

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

On the performance of robotic parts-to-picker order picking systems

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ABSTRACT

Order picking is the activity in which a number of items are retrieved from a warehousing system to satisfy a number of customer orders. Automating order picking systems has become a common response to the wide variety of products and components stored in today's warehouses and the short delivery lead times requested by today's customers. As a result, new technical solutions have reached the market, including robotic parts-to-picker order picking systems such as robot-based compact storage and retrieval systems (RCSRSs) and robotic mobile fulfilment systems (RMFSs).

Despite the increased use of robotic parts-to-picker order picking systems, knowledge about how they perform in terms of throughput, order lead time, human factors, quality, flexibility, operational efficiency, and investment and operational costs needs to be further developed, as does knowledge about how their performance is affected by the order picking system's design and context. Accordingly, the purpose of this thesis is to expand knowledge about the performance of robotic parts-to-picker order picking systems by investigating how their design and context influence their performance.

The thesis is built upon three studies: a systematic literature review study focusing on automated order picking systems, a multiple-case study on RCSRSs, and a single-case study on RMFSs. First, the systematic literature review study on the performance of automated order picking systems provides an overview of literature on order picking systems to date, aspects of their performance, and how their performance relates to their design. Second, the multiple-case study sheds light on characteristics of the performance of RCSRSs and the relationships between their performance and design. Third and last, the single-case study affords insights on how the context of RMFSs affects their performance.

The thesis contributes to practice by providing guidance to decision makers within industry in terms of the performance to expect of robotic parts-to-picker OPSs depending on their design and context. In turn, such knowledge can facilitate the selection and design of an OPS or else the redesign of a current system. At the same time, the thesis contributes to theory by providing a synthesis of literature addressing the performance of automated OPSs and by outlining the relationships between their design and performance.

Keywords: Order picking, automation, materials handling

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List of appended papers

Paper I:

Jaghbeer, Y., Hanson, R. and Johansson, M.I., 2019. Automation in order picking systems: a systematic literature review. Submitted to the *International Journal of Production Research*.

An earlier version of the paper was presented at the PLAN Forsknings-och tillämpningskonferens, held on 25–26 October 2017 in Göteborg, Sweden.

Contribution: The paper was designed by the first author, Jaghbeer, under the advisement of the other authors. The literature review and analysis were performed by the first author, who also wrote the paper. The paper was improved after being reviewed by the other authors and with reference to their comments.

Paper II:

Jaghbeer, Y., Hanson, R. and Johansson, M.I., 2019. Robot-based compact storage and retrieval systems: relations between performance and design.

An earlier version of the paper was presented at the EurOMA Conference, held on 24–26 June 2018 in Budapest, Hungary.

Contribution: The paper was designed by the first author, Jaghbeer, in consultation with the other authors. Data collection and analysis were performed by the first author, who also wrote the paper. The paper was improved after being reviewed by the other authors and with reference to their comments.

Paper III:

Hanson, R., Jaghbeer, Y., Medbo L. and Johansson, M.I., 2019. Robotic mobile fulfilment systems: links between context and performance.

An earlier version of this paper was presented at the INCOM IFAC Conference, held on 11–13 June 2018 in Bergamo, Italy.

Contribution: Jaghbeer participated in developing the paper after the conference. Jaghbeer wrote the literature review section, participated in data collection and analysis, and co-wrote the other sections with Hanson. All sections were improved after being reviewed by the other authors and with reference to their comments.

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1. Introduction

This thesis addresses the performance of robotic parts-to-picker order picking systems (OPSs) and the relationships between the performance of such systems and the systems' design and context. This introductory section presents the background to the problem in Section 1.1 and introduces the thesis's purpose in Section 1.2 and research questions in Section 1.3. The scope of the thesis is described in Section 1.4, after which its contents are outlined in Section 1.5.

1.1 Background

Today's warehouses operate in highly challenging environments. Not only has e-commerce increasingly required warehouses to store a wide variety of products (Andriansyah et al., 2014), but heightened expectations from consumers have also forced warehouses to process more orders within tighter delivery timeframes (Andriansyah et al., 2014; Marchet et al., 2015). Affected by that challenging environment, order picking at warehouses has been required to improve, particularly in terms of performance (Yu and de Koster, 2009; Andriansyah et al., 2014). As the activity in which a number of items are retrieved from a warehousing system to satisfy a number of customer orders, order picking is at the heart of warehouse operations (Goetschalckx and Ashayeri, 1989; Manzini et al., 2006). Far from a simple process, order picking entails selecting orders for picking, retrieving items to fulfil those orders, presenting items at a picking station, and consolidating the items for each order into one or more boxes (Beckschäfer et al., 2017).

Given the significance of order picking to a warehouse's overall performance (Marchet et al., 2015; Lenoble et al., 2018), automating OPSs has become a common response to the mentioned challenges (Andriansyah et al., 2014), one that can boost the performance of order picking by reducing labour costs, shortening order cycles, and increasing picking accuracy (Manzini, 2012). As a result, new forms of automation in OPSs have appeared on the market, including various parts-to-picker OPSs with carousels, crane-based systems, and, more recently, robotic parts-to-picker systems in which mobile robots move in storage areas and transport items (Huang et al., 2015), as detailed in Section 2.3. In parallel, interest in research on new automated technologies with the potential to improve the performance of order picking has also grown (de Koster, 2017). Several performance categories in order picking have been found to be important, including throughput, order lead time, human factors, quality, flexibility, operational efficiency, and investment and operational costs (e.g. Rouwenhorst et al., 2000; Staudt et al., 2015; Gils et al., 2018), as detailed in Section 2.4.

As highlighted by Taljanovic and Salihbegovic (2009), order picking performance is affected by a wide variety of factors. In turn, selecting which automated OPS to apply at a warehouse requires considering aspects related to the OPS's design, as well as the constraints of contextual aspects, to meet certain performance goals, as illustrated in Figure 1.1. In this thesis, the design of OPSs is conceived to encompass aspects related to the equipment used for storage, retrieval, and activities at picking stations, as well as aspects concerning the space and layout of the order picking area and policies related to storage, picking, batching, and routing as detailed in Section 2.5. The contextual aspects addressed in the thesis, as categorised and described in Section 2.6, relate to aspects

beyond the OPS designer’s control but nevertheless affect how the OPS performs. Altogether, contextual aspects include system profile (e.g. number of customers), demand profile (e.g. number of lines per order), and item profile (e.g. item size and weight).

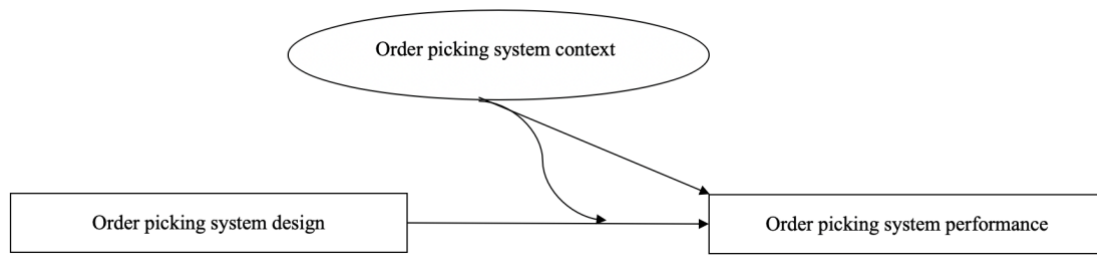


Figure 1.1. Overview of how the design and context of an order picking system influence its performance

Although automation in OPSs has received sustained attention from researchers, the study of the performance and design aspects of automated OPSs remains fragmented and devoted to isolated, micro-level problems. Accordingly, a structured overview of the performance aspects of different types of automated OPSs examined in the literature to date could clarify how different automated OPSs perform, considering that different types are likely to perform differently. Moreover, because the design of OPSs influences their performance (e.g. Goetschalckx and Ashayeri, 1989; Brynzér and Johansson, 1995; Rouwenhorst et al., 2000; de Koster et al., 2007) and given the complexity of assessing design–performance relationships (Gu et al., 2007), identifying those relationships in light of technological developments in the automation of OPSs (e.g. robotic parts-to-picker systems) becomes relevant to properly select and design OPSs for warehouses.

Marchet et al. (2015) have recommended conducting further empirical research on how automated OPSs perform. Some types of automation in order picking are more established in literature than others. The performance and design of automated OPSs, including automated storage and retrieval systems (AS/RSs), have been studied for several decades (e.g. Kusiak et al., 1985; Medeiros et al., 1986; Mahajan et al., 1998; Khojasteh et al., 2016), along with the use of vertical lift modules (e.g. Battini et al., 2015; Dukic et al., 2018), carousels (e.g. Chang et al., 1993; Lenoble et al., 2017), and conveyers (e.g. Armstrong et al., 1979; Andriansyah et al., 2009; Liu et al., 2015). However, more recent developments such as robotic parts-to-picker systems have received less attention. Such new technological developments motivate additional research on how their design affects the performance of OPSs. As a case in point, robotic parts-to-picker OPSs include systems with either static or movable racks (Azadeh et al., 2017), and examples of such systems that are being increasingly used in practice are robot-based compact storage and retrieval systems (RCSRSs) and robotic mobile fulfilment systems (RMFSs). However, despite the increased use of robotic parts-to-picker OPSs in practice, they remain hardly studied in academic literature (Azadeh et al., 2017).

RCSRSs are robotic parts-to-picker OPSs whose applications have increased in recent years (Azadeh et al., 2017). RCSRSs typically encompass a set of bins laid out in a grid, along the top of which robots move to store, retrieve, and transport bins to workstations, thereby rendering aisles useless (Beckschäfer et al., 2017), as detailed in Section 2.3.1. Although researchers have addressed some performance characteristics of RCSRSs and their relationships with aspects of design—for example, Beckschäfer et al. (2017) have

examined throughput, while Zou et al. (2016) have investigated throughput, throughput time, and operational efficiency—research on the performance of such systems remains necessary, as recognised by both Beckschäfer et al. (2017) and Zou et al. (2017).

An RMFS comprises a large storage area with storage pods, robots, and picking stations (Lamballais et al., 2017), in which robots move inventory pods to the picking stations, and pickers retrieve ordered items, as detailed in Section 2.3.2. The performance of RMFSs has been studied by several researchers, including Bauters et al. (2016), Lamballais et al. (2017), and Roy et al. (2019), who examined their throughput, as well as Zou et al. (2017), Yuan and Gong (2017), and, again, Roy et al. (2019), who examined throughput time in RMFSs. Even then, both Zou et al. (2017) and Lamballais et al. (2017) have called for additional research to adequately address the performance of RMFSs. In particular, Zou et al. (2017) have suggested that studying different order picking area layouts could prove insightful, while Lamballais et al. (2017) have indicated that RMFSs in general continue to offer several unexplored avenues for research.

1.2 Purpose of the thesis

As acknowledged in the foregoing section, automation in order picking can improve the performance of OPSs. At the same time, though researchers have examined automation in OPSs for decades (e.g. Kusiak et al., 1985; Chang et al., 1993; Liu et al., 2015; Khojasteh et al., 2016; Dukic et al., 2018), recent technological developments in automated OPSs warrant additional studies, especially studies focusing on the performance of not long-available types of OPSs but of new ones such as robotic parts-to-picker systems. The performance of an OPS varies from type to type, and selecting which automated OPS to implement should involve considering its design and context, both of which affect the system's performance. Indeed, researchers agree that an OPS's design affects its performance (e.g. Goetschalckx and Ashayeri, 1989; Brynzér and Johansson, 1995; Rouwenhorst et al., 2000; de Koster et al., 2007); nevertheless, studies on the performance and design of automated OPSs remain fragmented and focus primarily on micro-level problems.

Understanding the relationships between an OPS's performance and its design and context is essential to selecting an appropriate system from amongst the types available and their various designs. Such insights can support efforts to maximise the benefits of automated order picking recognised in the literature, in which knowledge remains limited about how OPS design and context affect the performance of robotic OPSs, as does industrial knowledge on how the various automated types of OPS perform depending on modifications to their designs. Therefore, the purpose of this thesis *is to expand knowledge about the performance of robotic parts-to-picker OPSs by investigating how their design and context influence their performance.*

1.3 Research questions

Three research questions have structured the thesis and aligned the work with the purpose presented in Section 1.2. The motivation of each research question is discussed and presented to provide an overview of the relevance of each question.

1.3.1 Research Question 1

Of the numerous aspects affecting an OPS's performance (Taljanovic and Salihbegovic, 2009), several design aspects have been increasingly examined, either separately or in conjunction, regarding how they affect the performance of automated OPSs. For example, Manzini et al. (2006) have examined how storage and picking policies affect throughput in an AS/RS, while Battini et al. (2015) have compared storage policies in a vertical lift module and, in turn, developed a model for studying their effects on throughput as well. More recently, with the aim of minimising order picking time, Lenoble et al. (2017) have proposed an optimisation model for batching policies in carousels, while Xue et al. (2018) have comparatively analysed how three picking policies in an RMFS affect order picking time.

The literature lacks an overview on which types of automated OPSs have been examined to date, their performance aspects, and the relationships between their design and performance. A structured overview on the performance of OPSs and how it relates to their design, however, would reveal particular gaps in knowledge on the topic and contribute to understandings on how the various automated OPSs perform in relation to their design. Therefore, Research Question 1 is:

Which performance aspects of automated OPSs and their relationships with design are addressed in the literature?

1.3.2 Research Question 2

Despite the increasing application of RCSRSs in practice (Azadeh et al., 2017), research on their performance has been scarce. Indeed, apart from a few published works addressing RCSRSs' throughput (e.g. Beckschäfer et al., 2017) and lead time (e.g. Zou et al., 2016) and showing, for example, that an RCSRS's throughput is affected by the number of robots used and number of stock keeping units (SKUs) per rack (Bauters et al., 2016), the literature provides limited insights into the different performance characteristics of RCSRSs or how the design of such systems affects their performance.

Although understanding the relationships between an RCSRS's performance and design is pivotal to effectively design and use such a system, such relationships in terms of throughput, order lead time, human factors, quality, flexibility, operational efficiency, and investment and operational costs are far from entirely understood. In fact, Marchet et al. (2015) have called for additional empirical research on those topics, while Zou et al. (2016) have highlighted a need to study how an OPS's design affects its performance—for instance, how an RCSRS's performance could vary depending upon the storage policy in place. More recently, Beckschäfer et al. (2017) have recommended further comparative research on the performance of RCSRSs versus other robotic parts-to-picker OPSs (e.g. RMFSs). Considering the above, Research Question 2 is formulated to be:

What are the performance characteristics of robot-based compact storage and retrieval systems, and how does the design of such a system affect its performance?

