In: Mobile robot automation in warehouses: a framework for decision making and integration. Cham, Switzerland: Palgrave Macmillan
DOI: 10.1007/978-3-031-12307-8

8 Research Agenda

This chapter discusses the mobile robot system selection according to Table 3.3 and the managerial decision framework presented in Table 7.1. At the end of each sub-section, research directions are outlined which, in combination, form a research agenda for mobile robot systems in warehouses.

8.1 Mobile robot systems and selection criteria

This book mentions five criteria for evaluating and choosing between different mobile robot systems (Chapter 3). The criteria outlined are derived from and supported by literature, whilst the authors specifically developed the rating system to support decision-makers in warehouses. The rationale of this selection support tool for mobile robot systems, as well as the ratings of each system were illustrated with regard to their applicability in supply chain practice. In combination, this forms a key contribution of this study which could be further supported by the research directions below.

- A list of criteria to select the correct mobile robot system (i.e., cost, flexibility in infrastructure, flexibility in material handling, scalability, time-to-implement) could be developed and refined through practical applications with empirical evidence to aid decision-makers in choosing the best solution.
- More than half of the empirical papers focus on picking operations. Even though it is the most time consuming and costliest activity in the warehouse, other operations such as sortation, put-away, and loading/unloading should also be evaluated when considering mobile robot system implementation.
- The performance (e.g., throughput, labour productivity) of mobile robot systems other than barcode-guided mobile robots have not been systematically evaluated due to a lack of simulations and real-life applications. Theory and practice should work together to define relevant performance indicators in this regard and subsequently analyse performance areas considering different user scenarios.

8.2 Managerial decision framework

The hierarchical decision framework (Table 7.1) is targeted at the design, planning and management of warehouses adopting mobile robot technologies in the digitalisation era. It synthesises decision areas that have been identified through the systematic literature review and organise these across managerial decision horizons. It considers the various choices put forward by the reviewed papers in order to capture a wide array of decision areas and criteria. Research areas stemming from the framework as a whole are as follows.

- To test and/or improve this conceptual framework's structure and robustness with more focus areas and/or decision questions, a further investigation needs to be carried out with experts and practitioners familiar with mobile robot implementation.
- The framework should be put into practice with various mobile robot systems to illuminate the differences within the focus areas in distinct systems.

The following sub-sections provide further reflection and provide research directions aimed at enhancing the applicability and generalisability of the managerial decision framework.

8.2.1 Strategic level focus areas

This book limits the strategic level to pre-implementation decisions, which would require a considerable amount of time (maybe a year) and investment to implement selected technologies. For instance, Bechtsis et al. (2017) consider the number of robots (fleet sizing) as a strategic decision, whereas Le-Anh & De Koster (2006) and Wang et al. (2020) suggest that it is of tactical nature. Although the initial number of robots is decided before the implementation of a solution, the total number may obviously be altered in the medium-term, at the tactical level. Keeping in mind this logic regarding strategic level decisions, the following pre-implementation research areas are identified.

- More than half of the studies do not mention how robots would be coordinated in the warehouse. To identify the applicability of robot coordination types in different scenarios, it should be explicitly considered in empirical studies.
- Most papers assume a fixed layout which does not adequately reflect the flexible use of mobile robots and decreases the generalisability of the results. Thus, researchers should incorporate alternative layouts into the implementation of mobile robot automation.
- Human-robot interaction is not mentioned adequately, and studying a mobile robot-only warehouse lacks practicality. Subjects such as 'change management' and 'human safety' require researchers' attention in order to support system implementations and raise managers' awareness of and sensibility to issues in human-robot interaction.

8.2.2 Tactical level focus areas

Tactical level decisions may have impacts across time horizons and decision levels and, depending on the situation, will impact strategic or operational decisions to different degrees. For example, storage assignment is considered at the strategic level and the operational level in separate studies (Füßler et al., 2019). Further, the order management plan is a common subject, but none of the papers reviewed allocates it to a particular level. We consider it at the tactical level as it does not necessarily need to be decided before the implementation of the system but observing its effect on the system would be in the medium-term. In support of managerial decisions at a tactical level, the following research avenues are put forward.

