment, we seek to demonstrate the driving factors of the moving process, such as the arrival of materials to be handled and their movement to the different buffers/temporary shelves. To that essence, DES enabled accurate and detailed representation of significant events in the material flow, facilitating the evaluation of the library material handling performance. To realize the described targets we use the AnyLogic software which is a powerful simulation package for analyzing varied discrete and continuous systems. Further details about the simulation and scenarios are presented in Section 5, and the results are discussed in Section 6.

3 Automated Moving in Library Material Handling

The term material handling (MH) refers to the movement, protection, storage, and control of materials which collectively aim to satisfy the fundamental factors: using proper means of transportation, deciding the respective order and quantity of materials, correct selection of the transportation nodes [21]. Equivalently, material handling seeks to ensure the availability of items as the core library operation through four processes to satisfy the patrons [2]: sorting, which is accountable for identifying the routes for transporting the books; controlling, which functions as an element of surveillance and inventory management; moving, which fundamentally refers to the act of transporting books between two locations; and storing, which serves the concerns of either short-term and long-term inventory of the books. In this regard, field observations conducted by authors corroborate that the majority of operational challenges are linked to the moving process.

Material flow within a library is resource intensive–requiring both human and specialized equipment–and influences the service provision and the operational costs. Librarians spend numerous hours to ensure smooth material flow, causing interruptions in allocating their time to provide services to patrons. This primarily stems from the moving process being conducted manually; for instance, librarians dedicate a considerable portion of their working hours to moving books between different locations.

Observations revealed that librarians spend 30% of their available time on handling the materials rather than serving patrons. This not only leads to ergonomic issues, but also adversely impacts library services. In practice, the manual moving process disrupts the librarians' agenda and equivalently reduces the service quality.

Despite the advantages of digital transition in the library environment discussed in Section 1, there has been limited scholarly effort on improving material handling processes to enhance the patron's experience. This research gap is significant given the fact that the manual moving process not only disrupts librarians' schedules, but also hampers the overall service quality provided to patrons. While technological advancements have transformed material handling processes in other service-oriented organizations such as hospitals [22] and airports [23], there is a remarkable potential to explore the integration of these solutions with the library settings. This agenda aligns with the recent technological developments that have facilitated the transformation of the material handling processes from manual to automated form [24]. Thus, according to the key role of the moving process in the library material handling, we present the results of the literature review–described in Section 2.2–to explore the latest technological improvements in connection with this process.

Automated guided vehicles (AGVs) have recently emerged as a critical element in the context of smart factories, offering high flexibility to adapt to changing business needs [25]. Their deployment not only reduces the transportation time and cost [26], but also allows workers to concentrate on other critical tasks [27]. Technological advancements of this sort are beyond AGVs, encompassing self-driving forklifts [28] and short-range logistics drones [29] which have shown advantages in enhancing material handling efficiency by reducing labor intensity. Intelligent transportation solutions such as cloth-roll handling robots [30], vertical robotic storage, and order picking systems [31] further contribute to efficient and safe material handling. Amongst the outlined developed technologies–which are not conclusive–autonomous mobile robots (AMRs) stand out for increased intelligence level and efficiency [32, 33]. Their introduction offered a more flexible solution, leading to efficient transportation processes, ergonomic workspaces, and increased production capacity [34]. AMRs utilize decentralized decision-making procedures for collision-free navigation and provide a platform for collaborative activities, and comprehensive services within a bounded area [32]. Using data from cameras and sensors, AMRs can detect obstacles and modify paths in real-time to ensure safe operations and create a safer working environment compared to AGVs [35]. Recently, AI and simultaneous localization and mapping (SLAM) technology have enabled AMRs to navigate flexible routes based on real-time environmental conditions. It is worthwhile to mention that a variant array of organizations have taken advantage of AMRs, including but not limited to, Amazon, DHL, and hospitals, in terms of cost, time, and improved resource allocation [22]. According to the latest developments discussed in the literature, AMR is perceived as a promising digital solution for improving the moving process pertaining to the library material handling by providing extensive adaptability features and real-time data exchange possibilities which are suitable for the library environment.