1.3.3 Research Question 3

Studies on robotic parts-to-picker systems, especially RMFSs, have been increasingly prevalent, particularly regarding their performance in terms of throughput (Bauters et al.,

2016; Lamballais et al., 2017) and lead time (e.g. Zou et al., 2017; Roy et al., 2019), and how those performance categories have been affected by changes to the system's design. However, aspects beyond design that act as constraints and need to be considered when designing an OPS—that is, *contextual aspects*—are hardly touched upon in the literature. For example, the number of items per order line, as a contextual aspect of an OPS, can affect the system's performance in terms of throughput time and picking quality. Moreover, varying demands from customers could impose certain requirements on the OPS's flexibility and throughput. Because such contextual aspects and their impact on the performance of RMFSs are important to identify in order to be able to make suitable design decisions, Research Question 3 is formulated as:

How does the context of a robotic mobile fulfilment system affect its performance?

1.4 Scope and delimitations

This thesis considers an OPS to encompass the order picking process, the equipment and layout of the order picking area, and the storage, picking, batching, and routing policies used. Interested only in the OPS's interface with its replenishment and takeaway functions, the thesis does not focus on deliveries from suppliers, the replenishment process of items, or deliveries to customers; however, it does consider the equipment and information systems used at picking stations. Furthermore, the thesis does not address the design process but, on the contrary, aspects of design that need to be considered when designing or selecting an OPS for implementation. Last, because the literature on evaluating the performance of order picking remains limited, some published reviews on evaluating warehouse performance have been considered to identify relevant performance categories in OPSs.

The thesis initially identifies a variety of aspects related to the performance of different automated types of OPSs (i.e. Research Question 1), including parts-to-picker systems, robot-to-parts systems, parts-to-robot systems, and picker-less systems, as illustrated in Figure 2.2. Later, it narrows its focus to robotic parts-to-picker OPSs in order to pinpoint how their performance can be affected by their design (i.e. Research Question 2) and their contextual aspects (i.e. Research Question 3). As such, the thesis exclusively treats the design and context of OPSs and how they influence the performance of the systems in terms of throughput, order lead time, quality, operational efficiency, flexibility, human factors, and investment and operational costs (see Section 2.4). The design categories considered herein concern the space and layout of the order picking area, equipment, and policies (see Section 2.5), whereas the context categories concern the system, demand, and item profiles (see Section 2.6).

1.5 Outline

Following this chapter, which has presented the thesis's background, purpose, and three corresponding research questions, as well as its scope, Chapter 2 explains the thesis's theoretical framework organised around three primary topics: the performance of OPSs, the design of OPSs, and the context of OPSs. Later, the chapter also describes the various types of OPSs, including robotic parts-to-picker systems, followed by a synthesis of those elements into the thesis's theoretical framework. Next, Chapter 3 explains the methodology of the thesis. Chapter 4 briefly summarises the three appended papers for the reader's reference, after which Chapter 5 presents the results of the thesis in relation

to how they help to answer the research questions. Chapter 6 discusses the results of the thesis, particularly by highlighting their contributions to the research's purpose and their implications for future research. Last, Chapter 7 articulates the conclusions of the thesis.

2. Theoretical framework

In this chapter, Section 2.1 defines the terms *order picking* and *automation* as used in the thesis, as well as elaborates upon different understandings of levels of automation (LoAs) in the literature. Next, Section 2.2 presents various systems available in the literature for classifying types of OPSs, followed by an explanation of how the classification system used in the thesis was derived. Section 2.3 delves further into robotic parts-to-picker OPSs, including both RCSRSSs and RMFSs, after which Section 2.4 describes the performance categories of OPSs derived in the thesis and literature relevant to each. After that, Section 2.5 characterises the categories of the design of OPSs, whereas Section 2.6 characterises aspects of OPSs context. Ultimately, Section 2.7 overviews the theoretical framework derived from considerations of all of the above.

2.1 Automation in order picking

Herein, Section 2.1.1 provides a definition of *automation* and a brief discussion of the different ways of understanding LoAs, after which Section 2.1.2 provides a definition of *order picking* and a description of the order picking process.

2.1.1 Automation and levels of automation

Although usually understood as being specific to context, *automation* can be defined as the “automatic control of the manufacture of a product through a number of successive stages; the application of automatic control to any branch of industry or science; by extension, the use of electronic or mechanical devices to replace human labour” (*Oxford English Dictionary*, 2006). According to Groover (2016), automation implies that human labour, both cognitively and physically, is replaced to a certain extent by mechanical or electronic devices.

Given that implication, companies tend to treat automation as a black-or-white choice to use exclusively humans or exclusively machines as labour, either of which could be regarded as a sort of sub-optimisation (Fasth et al., 2007; Parasuraman, 2000). However, companies should view automation as existing at different levels, with varying degrees of interaction and task division between humans and machines (Parasuraman et al., 2000).

Used to describe the extent to which a certain task is performed automatically or manually, LoAs have been studied by numerous researchers who have also developed models for differentiating them (Bright, 1958; Fasth et al., 2007; Groover, 2016). For instance, Groover (2016) has conceptualised LoAs as the manning level relative to the use of machines, which can be manual (i.e. based on human capabilities), semi-automated, or fully automated without any human involvement (Groover, 2016). This thesis borrows from Groover et al.’s (2016) conceptualisation of LoAs in referring to semi-automated or fully automated systems as automated.

For an alternative way to understand LoAs, Bright (1958) has identified 17 LoAs according to the source of control and type of machine response, ranging from using hands only (i.e. Level 1) to anticipating required actions and adjusting accordingly (i.e. Level 17). By contrast, Goetschalckx and Ashayeri (1989) have addressed LoAs in terms of the levels of mechanisation in the equipment used for order picking activities, which they divided into manual, mechanised, semi-automated, and automated. In that

categorisation, *manual* means that both power and control are provided by labour (e.g. shelf picking), *mechanised* that the power is provided by machines but control by labour (e.g. pallet picking with a forklift), *semi-automated* that all power and some control are provided by machines (e.g. mini-load systems), and *automated* that both power and control are provided entirely by machines (e.g. carousel with robot extraction). Table 2.1 presents the definitions of *LoAs* indicated by all of the works cited above.

Table 2.1. Definitions of levels of automation (LoAs)

| Source | Definition |
|----------------------------------|---|
| Bright (1958) | Referring to level of mechanisation, LoAs range from completely manual (i.e. using hands) to fully mechanised. |
| Goetschalckx and Ashayeri (1989) | Referring to level of mechanisation, the four LoAs are manual, mechanised, semi-automated, and automated. |
| Parasuraman et al. (2000) | LoAs represent a continuum from manual to fully automatic operations. |
| Groover (2016) | LoAs indicate manning levels relative to the use of machines, which can be manually operated, semi-automated, or fully automated. |

2.1.2 Order picking definition

In most warehouses, the major activity is regarded to be *order picking* (de Koster et al., 2007), defined as the process of obtaining the correct items in the correct amount for a set of customer orders (de Koster et al., 2007). Each customer order consists of a set of order lines, each of which indicates a certain product or SKU in a certain quantity to be included in the order (Tompkins et al., 2010).

Order picking, specifically, items retrieval, can be manual, automated, or semi-automated (Rouwenhorst et al., 2000). The order picking process in general has been described by Beckschäfer et al. (2017) and is illustrated in Figure 2.1. In particular, the manual order picking process in a warehouse involves four steps. First, one or more orders are selected for picking (Beckschäfer et al., 2017). Second, the items required to fulfil the order are retrieved from the warehouse by an operator walking or driving therein, and third, the operator places the retrieved items at a receiving station. Fourth and last, the operator consolidates the items for each order into one or more boxes and sends them to be stored until shipment (Beckschäfer et al., 2017). In automated OPSs, by contrast, the second step generally differs, because machines or robots replace operators in retrieving items for orders (Beckschäfer et al., 2017). In either case, the order picking process typically involves substantial travelling between storage locations in the warehouse. until the delivery of orders to customers.

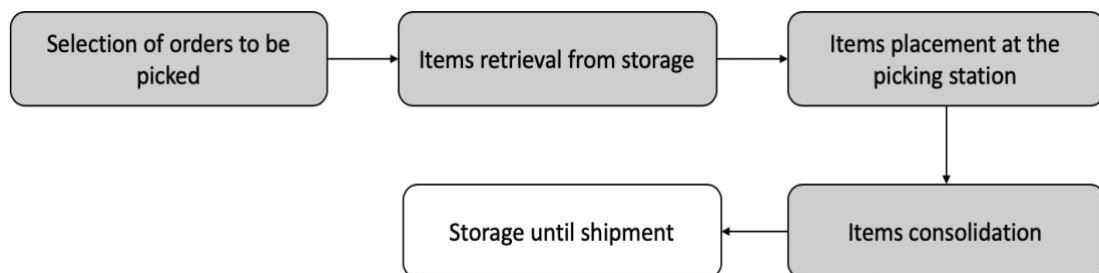


Figure 2.1. Schematic of the order picking process, with steps considered in the thesis identified in shaded boxes

2.2 Types of order picking systems

Several classifications of OPSs types have been provided by different researchers. Following a review of those classifications, this section explains the classification derived from them and used in this thesis to describe different types of automated OPSs. Ultimately, the derived classification is used in answering Research Question 1 of the thesis.

For one, van den Berg (1999) has divided OPSs into three types: picker-to-parts systems (i.e. in which order pickers move between picking positions), parts-to-picker systems (e.g. with AS/RSs, carousels, and mini-load systems that move products to order pickers at picking stations), and picker-less systems, which use either robots or automatic dispensers.

de Koster et al. (2007) have classified OPSs according to whether they use human or machine labour. Whereas ones using human labour are picker-to-parts systems, parts-to-picker systems, and put systems, ones using machines are either automated picking systems (e.g. A-frames and dispensers) or systems with picking robots. Within those categories, de Koster et al. (2007) have also identified two types of picker-to-parts systems: low level and high level. On the one hand, in a low-level picker-to-parts OPS, pickers pick items from picking locations such as storage racks or bins while travelling along aisles on foot. On the other, in high-level picker-to-parts OPSs, or so-called “man-on-board systems”, involve high storage racks that pickers access from aboard a lifting order pick truck or crane, which stops automatically in front of the picking location and waits for the picker to perform the picking task (van den Berg, 1999; de Koster et al., 2007). Unlike those systems, put systems, or “order distribution systems”, consist of a joint process of retrieval and distribution, in which parts are retrieved in a parts-to-picker or picker-to-parts manner, after which the carrier (e.g. a bin) is given to the picker who distributes them to the correct orders (de Koster et al., 2007). Last, completely automated OPSs typically include dispensers (e.g. A-frames) and robots, which are usually connected to other areas by conveyers (van den Berg 1999; de Koster et al., 2007).

Another classification has been developed by Dallari et al. (2009), who conceive picking systems as existing in five categories: picker-to-parts, parts-to-picker, pick-to-box, pick-and-sort, and completely automated picking systems, in which the level of automation gradually expands from that resembling a picker-to-parts system to one that is entirely automated. To further distinguish the five categories, Dallari et al (2009) have also sorted the systems according to who picks the goods, who moves within the picking area, whether conveyers are used to connect different picking zones, and the picking policy employed (Dallari et al., 2009). For instance, pick-to-box systems, or so-called “pick-and-pass systems”, divide the picking area into zones with one or more picker in each; all picking zones are connected via conveyers, and orders are picked sequentially zone by zone (Dallari et al., 2009). Such systems are preferable when there are a significant number of small items, small order sizes, and medium-sized flows (Melacini et al., 2011). In pick-and-sort systems, operators in the picking area are responsible for retrieving the required amount of each item needed due to the batching of multiple orders and putting them on a takeaway conveyor connecting the storage and picking areas. Afterwards, a computerised system specifies each item’s destination bay, where each destination bay resembles an individual order (Dallari et al., 2009; Marchet et al., 2011). Such systems are usually associated with downstream sortation (i.e. wave picking), which implies that

all orders in a picking wave are completely sorted before the next wave of picks for orders is released; consequently, the batch sizes for the systems are relatively high. Last, completely automated systems are suitable for high-speed retrieval activities and for relatively similar, regular-shaped items. Such systems are adopted less often than other OPSs due to their high associated investment costs and the specificity of contexts in which they may be feasible (Dallari et al., 2009).

More recently, Huang, Chen, and Pan (2015) have classified robot-based OPSs as being either parts-to-picker systems in which mobile robots move products to human pickers, parts-to-robot systems in which robots perform picking and packing at picking stations, and robots-to-parts systems in which mobile robots move to storage areas in order to pick products.

Based upon these four classifications, an OPS classification (Figure 2.2) was developed for this thesis. Although the thesis also covers robots-to-parts, parts-to-robot, and picker-less OPSs, its chief focus robotic parts-to-picker OPSs, as described in Section 2.3. The classification distinguishes OPSs according to whether humans, robots, or neither function within the system. For example, parts-to-picker systems are partly automated and include an automatic device that transports items from a storage area to a picking station, at which human pickers retrieve the required amount of items and possibly perform packing as well (Huang et al., 2015; Lenoble et al., 2016). Potential equipment for use in parts-to-picker systems includes AS/RSs, mini-load systems, vertical lift modules, and horizontal and vertical carousels. In addition to robotic parts-to-picker systems, in which a robot moves within the storage area and brings items from storage to the operator at the picking station (van den Berg, 1999; de Koster et al., 2007; Marchet, et al., 2015), OPSs with a robotic picker include robot-to-parts and parts-to-robot systems, in which a robot performs the picking. Robot-to-parts systems involve mobile robots that move to storage areas and pick items, whereas parts-to-robot ones involve robots that perform picking and packing at picking stations (Huang et al., 2015). Last, the classification also includes picker-less OPSs, which are fully automated and do not involve any human or robot to perform picking (e.g. dispensers).