- Storage assignment decision is one of the least attended subjects as it might be perceived as an inventory management decision rather than a mobile robot-related decision. However, decision-makers require support in this regard since considering how SKUs should be distributed in a warehouse holds the potential to decrease the number of robots needed and increase warehouse throughput.
- Accounting for the biggest portion of the variable cost, fleet sizing is a significant entry barrier for implementing mobile robot systems. Yet, many papers leave fleet size optimisation unattended as their main aim is to prove the feasibility of algorithms for mobile robot systems. Optimum fleet size considerations should thus be a focal point of research and should be included in empirical scenarios as well as simulation exercises.
- Maintenance and failure handling strategies require research attention since disregarding robot failures can lead to unforeseen and undesirable delays in, for example, inventory movements or picking tasks. Hence, maintenance strategies should be evaluated and compared with regard to their inherent trade-offs regarding costs, frequency, time requirements, prevention effectiveness, and so on. Predictive maintenance strategy for robot fleets is a promising research direction which could be coupled with investigations into the success of specific actions in case of robot failures to maintain the continuity of the operations.
- Robot energy management is understudied despite its impacts on warehouse throughput, traffic congestion, fleet size considerations, and space requirements for charging stations. Empirical studies could help to evaluate the practical implications of energy management decisions and new technology developments, whereas modelling

research could focus on optimisation approaches of different energy management strategies and their trade-offs.

8.2.3 Operational level focus areas

Operational level decisions may be altered in the short term, and the results could be observed within the same week or day, such as task allocation of mobile robots. Even though they are mentioned as a tactical level decision by (Le-Anh & De Koster, 2006), most authors consider them at the operational level because they can be altered daily with a new algorithm.

- Dynamic task allocation approaches need to be adapted to the application of mobile robot systems as they hold the potential to improve managing chaotic warehouse environments where there is an increased chance of occurrences of unforeseen events.
- In path planning, instead of focusing on algorithms such as Dijkstra's and A* that provide optimal solutions, computationally scalable sub-optimal approaches should be studied for large warehouses.
- To decrease task completion times and avoid delays, studies should concentrate on proactive conflict and deadlock management instead of reactive approaches (Lee et al., 2019). Proactive approaches are scarce in the current literature even though they eliminate the time loss of two robots coming across each other.
- Even though many warehouses require large fleets of mobile robots in practice, academic studies often avoid this reality and somewhat simplify the scale of problems. Thus, suggested algorithms tend to be developed for unrealistic scenarios and should hence be tested for larger-scale applications of mobile robots. Additionally, their traffic management should be studied as the required level of sophistication and flexibility of a solution may increase at scale.

8.3 Research Agenda Summary

Figure 8.1 presents the research agenda of key topics for warehouse mobile robot systems. Each topic highlights an information deficiency or a necessity for elaboration on a decision-level-related subject. These subjects are a synthesis of the authors' observations and the research suggestions gathered from the reviewed papers.

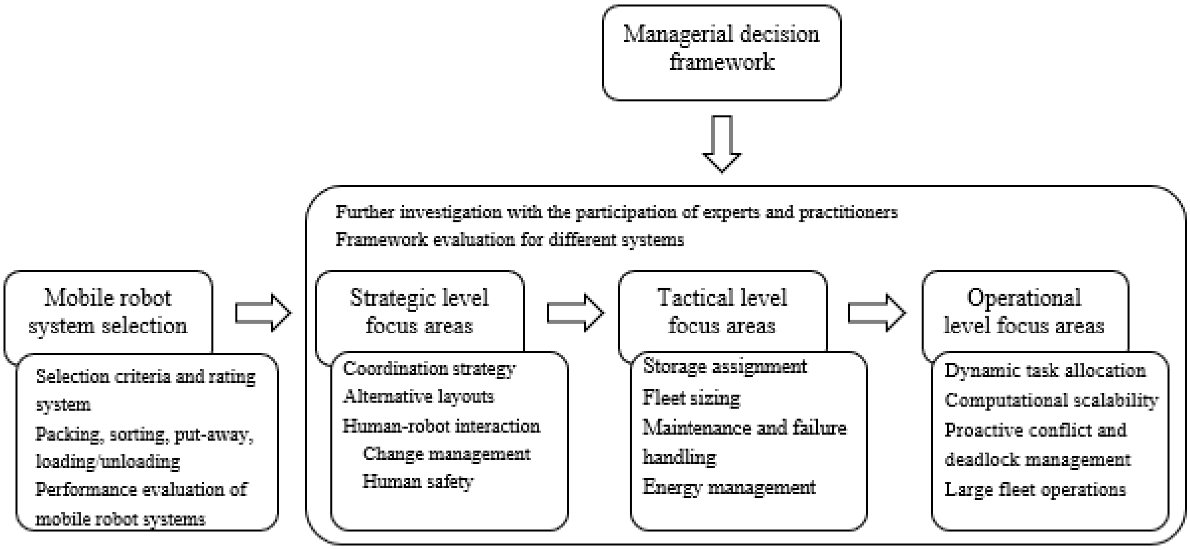

Figure 8-1 Key Topics for the Research Agenda

Reference List for Chapter 8

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Chapter 8: research agenda

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2023-01-04

Yildirim A, Reefke H, Aktas E. (2023) Chapter 8: Research agenda. In: Mobile robot automation in warehouses: a framework for decision making and integration. Cham, Switzerland, January 2023, pp. 121-126

https://doi.org/10.1007/978-3-031-12307-8_8