While this technological solution has been successfully deployed in various sectors in pursuit of enhancing material handling, its application in library environments remains unexplored. Hence, this study contributes to addressing this literature gap by investigating how AMRs can be integrated into the library environment to resolve the challenges of the manual moving process, thus, enhancing the overall library service performance.

4 Case Description

Trondheim Public Library (TPL) is one of the Norway's largest libraries, owned and operated by the Trondheim municipality. TPL–it is the headquarter and connected to nine branches–is composed of six floors, one storage area in the basement, one sorting area on the first floor, and one service elevator which is used for the moving process. Patrons have access to three floors: the first floor is designated for children, youth, and manga; the second and the third floors are commonly designated for adults. In this branch, in addition to lending diverse materials, patrons benefit from a variety of services, such as language café, assistance with basic computer needs, printing and scanning documents, and so forth. TPL organizes about 1,500 different events per annum, including workshops, meetings with authors, and lectures. TPL provides books to out-of-town libraries, schools, and the local prison. The collection of 430,000 books and media–growing 12,000 to 30,000 annually–reflects the TPL's commitment to diverse reading interests and intellectual inquiries. Given the benefits of digitalization, TPL has put effort into getting accustomed to evolving demands. Online reservations and self-service machines are a few examples in this context. Although these advancements have favored better service provisions, TPL is subjected to serve 600,000 items, both digitally and physically, per annum. This progressive challenge causes the librarians to spend a significant percentage of their working hours on the manual moving process, leading to fatigue, ergonomic, and operational challenges. The moving process is essential to ensuring the availability of the book in the right place at the right time. Meetings and discussions with librarians revealed that librarians spend more than three hours per day on manual material movement out of their daily agenda. This affirms that manual moving constitutes the highest proportion of challenges in TPL, emanating from the shortage of automated solutions; as opposed to other processes such as using the sorting machine to perform the sorting and controlling processes.

Trondheim Public Library Status Quo: AS-IS Scenario

The on-site observations provided an overview of the material handling processes in the TPL, and in particular, assisted in highlighting the key challenges associated with the moving process. Material flow in TPL begins with automated sorting and controlling processes. Firstly, and using a conveyor belt, the books flow to the sorting machine where they are controlled, sorted, and collected into the bins. The sorting machine reads the RFID/Barcode tag on the book's cover and sends the books into one of the 25 defined bins.

When a bin reaches its maximum capacity, librarians are notified by the light signals to move the full bin to its respective floor, next to the temporary shelf. Temporary shelves act as a buffer, which stores the books before they are moved and stored on their designated shelves. In practice, temporary shelves display the most requested and trending topics, which are of the patron's interest. Two temporary shelves exist on the first floor; one is dedicated to Children's, Manga, and Youth books, and the other is dedicated to reserved items. The second floor entails one temporary dedicated to the Adult collection, as well as a temporary table for CDs and DVDs. The third floor includes only one temporary shelf. It is worthwhile to outline that the aggregation of bins to be loaded and transported between floors per day is accounted for 55.

Once the items are placed on the temporary shelves, they will be stored on their respective shelves by seizing an available librarian. The empty bins are then moved to the buffer area next to the sorting machine. Although the material handling processes are partially automated, thanks to the utilization of a sorting machine, two processes are yet performed manually: moving and storing. Observations in this regard reveal that the moving process involves a notable proportion of repetitive and non-value-adding tasks which justifies the demand for further improvements.

5 Simulation Modeling

5.1 Assumptions and Scenarios

The literature review shed light on the importance of AMR as a promising solution to improve the material handling processes across a variety of organizations. Given the significant contribution of the moving process to material handling, particularly in the library environment, the simulation modeling seeks to investigate the application of AMR in TPL under the influence of four scenarios, represented in Table 2. The developed scenarios are fundamentally based on two layout configurations, represented in Figure 1:

a centralized layout featuring temporary shelves with 10 delivery points, and a decentralized layout with distributed buffers with 20 delivery points. It is worth noting that the third floor has only one delivery point which is consistent in both layout configurations, and thus, it is not illustrated in Figure 1. Moreover, the AMR commutes between the library floors using a specific elevator which is not used by patrons. To better overview the assumptions and metrics for simulation, Table 1 depicts the primary inputs.