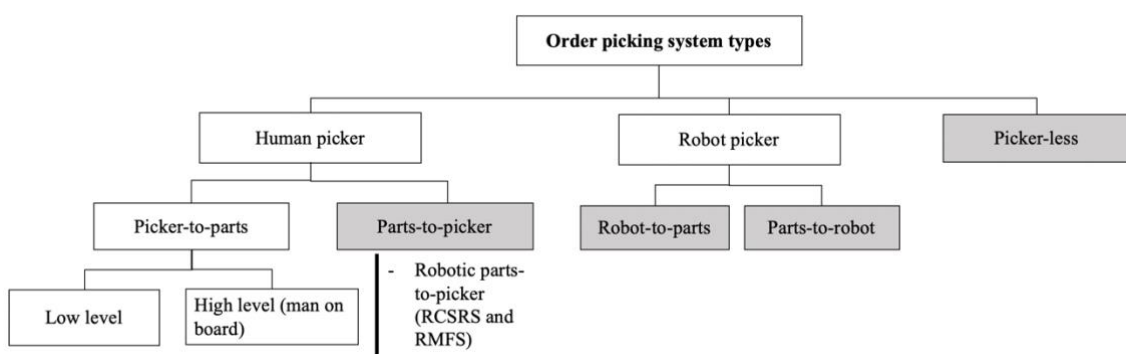


Figure 2.2. Classification of types of order picking systems, with ones addressed in the thesis appearing in shaded boxes

2.3 Robotic parts-to-picker order picking systems

Robotic parts-to-picker OPSs have either static or movable racks (Azadeh et al., 2017); ones with static racks include RCSRSs, whereas ones with movable racks include

RMFSs. Because this thesis addresses both RCSRSs and RMFSs, Sections 2.3.1 and 2.3.2 describe the components and picking processes in those systems, respectively.

2.3.1 Robot-based compact storage and retrieval systems

In RCSRSs items are stored in bins stacked on the top of each other and organised in a grid of rows and columns, and robots store, retrieve, and transport bins to operator ports—that is, workstations where an operator picks one or more items from the bin to satisfy an order. Although operator ports can be used for both input and output activities, in practice they are often used exclusively for one or the other (Beckschäfer et al., 2017). Because the top of the grid lacks aisles, robots can both lift and transport bins to the operator ports at a higher speed there (Beckschäfer et al., 2017). When an order is received, a robot starts working by first locating the requested bin; when that bin is not on the top of the grid, then the robot has to re-sort the bins. Next, the robot transports the requested bin to the operator port, and once the operator finishes processing the bin, the robot returns the bin to a storage location. Figure 2.3 illustrates the layout and components of an RCSRS.

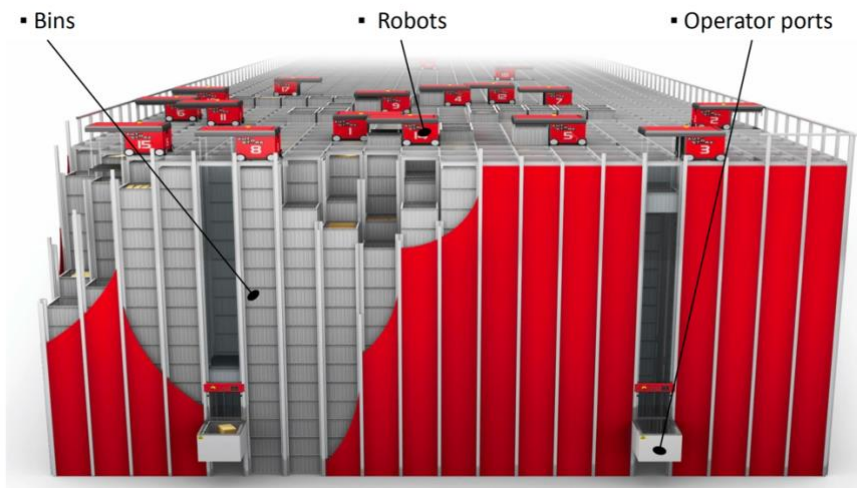


Figure 2.3. Layout and components of a robot-based compact storage and retrieval system (Element Logic, 2018)

2.3.2 Robotic mobile fulfilment systems

An RMFS comprises a storage area with a number of inventory pods (i.e. shelving racks for storage) and a number of robots and picking stations (Huang et al., 2015). According to Enright and Wurman (2011), such a system’s picking process commences when an order arrives and is soon or later assigned to a picking station. Because items are stored in inventory pods that are movable shelving racks, robots move in the storage area underneath the pods containing the items, carry the inventory pods containing the required items, and, using the aisles and cross aisles in the storage area, transport them to picking stations, where pickers select the required items (Enright and Wurman, 2011). When a picker has finished picking from an inventory pod, a robot transports the pod back to the storage area or to another picking station. While not carrying pods, however, robots can move underneath the pods instead of using the aisles and cross aisles. Last, the inventory pods can be replenished at picking stations or at stations dedicated to such replenishment (Enright and Wurman, 2011). Figure 2.4 depicts a schematic of an RMFS and its components.

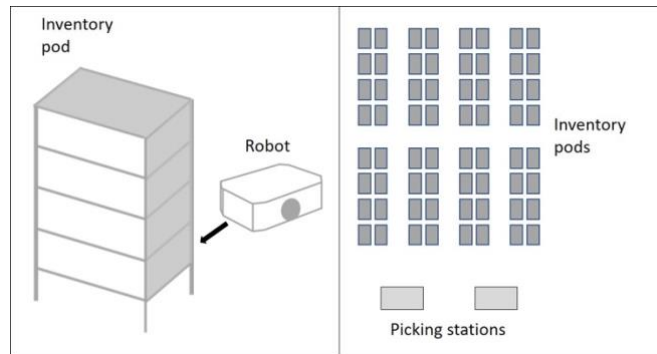


Figure 2.4. (Left) An inventory pod and robot and (right) the layout of a robotic mobile fulfilment system (Hanson et al., 2018)

2.4 Performance of order picking systems

This section aims to clarify the meaning of *order picking performance*, a central term in the thesis, by first identifying which categories of performance pertain to order picking. Following a presentation of several reviews on warehouse performance and categories of performance identified in the literature to date, the section describes those categories and provides relevant research conducted on each category in the context of automated and robotic parts-to-picker OPSs (see Sections 2.4.1–2.4.7). The performance evaluation is an important aspect to consider for the design and operation of warehouses and would act as a feedback about how a certain design option performs. Furthermore, it would assist in quickly evaluating the different design options (Gu et al., 2010). However, because literature concentrating on evaluating order picking performance remains slim, some reviews focused on the evaluation of warehouse performance are also considered to elucidate the characteristics of order picking performance.

Rouwenhorst et al. (2000) have developed a framework on the design and control of warehouses that identifies order picking as a major process therein. Their factors of warehouse performance include investment and operational costs, flexibility in volume and the mix of orders, throughput, storage capacity, response time, and order fulfilment quality, referred to as *accuracy*. Although their framework positions throughput as the most prominent characteristic of performance, Rouwenhorst et al. (2000) have stressed the importance of environmental and ergonomic characteristics of performance as well.

In their structured review of literature addressing the evaluation of activities contributing to warehouse performance, Staudt et al. (2015) identified order picking as one such activity and described its performance aspects. Dividing the aspects of warehouse and order picking performance into four categories—time, quality, cost, and productivity—they found that, for order picking performance, the most frequently used time-related aspects in literature on the topic have been order lead time and order picking time (Staudt et al., 2015). Meanwhile, for the quality of order picking, they identified the importance of picking accuracy, whereas for the cost, they highlighted inventory costs, order processing costs, labour costs, and maintenance costs (Staudt et al., 2015). Last, for productivity, sometimes termed *flexibility* in the literature, the aspects of throughput, resource utilisation, inventory space utilisation, and picking productivity have received attention from researchers (Staudt et al., 2015). In a later study, Gils et al. (2018) applied the performance categories identified by Staudt et al. (2015) to review and classify literature on manual OPSs.

In other notable work touching upon order picking performance, de Koster et al. (2007) have highlighted flexibility as an aspect of order picking pivotal to accommodating changes and uncertainties. From a different angle, Gu et al. (2010) have observed that warehouse design affects its performance in terms of throughput, quality, costs, space, and machine utilisation. More recently, Grosse et al. (2017) have stressed human factors—mental, physical, perceptual, and psychosocial ones—in order picking as major determinants of the performance of OPSs.

From those reviews, seven performance categories were derived for this thesis. Shown in Figure 2.5, the categories should not be conceived as unique or mutually exclusive; on the contrary, they can be coupled to varying extents, and drawing definitive boundaries around them can prove to be problematic.

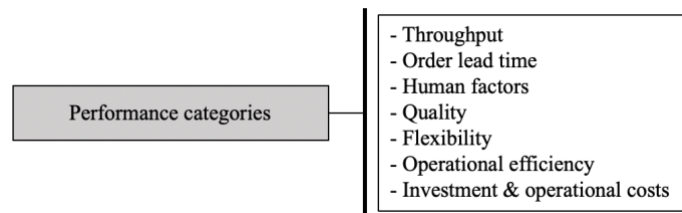


Figure 2.5 Categories of performance identified in literature

2.4.1 Throughput

Throughput can be defined as the number of items leaving the warehouse per hour (Gu et al., 2010). In order picking, throughput is measured according to either the number of completed orders or the number of completed order lines in a given period. Continually improving throughput is often a top objective in warehouses (Yu and de Koster, 2010), and in literature on automated order picking, throughput has been regarded as an aspect of the overall performance of OPSs for decades (e.g. Mahajan et al., 1998; Park et al., 2006; Bauters et al., 2011).

Likewise, in literature addressing robotic parts-to-picker OPSs, throughput has been regarded as important to evaluate as a factor of system performance. For example, Bauters et al. (2016), who compared the performance of an RCSRS and AS/RS in terms of throughput, have proposed that an RMFS's throughput is affected by the number of robots and SKUs per rack. The following year, Lamballais et al. (2017) revealed that the throughput of RMFSs is also affected by how workstations are situated around the storage area, while Beckschäfer et al. (2017) found that throughput in RCSRSs varies depending upon the storage policies in place. In other work on the topic, Zou et al. (2016) compared the throughput of an RCSRS to that in a manual OPS.

2.4.2 Order lead time

Particularly important in warehouses, especially in e-commerce and distribution warehouses, *order lead time* refers to the time from when a customer places an order until he or she receives it (Yang and Chen, 2012). Alternatively, *order lead time* can be defined as the time from an order's placement to its shipment (Yang, 2000). Whereas the former definition reflects the perspective of the customer, the second reflects the perspective of the warehouse.

In literature on automated OPSs, authors have used various terms to describe time-related aspects of performance in such systems, including *order picking time* (Yanyan et al., 2014; Lenoble et al., 2018; Zou et al., 2018), defined as the time spent picking items for an order line (Staudt et al., 2015). Others include *order retrieval time*; *order flow time*, also called *order fulfilment time*, *order cycle time* and *order processing time*, meaning the time required to complete an order (Andriansyah et al., 2010); and *job sojourn time*, meaning the time from when a job is requested to the job's completion (Park and Rhee, 2005). At the same time, de Koster et al. (2007) have conceived throughput in relation to time and called it *throughput time*, which is the time to complete an order or a number of order lines. Throughput time reduction is often an objective in warehouse design and optimisation (de Koster et al., 2007). In this thesis, the category of order lead time encompasses all of those terms, all of which contribute to order lead time.

In literature on robotic parts-to-picker OPSs in particular, aspects of lead time have been investigated by several researchers, including Lamballais et al. (2017), who developed models to estimate the average order cycle time in an RMFS. By some contrast, Xue et al. (2018) compared the impacts of different picking policies on picking time, whereas Zou et al. (2016), who modelled an RCSRS as a semi-open queuing network, compared two storage policies and their influence on the system's performance to reveal that having a single product type in a stack lowers throughput time.

2.4.3 Human factors

Although human factors and ergonomics are highly relevant in order picking, little work on evaluating them in automated OPSs or in order picking in general is published. Examples of such work include Dukic et al.'s (2018) study on the ergonomics of a vertical lift module, which they found to be better than the ergonomics of a manual OPS. In literature on robotic parts-to-picker OPSs in particular, Lee et al. (2017) have investigated the ergonomics of an RMFS with focus on posture and task simulation.

Highlighting the importance of human factors to an OPS's performance, Grosse et al. (2017) performed a systematic review of literature on manual order picking and, in turn, a content analysis to identify human factors considered in the literature to date. In the process, they divided human factors into four categories:

- Perceptual (i.e. information processing, reading, and confusion);
- Mental (i.e. learning, forgetting, behaviour, and training);
- Physical (i.e. ergonomics, risk, posture, fatigue, and workload in terms of number of orders, not physical workload); and
- Psychosocial (i.e. motivation, stress, monotony, goal orientation, and time pressure).

Although human factors, especially fatigue, pain, and learning ability, affect the performance of an OPS, how they relate to the design of OPSs remains understudied (Grosse et al., 2017). In response to that oversight, this thesis addresses both mental and physical human factors in assessing an OPS's performance.

2.4.4 Quality

In relation to order picking, *quality* can be defined as the ratio of order lines with errors to completed order lines (Grosse et al., 2017). Alternatively, Staudt et al. (2015) have referred to quality in order picking with the terms *picking accuracy* and *customer*

satisfaction. Whereas *picking accuracy* can mean the accuracy of the order picking process, in which errors may be detected prior to the order's shipment to the customer (Yang and Chen 2012), *customer satisfaction* can mean the number of complaints from customers compared to the total number of orders delivered (Voss et al., 2005), which is a measure often used in distribution warehouses. In this thesis, Grosse et al. (2017) definition of quality is adopted. Despite those clarifications, literature on quality in automated OPSs remains thin.

2.4.5 Flexibility

Flexibility, generally defined as the ability to respond to a changing environment (Beamon, 1999), is essential in environments marked by high variability in demand—for instance, e-commerce and distribution warehouses (Azadeh et al., 2017)—where it is usually associated with time and cost (Staudt et al., 2015). However, similar to quality in relation to performance, flexibility in relation to performance has received exceptionally little attention in literature on automated OPSs, especially robotic parts-to-picker systems (Azadeh et al., 2017).

Amongst researchers who have considered flexibility in order picking, de Koster et al. (2007) have defined *flexibility* as the ability to accommodate changes and uncertainties as well as highlighted its importance in order picking. When it comes to evaluating flexibility, as Staudt et al. (2015) have observed, its measurement depends upon the context and varies according to the researcher's objective. In literature on robotic parts-to-picker OPSs in particular, *flexibility* usually refers to the effort needed for required changes in equipment when adapting to shifts in demand (Heragu et al., 2011; Cai et al., 2014). Azadeh et al. (2017) have discussed the topic in relation to several robotic parts-to-picker OPSs, in which *flexibility* primarily means the ability to cope with changes in volume. In this thesis, the category of flexibility is conceived to modify the relationship between changes in order demand and, in response, the effort needed for necessary changes in the OPS.

2.4.6 Operational efficiency

Operational efficiency is the ability to deliver products or services to customers in the most cost-effective manner when considering the output for each unit of input. Resources utilisation is a common aspect of operational efficiency. Staudt et al. (2015) have discussed the evaluation of operational performance in warehouses especially in terms of resource-related aspects such as labour and equipment or building utilisation, if not both. In other work, space utilisation has been examined in warehouses (de Koster et al., 2007) and shown to be affected by the type of OPS in place (Zou et al., 2016).

In literature focusing on automated OPSs, operational efficiency has emerged as an important aspect to consider in evaluating the performance of the system. In particular, the utilisation of operators and machines has received sustained scholarly attention (e.g. Bozer and White, 1996; Ekren and Heragu, 2010; Cai et al., 2014), whereas picker and machine idle time have been touched upon by Wu and Mulgund (1998). In this thesis, the category of operational efficiency thus includes aspects related to the utilisation of operators, machines, and space.

2.4.7 Investment and operational costs

Decreasing the costs associated with order picking is a dominant objective in most warehouses (Grosse et al., 2017). Gu et al. (2010) have found that the design of a warehouse affects its performance in terms of cost, while Rouwenhorst et al. (2000) and Staudt et al. (2015) have discussed investment and operational costs, including order processing and fulfilment costs, as important to consider when evaluating warehouse performance.

In literature on automated OPSs, few researchers have discussed the relationships between the design and cost of such systems. Amongst them, Lee and Kuo (2008) have investigated how different picking policies affect picking costs in a carousel conveyer system. More broadly, Boysen et al. (2017) have examined the investment and maintenance costs of using robots in an RMFS, whereas Malmberg (2003) has partly investigated the investment and operational costs, where they relate the cost of used robots and equipment to the number of orders processed.

2.5 Design of order picking systems

With reference to the performance categories identified in the previous section as being important to OPSs, this section focuses on the categories of the design of OPSs that can be adjusted to alter their performance. Such categories of design are closely related to answering Research Questions 1 and 2, which focus on identifying the relationships between the performance and design of OPSs. Accordingly, this section first discusses four design frameworks for OPSs from the literature and their categorisations of the areas of design later used to derive the categorisation of those areas for this thesis (Sections 2.5.1, 2.5.2, and 2.5.3). Afterwards, the aspects of each category of design are discussed and defined. As mentioned in the description of its scope, the thesis examines the design aspects in the design process, not the design process itself, and it does not address those aspects at strategic, tactical, or operational levels, either.

Goetschalckx and Ashayeri (1989) have classified aspects affecting the design and operation of OPSs as either external or internal aspects, described below:

- External aspects include issues related to marketing channels that define the OPS-based interaction with suppliers and customers, as well as aspects related to the type and number of products, customer demand (e.g. number of customers and suppliers), supplier replenishment patterns, and inventory levels. As discussed in Section 2.6, all of those external aspects are conceived as contextual ones in this thesis;
- Internal aspects include policy about warehouse layout, equipment selection, and storage at the strategic level, as well as batching and picking policies at the operational level. Other internal aspects are the type of command cycle (i.e. single, dual, or multiple), the dimensionality of the warehouse (e.g. number of coordinates for each storage location), mechanisation level (i.e. manual, mechanised, semi-automated, or fully automated), and the availability of information about picking and batching sequences.

Ultimately, Goetschalckx and Ashayeri's (1989) classification suggests that the complexity of a warehouse's design intensifies as the level of automation increases.

Choe and Sharp (1991) have discussed the operation and design of small parts OPSs and identified areas of design relevant to consider when developing such systems. Those areas are:

- Equipment selection (i.e. storage and retrieval equipment, accumulation and sortation equipment, handling equipment, and auxiliary equipment);
- Operating strategies (i.e. storage policies, picking strategies, accumulation and sortation strategies, and packing policy); and
- Determination of the physical layout and dimensions (i.e. spatial requirements and efficient layout strategies).

According to Choe and Sharp (1991), the spatial requirements are complex because they are influenced by all issues associated with order picking. Determining the physical layout and dimensions contains two major steps: first, estimating peak and average inventory levels, and second, accommodating them within the limitations of the space (Choe and Sharp, 1991). They have also described the layout of an OPS as containing the layout of the facility with the system and the layout of elements within the system itself (Choe and Sharp, 1991).

Yoon and Sharp (1996) have proposed a procedure for designing OPSs in which factors of their design are operating strategies, system alternatives, environmental and economic constraints, material properties, and transaction data. To organise those factors, they developed a general design procedure consisting of three stages:

- The input stage, which involves identifying environmental (e.g. ceiling height) and economic constraints (e.g. payback period) upon the design process, all of which are conceived as contextual aspects in this thesis, as detailed in Section 2.6;
- The selection stage, which involves the specification of types of equipment and operating strategies; and
- The evaluation stage, which involves evaluating one or several alternatives to OPSs while taking into account the desired performance of the system.

Rouwenhorst et al. (2000) have developed a framework for designing and controlling warehouses. In relation to order picking, categories of design considered in the framework are picking equipment selection, area layout, and picking operational strategies. Furthermore, the authors have divided the relevant aspects in OPS design into strategic, tactical, and operational ones (Rouwenhorst et al., 2000) described below:

- Strategic aspects of design include decisions with long-term impact and are often associated with high investment costs. In order picking, such decisions address the type of warehousing system; for example a sorting process might be needed in order to batch and sort orders, which would require a sorter system;
- Tactical aspects of design include mid-term decisions with a less significant impact than strategic decisions; nevertheless, they should not be reconsidered often, because they account for some investment costs. In order picking, such decisions address the layout of the picking area, the storing and picking equipment, the peripheral equipment, and the workforce capacity. If batches are used, then batch size should be considered in such decisions as well;
- Operational aspects of design include decisions with only short-term impact, most of which are policy-related aspects such as batch formation, order sequencing, the assignment of picking tasks to order pickers, and the sequencing of picks per order.

All four frameworks for OPS design share several categories and aspects of design, and with reference to them, three categories of design were derived for this thesis, as depicted in Figure 2.6 and described in Sections 2.5.1, 2.5.2, and 2.5.3.

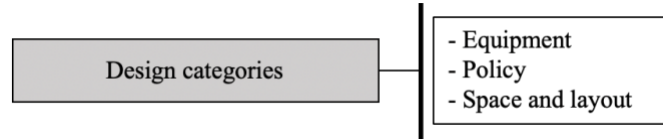


Figure 2.6. Categories of design identified in literature

2.5.1 Equipment

In the context of the design of OPSs, *equipment* refers to devices used in storage and retrieval as well as for picking activities at the picking station, including the screens used to show the order and packing details and the information system (e.g. pick to light systems). The equipment in automated OPSs are linked to the performance, where many design aspects are found to have an effect on the OPS performance. For example, the number of storage and retrieval devices are seen to moderate the performance (Andriansyah et al., 2011). As Medeiros et al. (1986) found, the speed of storage and retrieval equipment also influences picking performance, and as Khojasteh and Son (2008) and Chiang et al. (1994) have both found, rack shape and configuration affect order picking performance in particular. In robotic parts-to-picker OPSs, specifically RMFSs, the number of robots used, as investigated by Boysen et al. (2017) is found to affect the system's performance.

2.5.2 Policy

In the context of the design of OPSs, policy encompasses the storage policies, picking policies, batching policies, and routing policies that guide an OPS. Whereas storage policies concern the assignment of items to storage positions in the order picking area (Glock and Grosse, 2012). Picking policies concern the sequence of how individual items are picked for a single order and usually seek to reduce the picking time or picking travel distance required (Goetschalckx and Ashayeri, 1989). Batching policies concern the consolidation or splitting up orders to improve performance, which can entail the assignment of items to picking tours (Bozer and Kile, 2008). Last, *Routing policies* are dealt with by many researchers (Hwang et al., 2004; Manzini et al., 2006; Su et al., 2009), defined as the sequence in which an order picker or equipment retrieves items from shelves in the storage area.

Policies in automated OPSs directly affect the performance of the systems. Indeed, the effects of storage policies on their performance have been investigated by many researchers (e.g. Medeiros et al., 1986; Bozer and White, 1996; Manzini et al., 2006; Ramtin and Pazour, 2015; Battini et al., 2015), as have those of batching policies (Hwang et al., 1988; Lenoble et al., 2018). Moreover, Chang et al. (1993), Mahajan et al. (1998), Lee and Kuo (2008), Mahajan et al. (1998), Manzini et al., (2006) and Liu et al. (2015) have all studied how picking policies influence an OPS's performance.

In robotic parts-to-picker OPSs, several aspects of design have been found to affect the performance of the systems. Regarding RMFSs, Xue et al. (2018) have investigated the

effect of picking policies, Zou et al. (2018) the effect of battery-charging policies, and Kumar and Kumar (2018) the effect of robot routing. Furthermore, Roy et al. (2019) investigated the robot assignment policies such as adopting a dedicated (i.e. single command) or a pooled robots (i.e. dual command) assignment policy where robots may be pooled to perform both order picking and replenishment processes, it is found that the robot assignment policy affects both throughput and throughput time (Roy et al., 2019). By contrast, concerning RCSRSs, Beckschäfer et al. (2017) and Zou et al. (2016) have evaluated the effects of different storage policies on performance. Moreover, dwell point policies which are related to the decision of where the robot should be positioned when idle have been investigated by Roy et al. (2015). Beckschäfer et al. (2017) studied the effect of the retrieval policy which concerns the selection of the next available bin in an RCSRS on performance and finds that an empty retrieval policy allows for better performance than an adding retrieval policy in terms of throughput and replenishment rate. The empty retrieval policy prioritises the empty bins or bins with lowest number of items, and the adding retrieval policy prioritises the bins with enough capacity to fulfil an order.

2.5.3 Space and layout

The category of space and layout in relation to an OPS's design refers to the space used and design of the layout. In the order picking area, the layout determines the number of blocks therein, as well as the number, length, and width of aisles in each block (Roodbergen et al., 2015). Bauters et al. (2011) have formulated guidelines for selecting automated OPSs (i.e. parts-to-picker OPSs) that consider the floor space needed by the system. Concerning the design of the layout, Medeiros et al. (1986) have studied the effects of the layout of aisles on performance, whereas Khojasteh and Son (2008) have observed the effect of the number of aisles. In robotic parts-to-picker OPSs in particular, the layout of the picking area has been found to affect the system's performance as well (Chiang et al., 1994).

2.6 Context of order picking systems

Although several authors have acknowledged that an OPS's performance depends upon its context (e.g. Goetschalckx and Ashayeri, 1989; Choe and Sharp, 1991; Yoon and Sharp, 1996; Baker and Canessa, 2009), research on that relationship, especially in automated and robotic parts-to-picker systems, remains relatively scarce. However, because the contextual aspects of an OPS's performance need to be understood in order to answer Research Question 3, this current section discusses those aspects and their various categorisations in the literature, all of which were used to derive their categorisation applied in this thesis, as illustrated in Figure 2.7. As stated in Section 1.1, in this thesis contextual aspects are considered to be factors beyond the control of an OPS's designer but that can nevertheless affect the performance of the OPS. Because the range of possible contextual aspects is vast, the categorisation used in this thesis should not be viewed as a complete list of such aspects but of the ones identified in literature on order picking thus far.

Referring to contextual aspects as strategic factors, Choe and Sharp (1991) have characterised those aspects as being beyond the control of a system's designer but as affecting the system's performance, nonetheless. To organise the contextual aspects, they classified them into three categories: the system profile, the order profile, and the item

profile. More recently, Baker and Canessa (2009) have discussed sets of contextual aspects—that is, checklists—that a warehouse designer needs to consider and that practitioners often use. Those aspects have been divided into several activity profiles, including customer order profiles (e.g. number of orders), item details profile (e.g. item popularity), inventory profile, calendar profile, activity relationship profile, and investment profile (Baker and Canessa, 2009).

Based on the discussed classifications, this thesis distributes the contextual aspects into system, demand, and item profiles, as presented in Sections 2.6.1, 2.6.2, and 2.6.3 respectively.

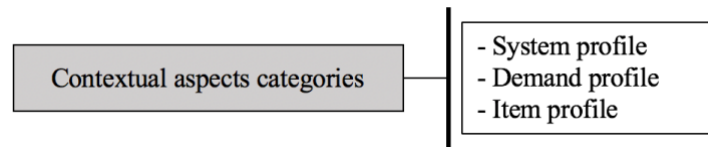


Figure 2.7. Categories of contextual aspects identified in literature

2.6.1 System profile

The system profile encompasses long-term aspects (Choe and Sharp, 1991), including the type and number of suppliers as well as the type and number of customers (Goetschalckx and Ashayeri, 1989). Also in the profile are safety standards and the safety of operators, as discussed by Marchet et al., (2015) and Li et al. (2012), respectively. Last, warehouse height has been found to affect order picking performance, as discussed by Ekren and Heragu (2010) and Yoon and Sharp (1996).

2.6.2 Demand profile

The demand profile clusters aspects related to customer demand and the picking order (Choe and Sharp, 1991) which affects the OPS performance directly or affects the OPS design which in turn affects its performance. Such aspects can be the volume of orders, the number of lines per order, and the quantity of items per order line (Choe and Sharp, 1991). In addition whether seasons of high and low demand exist in the company.

The relationships between contextual aspects and an OPS's performance have been recognised by Baker and Canessa (2009), who have discussed the effect of changes in the demand profile on the system's performance, especially in terms of flexibility. That same year, Andriansyah et al. (2009) proposed a simulation model for a conveyer-based OPS to predict not only the mean and variability of order flow times but also how the distribution of order sizes affect flow times. Andriansyah et al. (2010) examined the effect of the number of SKUs on the system's performance. Later, Yanyan et al. (2014) have proposed a method of selecting types of OPSs using a conveyer versus a carousel, particularly with reference to the density and quantity of customer orders and based on their effect on order picking time. Most recently, Khojasteh and Jae-Dong (2016) have developed a heuristic to minimise machine travel time in an AS/RS and studied the relationship between the number of items in an order and machine travel time.