Table 1. Simulation assumptions and inputs.

Parameter Explanation	Value
Number of Bins to Be Unloaded [per day]	55
Number of AMRs	1
Delivery Points	Centralized = 10; Decentralized = 20
Floor Height	3 meters
Elevator Speed	0.5 m/s
AMR Speed	0.8 m/s
Load/Unload Speed	20 seconds
Simulation Period	9:00 – 18:00 (9 hours)

Given the importance of temporary shelves as a means of displaying trending books, the first layout configuration seeks to examine an increased quantity of temporary shelves where the aim is to reduce the total distance between temporary shelves and the shelves belonging to the books. The second layout configuration, however, disregards the entire temporary shelves and investigates considering a buffer spot next to the books shelves. In this case, the books are moved to the buffer spots next to their respective shelves and they are further transferred to their respective spot on the shelf by the librarians. These layout configurations are examined under the influence of two forms of automation, namely fully-automated and semi-automated. In a fully-automated scenario, AMR is accountable for the entire moving processes throughout the library, including the movement of full and empty bins, seeking to increase the availability of librarians for other service provisions. In the semi-automated vis-a-vis, the AMR is in charge of moving the full bins, and the empty bins are supposed to be moved by the librarians to increase the availability of AMR for moving the full bins.

Table 2. TO-BE Scenarios.

	Centralized Layout	Decentralized Layout
Fully-automated	Scenario 1	Scenario 2
Semi-automated	Scenario 3	Scenario 4

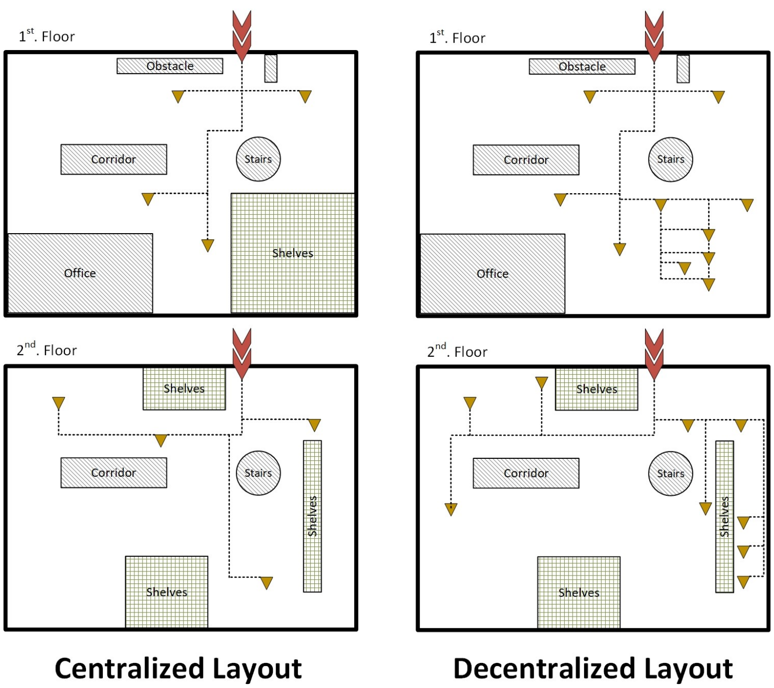

Fig. 1. Layout configurations.

5.2 Fleet Sizing

Prior to conducting the simulation modeling, we put forward performing an analytical assessment to estimate the fleet size for each scenario in accordance with the steady-state conditions. This assessment is undermined by the parameters represented in Table 3. The fleet size (Equation 1) is evaluated by dividing the total required travel time during the opening hours by the total available time for each AMR.