2.6.3 Item profile

An item profile represents the physical characteristics of items to be picked, including their size, weight, and shape, all of which Yoon and Sharp (1996) have underscored as pivotal to understand. For example, small items are more easily picked in an RCSRS than in other OPSs, and such systems can achieve outstanding performance as a result (Huang et al., 2015).

2.7 Synthesis of the framework into a conceptual model

Given the thesis's purpose, as presented in Section 1.2, to determine how an automated OPS's context and design affect its performance, this section presents the synthesis of the theoretical framework previously outlined in the chapter into a conceptual framework. Shown in Figure 2.8, the framework has been used to organise the results of the research presented in Chapter 5.

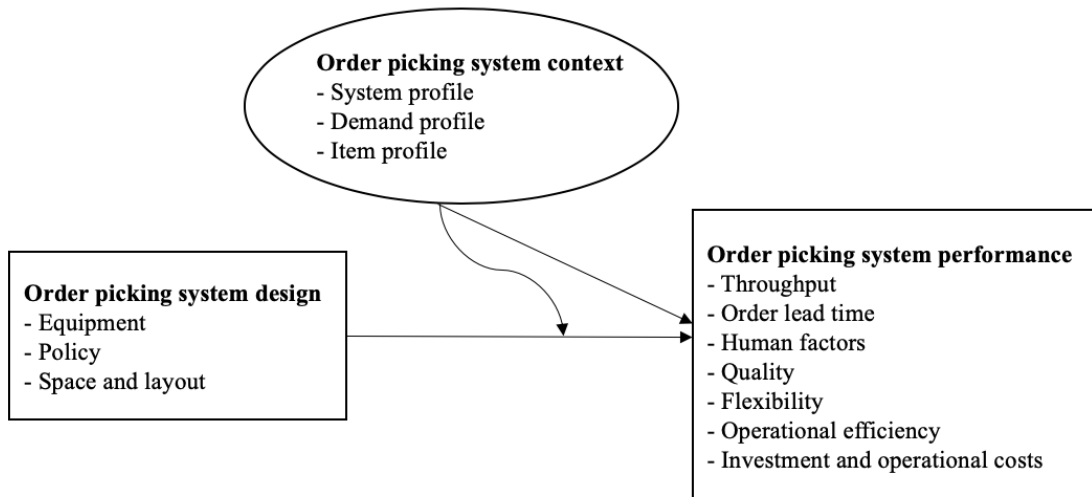


Figure 2.8. Derived framework of how an order picking system's design and context affect its performance

3. Methodology

This chapter presents the research methods applied in the three studies, each respectively reported in the three appended papers, as well as the motivation for using those methods. To begin, Section 3.1 describes the research process, after which Section 3.2 explains the overall research design, the selection of research methods, data collection and data analysis used in each study. Last, Section 3.3 discusses aspects of the quality of the research conducted.

3.1 Research process

The research presented in this thesis was performed as part of the Automation of Kitting, Transport and Assembly (AKTA) project financed by VINNOVA and undertaken from October 2016 to January 2019. The project represented a collaborative effort between Chalmers University of Technology and several Swedish industrial partners, including original equipment manufacturers, their suppliers, developers of automation systems, and a third-party logistics provider. The author was not involved in the project from the beginning but joined in the second quarter of 2017, at which time three studies were conducted. Whereas the first, Study 1, was a systematic literature review, Study 2 involved a multiple-case study: one of a third-party logistics provider, the other of a distribution warehouse. Last, Study 3 involved a single-case study of a different third-party logistics provider. Figure 3.1 presents the timeline of the research performed study by study as well as each study’s underlying phases.

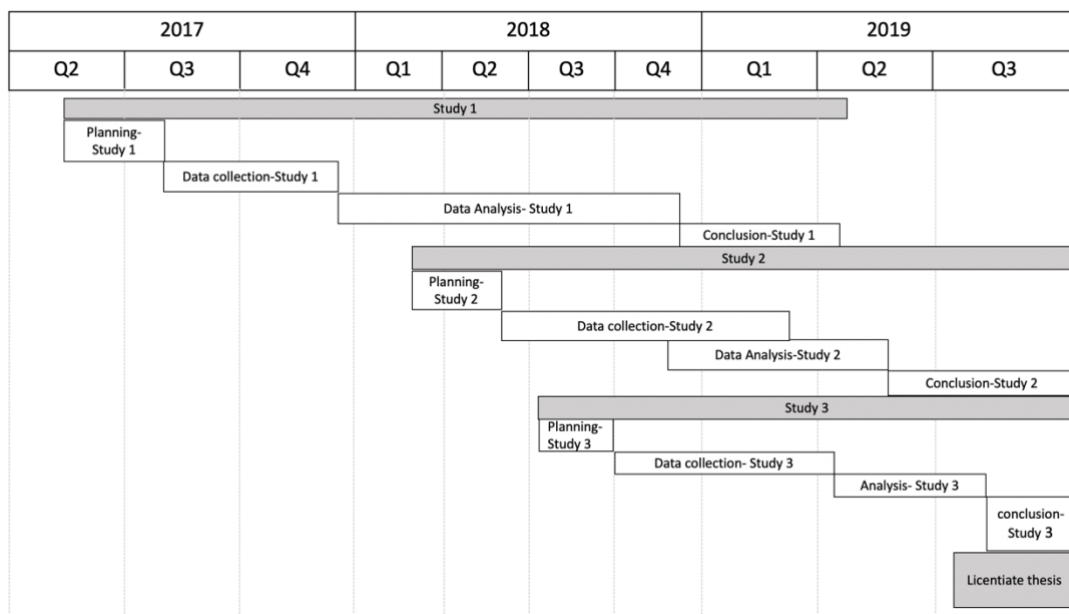


Figure 3.1. Timeline of the research process

From the project focus on the automation of kitting, transport and assembly, in addition to discussions with the industrial partners, and, not least, reviewing relevant literature all indicated that the problem of automation in order picking remains a relevant topic of inquiry for both researchers and practitioners. Accordingly, Study 1 focused on automated OPSs taking into consideration several OPS types (Figure 2.2). As a result, the study revealed that research on robotic parts-to-picker OPSs has emerged in the past 3

years. The same finding was confirmed during discussions with industrial experts, who generally expressed the need for additional knowledge on the performance of robotic parts-to-picker OPSs, particularly owing to their intensified practical application in recent years. By extension, after a preliminary analysis of Study 1’s findings, Research Questions 2 and 3 were developed for Studies 2 and 3. For that reason, Study 1 did not focus exclusively on robotic parts-to-picker OPSs, whereas Studies 2 and 3 did. The narrowing of the research focus to robotic parts-to-picker OPSs is depicted in Figure 3.2 in order to clarify the focus of the studies before and after Study 1.

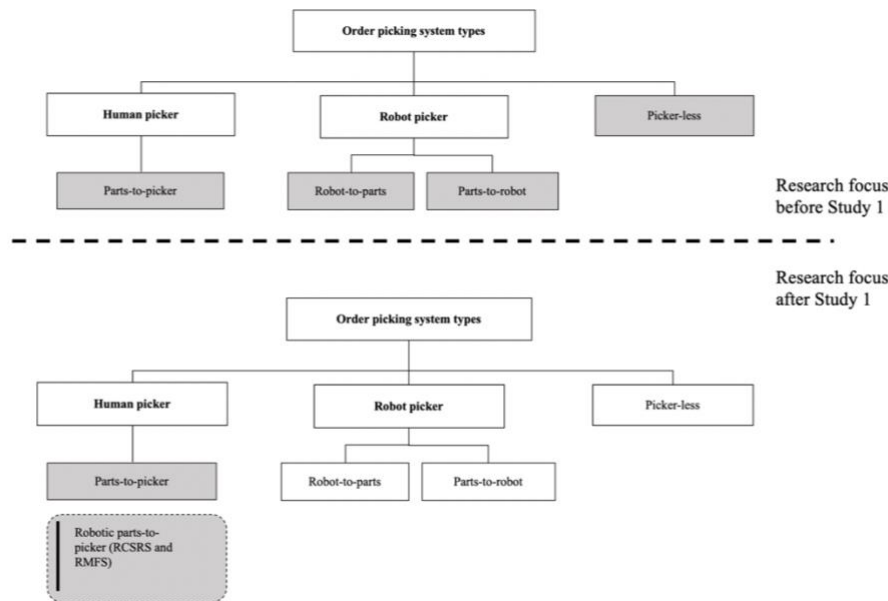


Figure 3.2. Focus of the research before and after Study 1 (highlighted in grey)

Despite the shift in focus, Study 1 nevertheless contributed to the examination of robotic parts-to-picker OPSs by identifying gaps in knowledge on the topic and by providing an overview of the extent to which the literature has addressed each performance-related category (Section 2.4).

3.2 The three studies

This section describes the research design, the used research methods, data collection and data analysis used in each of the three studies, after which it describes aspects of the quality of the research conducted.

3.2.1 Research design

According to Maxwell (2012), a research design typically includes the components: research questions as the central point in research, research goals, a conceptual framework, research methods, and the research validity. The interaction and coherence of those components are described in the following sections in terms of how the research in each of the three studies was conducted. Figure 3.3 visualises the three corresponding papers written about the studies and which papers helped to answer which research question.

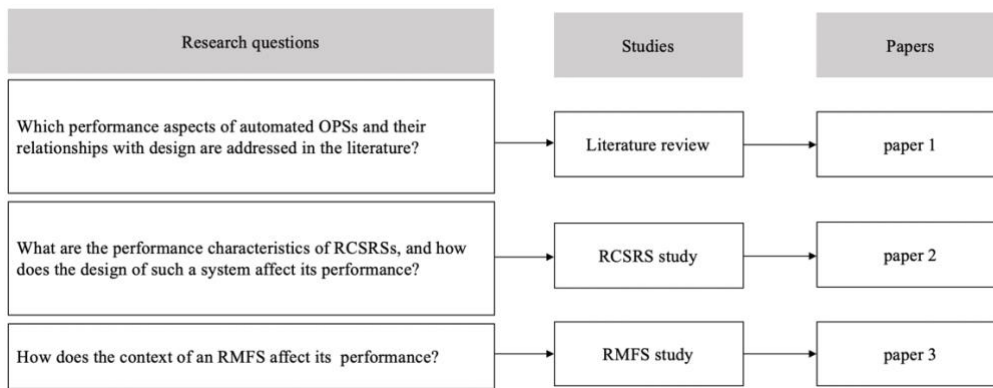


Figure 3.3. The research design

3.2.1.1 Research design of Study 1

Despite the abundance of literature addressing automated OPSs and focusing on certain aspects of their performance or micro-level problems, the literature lacks an overview on which types of automated OPSs have been examined to date, their performance aspects, and the relationships between their design and performance. In response to that shortcoming, a systematic literature review was chosen in Study 1 to summarise academic knowledge about automation in order picking and to provide a structured overview of the studied types of OPSs in literature, aspects of their performance, and the relationships between the systems performance and their designs studied this far. Moreover, Study 1 identified gaps in research on automated OPSs which partly motivated Studies 2 and 3.

The method of the systematic literature review, as proposed by Denyer and Tranfield (2009), was adopted in Study 1 to ensure a scientific, transparent approach and support the study's reliability and validity. Compared to a traditional literature review, a systematic literature review, characterised by objectivity, systematicness, and transparency. Prior to the systematic literature review, a research protocol was developed that included a detailed description of how the review should be conducted (Denyer and Tranfield, 2009). To minimise bias in the review process, the protocol prescribed the coding of all papers reviewed according to their purpose, author, year, and the frame of reference. Afterwards, descriptive and content analyses were performed. The systematic literature review formed the basis for a paper presented at the PLAN conference in October 2017 and later developed into a journal article manuscript submitted to the *International Journal of Production Research* in May 2019 and appended to the thesis.

3.2.1.2 Research design of Study 2

Although Study 1 revealed an increase in the number of studies addressing robotic parts-to-picker OPSs, research focusing on the performance of RCSRSs appears to be relatively limited, with only a few studies on such systems (e.g. Zou et al., 2016; Beckschäfer et al., 2017). However, identifying and understanding the relationships between the design and performance of RCSRSs is pivotal for an effective use and design of those systems. In response both to that gap and to increased interest amongst industrial actors in evaluating such systems, Study 2 involved investigating the performance of RCSRSs in order to elucidate their performance characteristics in terms of throughput, quality, flexibility, lead time, human factors, operational efficiency, and investment and operational costs (Section 2.4). The study particularly focused on pinpointing the relationships between

those categories of performance and the design of RCSRSs in terms of space and layout, policies, and equipment (Section 2.5).

From the review of some literature on the design and performance of OPSs (e.g. Goetschalckx and Ashayeri, 1989; Rouwenhorst et al., 2000; Staudt et al., 2015), a framework of the design- and performance categories was derived that was later used to structure the literature review and support data collection and analysis. A literature review on robotic parts-to-picker OPSs, including RCSRSs, RMFSs, and autonomous vehicle storage and retrieval systems (AVS/RSs), was conducted by following the performance categories identified in the framework and resulted in the formation of a matrix of relationships between the performance and design of RCSRSs. Given the various design options available for such systems and to identify additional relationships between their design and performance, a multiple-case study was undertaken to clarify the performance characteristics of RCSRSs and complement the derived matrix as a means to answer Research Question 2. After all, according to Yin (2017), the “how-questions” can be more suitably answered with case studies. The preliminary results of the case study were presented at the EurOMA conference in June 2018. After constructive feedback was received at the conference, supplementary data were gathered, another case study was added, and additional refinements to the paper were made, which is appended to this thesis.

3.2.1.3 Research design of Study 3

Research on robotic parts-to-picker OPSs has increasingly paid attention to the performance of RMFSs (e.g. Bauters et al., 2016; Lamballais et al., 2017; Roy et al., 2019), which is in line with the findings of Study 1. However, contextual aspects that need to be considered when designing an RMFS and that affect its performance have been largely disregarded in existing literature. Because identifying the relationships between the performance and context of an RMFS is important when making decisions about its design, Study 3 focused on pinpointing how the context of RMFSs impact the RMFSs performance.

Owing to the need for an in-depth investigation into how the context of OPSs influences the performance of RMFSs, a single-case study was selected for Study 3. A review of literature on order picking revealed performance (Section 2.4) and context categories (Section 2.6) that were used to analyse the data and identify the relationships between the context and performance of RMFSs. An earlier version of this study was presented at the INCOM IFAC conference in 2018, after which additional data and further analysis were compiled to a paper, which is appended to this thesis.

3.2.2 Research methods

This section describes the methods used in the studies. Section 3.2.2.1 details the search and selection of studies for the systematic literature review. Case research is selected for Studies 2 and 3, Section 3.2.2.2 presents the multiple-case study undertaken in Study 2, and Section 3.2.2.3 presents the single-case study undertaken in Study 3. According to Yin (2017), in case studies, the generalisation of findings by way of theoretical propositions is performed analytically instead of statistically. And generalising results through multiple-case studies should be dependent on a replication logic (Voss et al., 2002).

Accordingly, this section describes how the studies location and selection in the systematic literature review study was performed, how the replication logic was used in the case selection procedure in study 2, and the unique characteristics of the single case in study 3.

3.2.2.1 Research methods in Study 1

The systematic literature review in Study 1 was conducted to review the academic knowledge on the performance of automated OPSs. A theoretical goal of the first study was to summarise the academic knowledge in order to contribute to an overview of the body of knowledge on the topic, including the relationships between the performance and design of automated OPSs.

According to the research method for a systematic literature review proposed by Denyer and Tranfield (2009), locating and selecting published works relevant to the research's scope should follow the formulation of research questions. To ensure broad coverage on the topic of automation in OPSs, the Scopus database was selected for the literature search, because it hosts the majority of literature available from scientific journals and conferences in the area. Afterwards, to reflect the research's focus on automation in OPSs, the following search terms were used:

- Auto* and “order picking” OR Robo* and “order picking”;
- Robo* AND “order picking”;
- Parts to picker;
- Robot to picker;
- Auto* AND “order fulfilment” OR “order fulfilment”; and
- Robo* AND “order fulfilment” OR “order fulfilment”.

The search terms were sought in the abstracts, titles, and keywords of available literature in a bid to yield published works dedicated to automation in OPSs, not ones that only briefly mention the topic.

Next, literature was selected with reference to selection criteria (SC) for the inclusion and exclusion of papers. Reflecting aspects of Research Question 1, such SC primarily focused on the content of papers (Denyer and Tranfield, 2009). In reviewing the titles, abstracts, and, if needed, the full text of papers, three SC were applied:

- SC1: Papers had to be English-language conference papers or journal articles published before 2018;
- SC2: Duplicate papers were excluded; and
- SC3: Relevant publications were included. In their titles or abstracts, publications needed to mention at least one type of automated OPS and at least one aspect of their performance. That criterion prompted the exclusion of irrelevant works, including ones (1) not dealing with a certain type of automated OPSs, (2) without any aspect of performance identified, or 3) focusing only on the design of a particular material-handling part or a new technology in equipment (e.g. carousel rack dimensions or unit load sizes for automated guided vehicles (AGVs) or sensor types in particular robots). In light of SC3, some papers were removed following their complete review.

3.2.2.2 Research methods in Study 2

Due to the lack of empirical identification on the RCSRSs performance characteristics and how the design of an RCSRS impacts the system's performance, an exploratory theory-building approach was adopted (Eisenhardt and Graebner, 2007). A multiple-case study approach was used in Study 2, because multiple-case studies are considered to be suitable for investigating questions about how contemporary events occur (Yin, 2017; Voss et al., 2002). A literature review was conducted at the beginning of Study 2 in order to identify relevant performance and design categories that could guide data collection for the study. From the literature review, a matrix of relationships between design and performance in robotic parts-to-picker OPSs was derived that later guided both data collection and data analysis.

To accommodate the objective of theoretical replication and in line with the purpose of Study 2, two cases involving RCSRSs in order picking applications in a delivery- to-customer context were selected. Both cases were chosen to reflect the contrast in the design of RCSRSs. Whereas the first case—Company A— have fewer robots in the system, fewer bins and articles, and fewer order picking and replenishment stations. And company B—involve a relatively high number of robots, bins, and articles in the grid, along with a relatively high number of order picking and replenishment stations. Moreover, the cases differed in terms of the demand and picking profiles, especially in terms of the number of order lines per day and average lines per order. In particular, Company A is a third-party logistics provider that has installed and is currently operating an RCSRS for one of its customers that sells a range of products, including tools and machining instruments, via e-commerce. By contrast, Company B is an e-commerce and distribution warehouse. Table 3.1 presents an overview of the two selected cases, including differences between them concerning the design of their RCSRSs and concerning contextual aspects of their demand and order profiles.

Table 3.1. Characteristics of case companies in Study 2

| Aspect of context or design | Company A | Company B |
|---|-----------------------|---|
| Warehouse area | 28,000 m ² | 42,000 m ² |
| Storage free height | 11.5 m | 10 m |
| Ceiling height | 14 m | 13 m |
| Number of bins | 69,000 | 151,000 (only large bins) |
| Number of robots | 52 | 114 |
| Number of order picking stations | 10 | 17 |
| Number of replenishment stations | 5 | 7 |
| Number of articles | 34,000 | 266,000 |
| Average number of orders per day | 2650 | E-commerce: 3000 Stores: 650 Total: 3650 |
| Number of order lines per day | 12,000 | E-commerce: 5400 Stores: 78,000 Total: 83,400 |
| Average number of order lines per order | 4.5 | E-commerce: 2 Stores: 120 |
| Average number of picks per order line | 4 | Unknown |

3.2.2.3 Research methods in Study 3

To explore the relationships between the context and performance of an RMFS, Study 3 relied upon a single-case study of a third-party logistics provider that employs an RMFS in picking to customer in an e-commerce setting.

According to Yin (2017), single-case studies allow researchers to question old theoretical relationships and explore new ones, which aligns with Study 3's purpose of exploring the relationships between the context and performance of an RMFS. Yin (2017) has added that the rationale for conducting a single-case study should be to accommodate a critical case, a unique or extreme case, a representative or typical case, a revelatory case, or a longitudinal case. Along those lines, the selected case was considered to be a representative one, as the RMFS could be considered typical of RMFSs regarding the number of items stored in the system and the system's size.

Regarding the case characteristics, the inventory pods had different configurations to handle goods of different dimensions. However, all of them had the same basic configuration: essentially, they consisted of small shelf section, with slots for goods on both sides. In total, the RFMS had a capacity of approximately 67,000 slots for storing goods. Approximately 30,000 SKUs were handled in the RMFS, which included 68 robots and 1,550 inventory pods.

3.2.3 Data collection

This section explains the process of collecting data for the three studies. Section 3.2.3.1 describes the data collection used in Study 1, the systematic literature review, whereas Sections 3.2.3.2 and 3.2.3.3 describe the respective processes of data collection used in Studies 2 and 3, the case studies, for which Yin (2017) has recommended consulting several sources of evidence, including interviews, archival records, and observations.

3.2.3.1 Data collection in Study 1

In Study 1, a total of 766 results were returned for all of the search strings used. After SC1 was applied, 734 journal articles and conference papers remained. After removing duplicate works according to SC2 527 were left to be further examined for selection. Next, in applying SC3, the abstracts were read, which left 81 works for full review, and once their full texts were read, 14 additional papers determined to be irrelevant to the study's scope were removed. Ultimately, the remaining 67 works were included in the literature review. Figure 3.4 summarises the data collection process conducted in Study 1 and the SC applied therein.

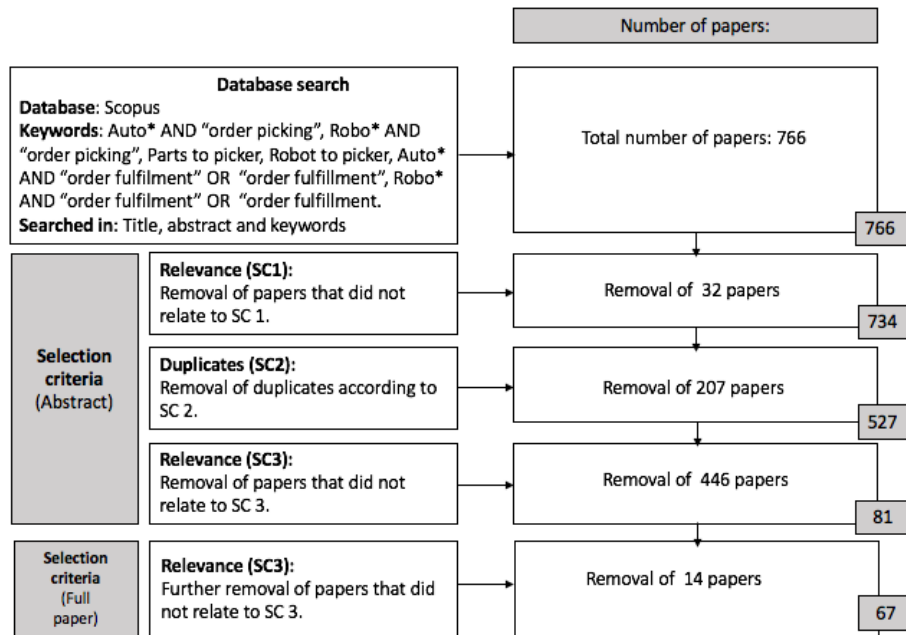


Figure 3.4. Overview of the data collection process and selection criteria applied in Study 1

3.2.3.2 Data collection in Study 2

To scrutinise the operations and components of the RCSRSs at the case companies, site visits involving direct observation were conducted at the outset of each case study. Subsequently, semi-structured interviews were conducted with representatives of the case companies and the provider of the RCSRSs.

At Company A, a phone interview was conducted with the person responsible for the RCSRS's installation and operation as well as with the performance manager, who has several years of experience working with the RCSRS. At Company B, a face-to-face interview with the leader of the department managing the RCSRS was performed. Along with those interviews, the RCSRS provider for both case companies was interviewed over the phone. Whereas the interview at Company A lasted 90 minutes in total, the interview at Company B lasted 120 minutes, and the interview with RCSRS provider lasted 60 minutes. The interviews with Company A and the system provider were led by the author, with the presence of another researcher who listened to the conversations and expanded upon key points to be considered. Conversely, the interview at Company B was conducted and led solely by the author.

All interviews were semi-structured in order to allow for extended discussions and the exploration of additional aspects regarding the performance and design of RCSRSs. The interview questions were divided into themes corresponding with the framework derived from the literature: throughput, lead time, flexibility, quality, human factors, operational efficiency, and investment and operational costs. An interview template was sent to each interviewee before the interview to allow him or her to preview the questions. The template began with open-ended questions, followed by more specific questions. The semi-structure nature of the interviews and the open-ended questions enabled the interviewees to answer the questions without being led in a specific direction, which increased the study's internal validity (Yin, 2017). All interviews were audio-recorded

and, once completed, transcribed within a few days. To increase the study's validity, the interviews results and analysis were sent to the interviewees for verification.

3.2.3.3 Data collection in Study 3

In Study 3, several interviews were conducted at a case company whose RMFS had been in operation for approximately 3 years, during which time it had been possible to learn about the system's operational performance. The interviewees were responsible for the introduction and operation of the RMFS at the company, and an interview with the RMFS provider was performed as well.

In connection with those interviews, site visits at the case company were also conducted, and observations were made of the system's components and operation. At a later stage of data collection, another site visit at the company was performed, at which time data about the RMFS's performance were collected from historical records. In conjunction with the site visits, complementary interviews were conducted as well, the purposes of which were to clarify the performance and context of the RMFS in greater detail and to confirm the interpretation of the data collected from the company's records.

An interview template was sent to each interviewee before the interviews to allow him or her to preview the questions. To facilitate discussion about the performance and context of the RMFS, all interviews were semi-structured and conducted face-to-face with two researchers. Afterwards, to increase the study's validity, the researchers' notes from the interviews were sent to the respective interviewees for verification.

3.2.4 Data analysis

This section summarises the process of data analysis employed in the three studies. Section 3.2.4.1 describes the descriptive and content analyses performed in Study 1 (i.e. the systematic literature review), whereas Sections 3.2.4.2 and 3.2.4.3 describe the analyses performed in Study 2 (i.e. the multiple-case study) and Study 3 (i.e. the single-case study), respectively.

3.2.4.1 Data analysis in Study 1

The analysis performed in Study 1 included breaking down individual literature into their constituent parts and describe how each relates to the other, as advised by Denyer and Tranfield (2009). The findings of the systematic literature review thus stemmed from two steps (Figure 3.5):

- Descriptive analysis, in which papers were categorised by their year and type of publication; and
- Thematic content analysis, which was performed in two sub-steps:
 - Content analysis, in which papers were analysed in terms of themes based on the type of OPS (Figure 2.2); and
 - A second round of content analysis, in which papers were analysed in terms of aspects of performance being studied (Section 2.4) and their relationships to aspects of design (Section 2.5).

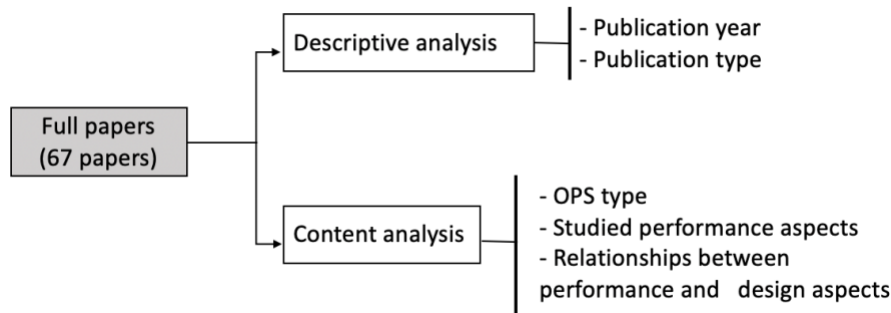


Figure 3.5. Process of literature analysis in Study 1

3.2.4.2 Data analysis in Study 2

Once some literature focusing on the performance and design of order-picking was reviewed, a framework of the categories of performance and design relevant in order-picking was developed, as detailed in Paper 2, to serve as a basis for data collection. The framework also served to structure the literature review on robotic parts-to-picker OPSs, which resulted in a matrix of relationships between the performance and design of robotic parts-to-picker OPSs. The performance categories of OPSs were throughput, lead time, human factors, quality, flexibility, operational efficiency, and investment and operational costs, whereas design categories were equipment, policies, and the space and layout of the order picking area.