Table 3. Statistics for Fleet Sizing

Variable	Explanation	Evaluation
i	Pickup buffer	Buffer in macro/micro areas
j	Drop-off buffer	Buffer in macro/micro areas
N_{ij}	Matrix of loaded trips	Average unload/day of each bin
d_{ij}	Matrix of distance between i and j	From 3D model of the library
v	AMR's average speed	0,8 [m/s]
T^L	Loading time in i	18.6 [s]
T^U	Unloading time in j	18.6 [s]
T_{ij}^T	Travel time from i to j	d_{ij}/v
T_{ij}^L	Matrix of loaded travel time	$T^L + T^U + T_{ij}^T$
A	Availability of the robot	80%
T_{AMR}	Working hour/day	9 hours
$NF(i)$	Net flow	$\sum_J N_{ji} - \sum_i N_{ij}$
T_L	Loaded travel time	$\sum_i \sum_J N_{ij} * T_{ij}^L$

Macro areas refer to the centralized layout.
Micro areas refer to the decentralized layout.

$$N_v = \frac{T_{TU} + T_{TL}}{T_{AMR} * A} \tag{1}$$

The Travel Time Loaded (T_{TL}) refers to the time that takes the AMR to move the full bin from the pickup buffer to the drop-off buffer. The Travel Time Unloaded (T_{TU}) refers to the time that AMR is moving without any load between the working stations–re-balance the AMR among the workstations. However, the latter depends on the number of empty trips (X_{ij}) between the different temporary shelves/buffers (Equation 2).

$$T_{TU} = \sum_i \sum_J X_{ij} x T_{ij}^T \tag{2}$$

Therefore, X_{ij} is defined as a positive integer variable, where the main objective is to minimize the unloaded travel time (T_U) as represented in Equation 3, under the influence of constraints 4 and 5:

$$\min \sum_i \sum_j X_{ij} \times T_{ij}^T \tag{3}$$

$$\text{Leaving empty trips} \quad \forall i \rightarrow \sum_{J} X_{ij} = \begin{cases} NF(i) & \text{if } NF(i) > 0 \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

$$\text{Arriving empty trips} \quad \forall i \rightarrow \sum_{i} X_{ij} = \begin{cases} |NF(i)| & \text{if } NF(i) < 0 \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

As depicted in Table 4, the results demonstrate that a fully-automated scenario with one AMR efficiently manages the average flow under the assumption of the steady-state condition. Consequently, one robot will also be considered in the semi-automated scenarios.

Table 4. Fleet sizing results for fully automated scenario

Scenario	T_{TL} [sec]	T_{TU} [sec]	A	T_{AMR} [sec]	N_V
1	9270.34	377	0.8	32400	0.44
2	8630.95	41.25	0.8	32400	0.40

Subsequently, a simulation approach is used to evaluate the efficiency of fleet size and its impact on library material handling performance under non-stationary conditions. To that end, the Anylogic simulation package is used to evaluate the flow dynamics in the TPL during the nine-hour opening hours, taking into account the variability of the full bins and the waiting time for the elevator.

5.3 Key Performance Indicators Used for Analysis

The simulation study calls for identifying relevant and measurable key performance indicators (KPIs) to facilitate meaningful and reliable assessment. In this study, 'time to shelf' is an indicator of the time it takes for the books to become available for lending after they arrive in the library. In simple terms, this index is beneficial in evaluating the effectiveness of the moving process given the fact that it reflects 'how quickly the books are moved and placed on the shelves for the use of patrons'. 'Time to shelf' is a function of several factors, including the average time a full bin waits in the sorting machine before being picked up by the robot, the average time it takes to move the full bins to the designated temporary shelf/buffer, and the time it takes to manually empty the bins and store the books on the shelves. In the simulation phase, 'time to shelf' is calculated as the sum of two different rates:

1. Time in the Machine: the average time a full bin waits in the sorting machine before being picked up by the robot.
2. Total Time for Moving and Emptying: the average time it takes to move a full bin from the sorting machine to its respective buffer, plus the time it takes to manually empty the bin and place the books on the temporary or non-temporary shelves.