Data from the case studies were analysed in three stages. In the first stage, the data collected through interviews were analysed based on its content following the performance categories to support the understanding of the system's performance characteristics. In the second stage, within-case analysis involved investigating the data for each case in an effort to probe the relationships between the system's design and performance and, in turn, complement the matrix derived from the literature. In the third stage, the findings were compared between the cases, and differences between the performance characteristics of the RCSRSs were identified and assessed with reference to the systems' specifications and expectations.

3.2.4.3 Data analysis in Study 3

According to Stake (2000), the in-depth analysis of single cases can reveal many facets of a phenomenon under study. In turn, exploring the relationships between the context of an RMFS and the associated performance of the system requires an in depth analysis of the performance characteristics. To facilitate such an analysis for Study 3, a review of literature in the order picking area was conducted to identify the studied performance categories in literature. A framework of context-related aspects was also developed with reference to the literature and organised according to the demand profile, order profile, and item profile, as detailed in Paper 3.

The aspects of performance identified and the framework developed were used to aid data collection and support data analysis. Data from the case study were analysed in two stages. The first stage involved analysing the collected data in terms of the RMFS's performance—that is, according to throughput, lead time, human factors, quality, flexibility, operational efficiency, and investment and operational costs. In the second

stage, a more detailed analysis was conducted to link those performance categories with the context of the RMFS, which was done with reference to the framework of context-related aspects derived from the literature.

At a future stage of the study, additional data will be collected, and a refined analysis will be performed, both to further explore the relationships between the performance and context of the RMFS.

3.3 Research quality

This section presents considerations of the quality of the research conducted in the three studies. Section 3.3.1 explains those considerations for Study 1 (i.e. systematic literature review), whereas Section 3.3.2 explains the considerations for Studies 2 and 3—that is, the case studies.

3.3.1 Research quality of Study 1

Denyer and Tranfield (2009) have developed four principles for judging the quality of systematic literature reviews in management and organisation studies: the transparency principle, the inclusivity principle, the explanatory principle, and the heuristic principle.

Denyer and Tranfield (2009) have argued that the aim of documenting the literature review method is not to facilitate replication or the elimination of bias but to achieve transparency, namely in three aspects. First, throughout the review, the steps taken have to be specified, applied, recorded, and monitored (Tranfield et al., 2003). Following those steps, transparency can be achieved by developing a review protocol and clearly reporting methods applied in the literature review (Denyer and Tranfield, 2009). In Study 1 of this thesis, transparency was achieved by creating a protocol for the systematic literature review prior to commencing the study that enabled the author to gain insights later channelled into, for example, the selection of search terms and databases. Moreover, a section detailing the methods applied in Study 1 was included in Paper 1, which delineates the scope and boundaries of the research and provides a detailed description of the steps followed in the study. Second, the review's findings were presented in a way that elucidates the links between the evidence found and the conclusions and recommendations of the reviewer (Denyer and Tranfield, 2009). The results of the analysis accompanying the systematic literature review have been organised to reflect several categories of the performance and design of OPSs, as well as summarised in tables presenting the performance aspects studied for each automated OPS and the relationships between their design and performance. With reference to those tables, conclusions were reached and recommendations for future research drawn. Third, because the reviewer's prior knowledge of literature might have influenced the literature review (Denyer and Tranfield, 2009), the synthesis of literature strictly followed the inclusion and exclusion SC, and no snowballing of literature was performed, which prevented the selection of certain literature based on the reviewer's prior knowledge or judgement.

Next, the inclusivity principle in systematic literature reviews prescribes satisfying the criterion of being so-called "fit for purpose", which allows for a notion of appropriateness to guide the evaluation of literature under review (Boaz and Ashby, 2003, p.4). Denyer and Tranfield (2009) have recommended justifying the reasons for the inclusion and exclusion of certain literature as a means to increase the review's validity. In Study 1, the

SC formulated for the inclusion and exclusion of published works reflected aspects of Research Question 1, as detailed in Paper 1. At the same time, because the selection of search terms used to find relevant literature bears a direct effect on the search results, using a different set of search terms might have resulted in the inclusion of different pieces of literature. However, because an initial goal in Study 1 was to identify relevant literature, the selected works had to have the term order picking or a certain OPS type in their title, abstract, or keywords to be included in the review.

The explanatory principle concerns going beyond a descriptive reporting of the evidence, and by extension, an explanatory synthesis is considered to be creative as well as active (Pawson, 2006). As such, the synthesis can provide a feasible explanation of the study's findings instead of a replicable explanation (Noblit and Hare, 1988), and the review can include the systematic organisation of data into a format that facilitates summary (Denyer and Tranfield, 2009). To that end, the review process in Study 1 included coding each reviewed paper by year of publication, purpose, performance aspects studied, relationships to the design of OPS, and suggestions for future research. The coding of the literature aided its explanatory synthesis and facilitated summaries of the studied aspects of the performance of each type of automated OPS, in addition to their relationships with the design of the systems.

Last, the heuristic principle describes the outputs of the literature review, which are likely to be rules, suggestions, guidelines, or protocols that allow progressing towards a solution of a problem, instead of providing a detailed solution (Denyer and Tranfield, 2009). Accordingly, in management research, managers are presented with clues, ideas, tools, and methods instead of valid evidence (Denyer and Tranfield, 2009). Therefore, determining the degree to which the findings of a literature review can inform practice is a matter for the judgement of the practitioner. In that light, the literature review in Study 1 offered a clear understanding and overview of the performance and design aspects of various automated OPSs, all of which can be considered to inform and support decision making regarding automation in OPSs.

3.3.2 Research quality of Studies 2 and 3

To assess the reliability and validity of case studies, Voss et al. (2002) have recommended using Yin's (2017) framework, which consists of four elements to be assessed—construct validity, internal validity, external validity, and reliability—as detailed in the four following subsections.

3.3.2.1 Construct validity

Voss et al. (2002, p.211) have defined *construct validity* as “the extent to which we establish correct operational measures for the concepts being studied”. Yin (2017) has stated that construct validity can be attained by using multiple sources of evidence, which should together act as a chain of evidence by making the collected data traceable over a set period. In turn, the traceability of data can be ensured by having key informants' review and approve drafts of the case study report. To ensure construct validity by confirming the relationships between constructs, Voss et al. (2002) have recommended conducting observations.

To ensure construct validity and develop a chain of evidence, similar procedures were adopted in Studies 2 and 3. Site visits were conducted at the outset of each study, during which direct observations were made that partly informed the descriptions made of the cases. Moreover, a case study database was developed for each study by archiving records and formal as well as informal documents (e.g. presentation slides and reports) sent by the companies.

When allowed, all interviews were audio-recorded and, once completed, transcribed within a few days. When audio-recording was not allowed, thorough interview notes were taken throughout the interview and organised directly afterwards. The case study descriptions and interview notes were sent to key informants in the respective companies for review and feedback.

3.3.2.2 Internal validity

Internal validity is defined as the extent to which a causal relationship can be established by demonstrating how certain conditions prompt other conditions (Voss et al., 2002). According to Yin (2017), internal validity can be ensured by matching patterns, constructing explanations, addressing rival explanations, and using logic models. Bearing those considerations in mind, correspondence between findings in the literature and the interviewees' statements was sought, and to mitigate threats to internal validity, pattern matching with literature and developed frameworks was performed. Moreover, findings from the literature and interviews were combined.

The semi-structured nature of the interviews and the open-ended questions enabled the interviewees to answer the questions without being led in a specific direction, which increased the internal validity (Yin, 2017). Moreover, interview data enabled cross-case analysis in Study 2, which strengthened the internal validity as well by highlighting differences between the cases. Some of the difficulties faced during Study 2 were limitations in collecting data about order lead times. However, accessing such data could have enabled a more in-depth analysis of time-related issues in RCSRSSs.

In Study 3, the case study included interviews with representatives from both the provider and the operator of the RMFS—that is, two parties with different perspectives of the system. The fact that both parties were aligned well in terms of their statements further strengthened the validity of the findings.

3.3.2.3 External validity

External validity refers to the extent to which research findings can be applied beyond the scope of the study—that is, *generalisability*. However, generalising findings in case studies has received criticism for not being based on sufficient evidence. In response to that criticism, Yin (2017) has suggested applying replication logic in multiple-case studies. Moreover, the main approach for generalisation in case studies is analytic generalisation to theory by means of propositions (Yin, 2017).

Replication is an approach to increase external validity (Yin, 2017). The case studies included in this thesis do not reflect considerable replication, however, because Study 3 was a single-case study, and Study 2 consisted of only two cases. Studies 2 and 3 involved

deploying pattern matching with the theoretical framework used for case analysis, which strengthened the external validity of the conclusions of both studies.

3.3.2.4 Reliability

In research, reliability refers to the replicability of a certain study, specifically whether its findings could be obtained if the study were replicated by another researcher. According to Yin (2017), a case study's replicability can be ensured by developing a research protocol and database. Such a database was developed and maintained for Study 2 and another for Study 3, in each of which recordings, interview transcripts, and notes were carefully organised and archived. Moreover, a case study protocol was used in each of the studies that served as a template for data collection.

4. Summary of papers

This chapter summarises the three appended papers in order to give the reader an overview of them.

4.1 Paper I

Amid new market developments, the rise of e-commerce, and customers' increased expectations, the use of and interest in automation for order picking have increased as well. Paper I presents a systematic review and content analysis of literature on automated order picking aimed at identifying aspects of the performance of automated order-picking systems (OPSs) and how their design influences their performance. To that purpose, 67 papers were selected and their content analysed on two levels. First, the papers were classified according to the type of OPS studied, which revealed that parts-to-picker OPSs, especially automated storage and retrieval systems, have received the most attention by far, whereas systems employing parts-to-robot or robot-to-parts approaches have been less studied. Second, the papers were analysed according to the performance aspects of OPSs studied and the relationships identified between their performance and design. Despite differences between the types of OPSs, the performance aspects of throughput, order lead time, and operational efficiency have consistently received the most attention. The paper identifies other relationships between design and performance that have been studied as well as relationships that appear to be under-researched. The paper ultimately discusses what the findings imply for future research.

4.2 Paper II

This paper addresses the performance of robotic parts-to-picker order picking systems, particularly robot-based compact storage and retrieval systems (RCSRSs), in order to identify the performance characteristics of RCSRSs and the relationships between their design and performance. The methods involved, on the one hand, a literature review aimed at developing a framework of performance and design areas to support data collection and analysis. The review's results derived the relationships between the design of RCSRSs and their performance, as well as an overview of research on robotic parts-to-picker order picking systems conducted to date. On the other hand, the paper presents two case studies on the implementation and operation of RCSRSs conducted to understand the performance characteristics of RCSRSs and to investigate other relationships between the design and performance of the systems. The paper contributes to the literature by clarifying the performance characteristics of RCSRSs in terms of throughput, quality, flexibility, lead time, human factors, operational efficiency, and investment and operational costs. For practitioners, the results presented in the paper can be applied in designing RCSRSs and determining whether or not to use an RCSRS in a specific context.

4.3 Paper III

This paper addresses the application of automation in warehouse order picking, specifically with robotic mobile fulfilment systems (RMFSs). The literature to date has indicated that RMFSs can benefit several performance areas, although research addressing those benefits in detail has been scarce. Thus, the purpose of the paper is to

identify the performance characteristics of RMFSs and the relationships between them and the context of the RMFSs in which they are applied. The paper includes a review of literature on RMFSs, along with another review of literature on order picking, both undertaken to identify relevant performance and contextual areas to support data collection and analysis. Moreover, the paper presents a case study on the application of an RMFS in the order picking of consumer goods in an e-commerce setting.

5. Results

This chapter presents the results for each research question. Since each study addressed one research question and one paper was developed for each study, as shown in Figure 3.3, the following sections are structured according to the responses to each research question. Section 5.1 responds to Research Question 1, Section 5.2 to Research Question 2, and Section 5.3 to Research Question 3.

5.1 Research Question 1

The first research question consists of two parts and concerns identifying the performance aspects studied for each type of automated OPS (Figure 2.2) and the relationships between each system's design and performance. The first research question is studied by means of a systematic literature review and stated as:

Which performance aspects of automated OPSs and their relationships with design-related aspects are addressed in the literature?

The types of automated OPSs considered, for which details are given in Section 2.2,

- Parts-to-picker OPSs (i.e. AS/RSs, vertical lift modules, conveyers, carousels, and robotic parts-to-picker);
- Robot-to-parts OPSs;
- Parts-to-robot OPSs; and
- Picker-less OPSs.

The performance categories (Section 2.4) used in Study 1 to structure the performance aspects addressed in literature were:

- Throughput;
- Order lead time;
- Human factors;
- Quality of order picking concerning the picking errors and picking accuracy;
- Flexibility;
- Operational efficiency in terms of resource and space utilisation; and
- Investment and operational costs.

Moreover, the design categories of OPSs (Section 2.5) considered were:

- Equipment;
- Policy; and
- Space and layout.

The remainder of this section is divided into four subsections (i.e. Sections 5.1.1–5.1.4), each presenting one automated type of OPS (i.e. parts-to-picker, robot-to-parts, parts-to-robot, and picker-less OPSs). In each subsection, the performance categories examined in the respective OPS and the relationships between the OPS design and performance are presented. Afterwards, Section 5.1.5 summarises the performance categories studied in the automated OPSs considered. Providing a breakdown of the types of OPSs identified in the literature, Figure 5.1 shows that 70% of the papers reviewed address parts-to-picker OPSs, followed by a 15% on picker-less OPSs, 9% on parts-to-robot OPSs, and 6% on robot-to-parts OPSs.