6 Simulation Results and Discussion

The summary of the simulation results with respect to the introduced KPIs is presented in Table 5. The immediate impression from the simulation indicates that semi-automated scenarios outperform the fully-automated scenarios (see Table 5). It is evident that both semi-automated scenarios demonstrate higher performance in comparison to the fully-automated scenarios in all aspects. This initially implies that a high degree of automation has not yielded any better performance of the moving process. Equivalently, the fully-automated approach in a decentralized layout configuration–Scenario 2–demonstrates the lowest performance with respect to both KPIs. In the same vein, semi-automated solutions contribute to higher performance in terms of both 'time in the machine' and 'time for moving/emptying the bins'. Collectively, the 'time to shelf' for Scenario 3 and Scenario 4 is 1,234 and 770, respectively, and the notable improvement of this element–compared to Scenario 1 and Scenario 2–underscores the superiority of semi-automated over fully-automated scenarios. Furthermore, the analysis of the simulation results signifies that the layout configuration has no dominant contribution to the improvement of moving processes. More precisely, in the fully-automated condition, the centralized layout (Scenario 1) shows higher performance compared to the decentralized layout (Scenario 2), while it is a reverse relationship in the semi-automated condition–decentralized layout (Scenario 4) shows higher performance than the centralized layout (Scenario 3). Hence, in the case of pushing the boundaries of automation to the ultimate level, one is suggested to consider the centralized layout configuration.

Table 5. Simulation results

Scenario	Time in the Machine [sec]	Time for Moving and Emptying [sec]	Time to Shelf [sec]
1	1891 [967.23, 366.79]	2558 [728.47, 1007.81]	4448
2	3522 [2124.22, 750.02]	2928 [709.94, 925.35]	6449
3	214 [154.07, 53.64]	1019 [235.55, 275.7]	1234
4	180 [102.46, 33.24]	590 [81.4, 88.52]	770

Values: Mean Value [Standard Deviation, Mean Confidence Interval (95%)]

In addition, there is a significant difference between the maximum duration that each full bin awaits on the average to be picked up by a robot associated with the semi-automated and fully-automated scenarios, 214 sec as opposed to 3522 sec, respectively. The same implication is evident with respect to the 'time for moving and emptying': 1,019 sec as opposed to 2,558 sec. In corollary, the simulation results corroborate the better performance of semi-automated scenarios corresponding to the collective value of 'time to shelf'.

7 Conclusions

Material handling processes play a core role within the library operations. In this regard, the absence of an efficient material handling leads to various operational challenges, lower performance, and ultimately dissatisfied patrons. Field observations and focus groups conducted at the Trondheim Public Library revealed that the moving process, as one of the four major material handling processes, is particularly time- and labor-intensive. While technological advancements have introduced digital solutions to streamline and expedite material handling in various organizations, academic efforts short fall toward improving material handling in libraries. Therefore, this study aimed to enhance library material handling by leveraging mobile robot solutions. To this end, we initially investigated the challenges stemming from inefficient material handling and subsequently conducted a simulation study to investigate the utilization of mobile robots under the influence of four scenarios.

Manual material handling processes, particularly the moving process, pose numerous operational challenges and negatively impact library operations. According to the automation agenda in service-oriented organizations, the use of mobile robots in semi-automated conditions represents a potential solution in response to the challenges that particularly engage humans, such as reducing the load of non-value-adding tasks performed by librarians. However, the simulation results corroborate that eliminating the human element does not yield any high performance. In fact, the results indicated that the semi-automated scenarios outperform the fully-automated scenarios which underscores the essence of human presence in collaboration with mobile robots.

The simulation study was under the influence of some limitations that are worth mentioning. The working hours of mobile robots were limited to the library's opening hours. Therefore, it is advantageous to extend the operational hours of the mobile robots beyond the official working hours of the library, for example, the night shift. Moreover, the dynamics of rush hour were simplified, and thus, a constant flow of patrons was considered for accomplishing the simulation study. Therefore, it is recommended to address this issue in similar further studies. Additionally, the fleet size suggested the use of one robot for this research while developing simulation studies upon the use of more mobile robots is of advantage in future studies. Last but not least, the specific characteristics of the library's atmosphere–the presence of patrons and staff–necessitate translating and incorporating the technical and safety features of the mobile robots, i.e., loading and unloading tools, avoiding collision, etc., into the future simulation experiments.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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