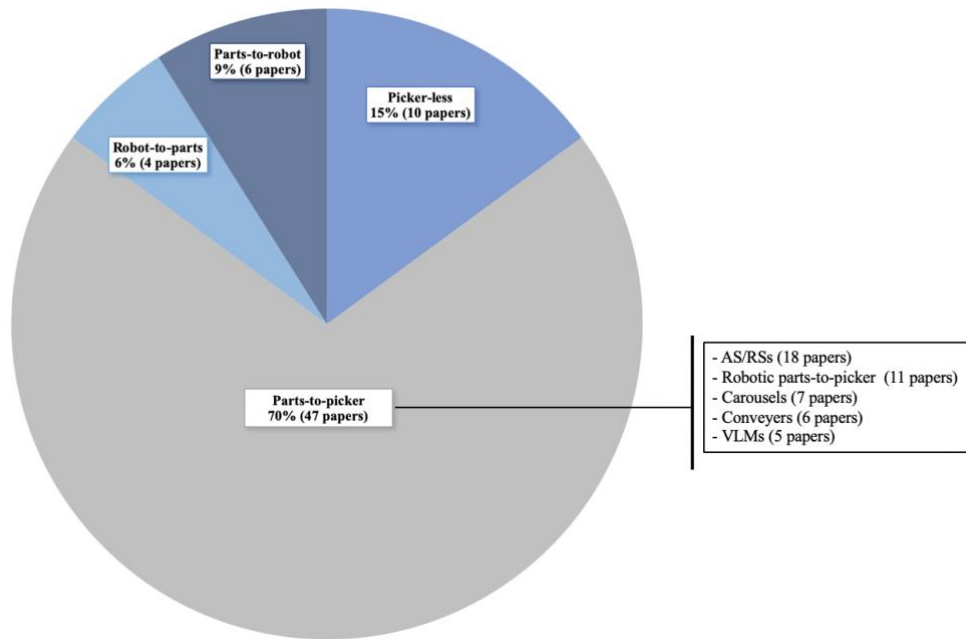


Figure 5.1. Breakdown of order picking systems types studied in the literature

5.1.1 Parts-to-picker

The performance categories—throughput, order lead time, human factors, quality, operational efficiency, and investment and operational costs—and underlying aspects in the literature of parts-to-picker OPSs (i.e. AS/RSs, vertical lift modules, conveyers, carousels, and robotic parts-to-picker) are presented in Table 5.1.

The relationships identified between the performance and design categories in parts-to-picker OPSs are presented in separate tables below for each of AS/RSs, vertical lift modules, conveyers, carousels, and robotic parts-to-picker systems.

The relationships between the performance and design categories in parts-to-picker OPSs with AS/RSs are presented in Table 5.2. The effect of storage and retrieval policies on the throughput in AS/RSs has been widely studied (e.g. Manzini et al., 2006; Andriansyah et al., 2011). Moreover, the effect of the storage policy on both machine travel time and operator and machine utilisation is commonly studied among papers dealing with AS/RSs (e.g. Bozer and White, 1996; Ramtin and Pazour, 2014).

The relationships identified between the performance and design categories in parts-to-picker OPSs with vertical lift modules appear in Table 5.3. Order batching was reported to affect order picking time and increase throughput (Lenoble et al., 2016), while Battini et al. (2015) found that the storage policy affects throughput as well.

Table 5.1. Studied performance aspects of parts-to-picker order picking systems identified in the literature

| Performance category | Studied performance aspects |
|--|---|
| Automated storage and retrieval systems | |
| Throughput | Throughput (Mahajan et al., 1998; Manzini et al., 2006; Park et al., 2006; Andriansyah et al., 2011; Güller and Hegmanns, 2014; Ramtin and Pazour, 2015) |
| Order lead time | Order retrieval time (Khojasteh and Son, 2008) and order flow time (Andriansyah et al., 2010) |
| Operational efficiency | Weighted tardiness (Kusiak et al., 1985), operator and machine utilisation (Medeiros et al., 1986; Bozer and White, 1996), machine travel time (Hwang et al., 1988; Chiang et al., 1994; Su, 1995; Su et al., 2009; Ramtin and Pazour, 2014; Khojasteh and Jae-Dong, 2016), and picker and machine idle time (Wu and Mulgund, 1998) |
| Vertical lift modules | |
| Throughput | Throughput (Bauters et al., 2011; Battini et al., 2015; Lenoble et al., 2016) |
| Order lead time | Order picking time (Lenoble et al., 2018) |
| Human factors | Ergonomics (Dukic et al., 2018) |
| Operational efficiency | Space utilisation (Dukic et al., 2018) |
| Conveyers | |
| Throughput | Throughput (Andriansyah et al., 2014) |
| Order lead time | Order processing time (Armstrong et al., 1979), order flow time (Andriansyah et al., 2009), order fulfilment time (Wu et al., 2017) |
| Operational efficiency | Picking efficiency (Wu and Wu, 2014; Liu et al., 2015) |
| Carousels | |
| Throughput | Throughput (Park et al., 2003; Park and Rhee, 2005) |
| Order lead time | Job sojourn time (Park and Rhee, 2005), order picking time (Yanyan et al., 2014; Lenoble et al., 2017), and retrieval time (Chang et al., 1993) |
| Operational efficiency | Machine travel time (Litvak and Adan, 2001) and picker utilisation (Park et al., 2003) |
| Investment and operational costs | Picking cost (Lee and Kuo, 2008) |
| Robotic parts-to-picker | |
| Throughput | Throughput (Bauters et al., 2016; Lamballais et al., 2017) |
| Order lead time | Average order cycle time (Ekren and Heragu, 2010; Lamballais et al., 2017), throughput time (Yuan and Gong, 2017), and picking time (Xue et al., 2018; Zou et al., 2018) |
| Human factors | Ergonomics (Lee et al., 2017; Hanson et al., 2018) and training of operators (Hanson et al., 2018) |
| Quality | Picking accuracy (Hanson et al., 2018) |
| Flexibility | Flexibility (Hanson et al., 2018) |
| Operational efficiency | Robot utilisation (Lamballais et al., 2017), average utilisation of vehicles and lifts (Ekren and Heragu, 2010), uptime (Hanson et al., 2018), collision-free paths (Kumar and Kumar, 2018), and wait times for vehicles (Ekren and Heragu, 2010) |
| Investment and operational costs | Investment and operational costs (Boysen et al., 2017) and costs (Li et al., 2017) |

Table 5.2. Relationships between performance and design in parts-to-picker order picking systems with automated storage and retrieval systems addressed in the literature

| | | Performance categories | | |
|-------------------|------------------|--|---|--|
| | | Throughput | Order lead time | Operational efficiency |
| Design categories | Equipment | Crane speed affects throughput (Medeiros et al., 1986). Number of mini-load machines affects throughput (Andriansyah et al., 2011). | | Crane speed affects operator and crane utilisation (Medeiros et al., 1986). |
| | Policy | Storage policy affects throughput (Medeiros et al., 1986; Ramtin and Pazour, 2015), as does picking sequencing policy (Mahajan et al., 1998), storage policy, order consolidation, routing, and sequencing policies (Manzini et al., 2006), storage turnover (Park et al., 2006), retrieval policy (Andriansyah et al., 2011). | Order release strategies affect order flow time (Andriansyah, et al., 2010). | Storage policy affects operator and crane utilisation (Medeiros et al., 1986). Order batching affects machine travel time (Hwang et al., 1988), as do order picking sequencing and routing (Su et al., 2009) and storage policy (Ramtin and Pazour, 2014). Storage and retrieval policies affect operator and machine utilisation (Bozer and White, 1996). |
| | Space and layout | Aisle layout affects throughput (Medeiros et al., 1986). | Number of aisles and rack configuration affect throughput time (Khojasteh and Son, 2008). | Aisle layout affects operator and crane utilisation (Medeiros et al., 1986). Number of locations affects weighted tardiness (Kusiak et al., 1985). Rack shape and picking area layout affect machine travel time (Chiang et al. (1994). |

Table 5.3. Relationships between performance and design in parts-to-picker order picking systems with vertical lift modules identified in the literature

| | | Performance categories | |
|-------------------|--------|---|---|
| | | Throughput | Order lead time |
| Design categories | Policy | Storage policy affects throughput (Battini et al., 2015). Batching increases throughput (Lenoble, et al., 2016). | Order batching policy affect order picking time (Lenoble et al., 2018). |

The relationships identified between the performance and design categories in parts-to-picker OPSs with conveyers appear in Table 5.4. Order lead time was reported to be affected by the batching policy (Armstrong et al., 1979) and the open space in the order picking area (Wu et al., 2017). Moreover, Adriansyah et al. (2014) found that picking policy affects throughput. Wu and Wu (2014) reported an impact of the conveyers idle time and the order fulfilment time.

Table 5.4. Relationships between performance and design in parts-to-picker order picking systems with conveyers addressed in the literature

| | | Performance categories | | |
|-------------------|------------------|---|--|--|
| | | Throughput | Order lead time | Operational efficiency |
| Design categories | Policy | Picking policy affects throughput (Andriansyah et al., 2014). | Batching policy affects order processing time (Armstrong, Cook and Saïpe, 1979). | Idle time affects order fulfilment time (Wu and Wu, 2014). |
| | Space and layout | | Open space affects order fulfilment time (Wu et al., 2017). | |

The relationships identified between the performance and design categories in parts-to-picker OPSs with carousels appear in Table 5.5. In studies of carousels, some of the identified relationships concerns the picking policy which is shown to affect retrieval time (Chang et al., 1993) and picking cost (Lee and Kuo, 2008). Furthermore, batching policy has been found to affect order picking time (Lenoble et al., 2017).

Table 5.5. Relationships between performance and design in parts-to-picker order picking systems with carousels addressed in the literature

| | | Performance categories | | | |
|-------------------|--------|--|---|---|--|
| | | Throughput | Order lead time | Operational efficiency | Investment and operational costs |
| Design categories | Policy | Dwell point policy affects throughput (Park and Rhee, 2005). | Picking policy affects retrieval time (Chang et al., 1993). Dwell point policy affects job sojourn time (Park and Rhee, 2005). Batching policy affects order picking time (Lenoble et al., 2017). | Retrieval policy affects carousel traveling time (Litvak and Adan, 2001). | Picking policy affects picking cost (Lee and Kuo, 2008). |
| | | | | | |

The relationships identified between the performance and design categories in parts-to-picker OPSs with robotic parts-to-picker systems are shown in Table 5.6. In robotic parts-to-picker OPSs, the battery management policy is found to affect the system's flexibility and robots uptime (Hanson et al., 2018). Along similar lines, Zou et al. (2018) found that the battery management policy affects throughput time. Picking policy is found to affect the order picking time (Xue et al., 2018). Order batching is seen to have an effect on the number of used robots in the OPS and the maintenance and charging costs (Boysen et al., 2017). Moreover, throughput is found to be affected by the location of workstations (Lamballais et al., 2017) and the number of robots (Bauters et al., 2016).

Table 5.6. Relationships between performance and design in parts-to-picker order picking systems with robotic parts-to-picker addressed in the literature

| | | Performance categories | | | | |
|-------------------|------------------|---|---|--|---|---|
| | | Throughput | Order lead time | Flexibility | Operational efficiency | Investment and operational costs |
| Design categories | Equipment | Number of robots affects throughput (Bauters et al., 2016). | | Sensors type affects flexibility (Hanson et al., 2018). | Order batching and sequencing affect used robots number (Boysen et al., 2017). | |
| | Policy | Robot sharing policy affects throughput time (Yuan and Gong, 2017), picking policy affects picking time (Xue et al., 2018), battery management policy affects throughput time (Zou et al., 2018). | | Battery management policy affects flexibility (Hanson et al., 2018). | Battery management policy affects robots uptime (Hanson et al., 2018), robot routing policy affects collision rate (Kumar and Kumar, 2018). | Order batching and sequencing affect robot maintenance and charging costs (Boysen et al., 2017), shelves moving time affects costs (Li et al., 2017). |
| | Space and layout | Location of workstations affects throughput (Lamballais et al., 2017). | Warehouse height and footprint affects average cycle time (Ekren and Heragu, 2010). | | Warehouse height and footprint affects vehicle and lifts waiting times and average utilisation (Ekren and Heragu, 2010). | |

5.1.2 Robot-to-parts

The performance aspects studied in literature addressing robot-to-parts OPSs are categorised under the performance categories of order lead time, flexibility, and investment and operational costs, as shown in Table 5.7.

Table 5.7. Performance aspects of robots-to-parts order picking systems identified in the literature

| Performance-related category | Studied performance aspects |
|----------------------------------|--|
| Order lead time | Picking time (Zhu et al., 2016) and picking cycle time (Boudella et al., 2018) |
| Flexibility | Easily adjusted to changes in products quantity (Kimura et al., 2015) |
| Investment and operational costs | Investment costs and payback period (Bonini et al., 2016) |

The relationships identified between the performance and design categories in robot-to-parts OPSs appear in Table 5.8. Picking time has been reported to be affected by the picking policy (Zhu et al., 2016) and the storage assignment of SKUs (Boudella et al., 2018). Moreover, the number of robots and the number of grippers, as well as whether the robots used have a dual or a single arm, influences the flexibility of the OPS (Kimura et al., 2015).

Table 5.8. Relationships between the performance and design of robot-to-parts order picking systems addressed in the literature

| | | Performance categories | |
|-------------------|-----------|--|-------------|
| | | Order lead time | Flexibility |
| Design categories | Equipment | Changing the number of robots used, the use of dual- or single-armed robots, and the number of grippers affects the system's flexibility to adjust to changes in product quantity (Kimura et al., 2015). | |
| | Policy | Picking policy affects picking time (Zhu et al., 2016). The storage assignment of stock keeping units affects picking cycle time (Boudella et al., 2018). | |

5.1.3 Parts-to-robot

The performance aspects studied in the literature addressing parts-to-robot OPSs can be categorised in the performance categories of throughput, order lead time, flexibility, and operational efficiency (Table 5.9).

Table 5.9. Performance aspects of parts-to-robot order picking systems identified in the literature

| Performance category | Studied performance aspects |
|------------------------|--|
| Throughput | Throughput (Derby, 2008) |
| Order lead time | Cycle time (Kim et al., 2003a) and picking time (Khachatryan and McGinnis, 2005) |
| Flexibility | Adaption of robots to pick new items (Schraft and Ledermann, 2003) |
| Operational efficiency | Robot travel time (Kim et al., 2003b) and robot utilisation (Li and Bozer, 2010) |

The relationships between the performance and design related categories in parts-to-robot OPSs appear in Table 5.10. Throughput has been reported to be affected by robot speed and acceleration (Derby, 2008). Moreover, the retrieval policy was found to influence robot utilisation (Li and Bozer, 2010).

Table 5.10. Relationships between the performance and design of parts-to-robot order picking systems addressed in the literature

| | | Performance categories | | |
|-------------------|-----------|---|--|--|
| | | Throughput | Order lead time | Operational efficiency |
| Design categories | Equipment | Robot speed and acceleration affect throughput (Derby, 2008). | | |
| | Policy | | Replenishment policy affects cycle time (Kim et al., 2003a). Number of buffers affects picking time (Khachatryan and McGinnis, 2005). | Retrieval policy affects robot utilisation (Li and Bozer, 2010). |

5.1.4 Picker-less

Performance aspects of picker-less OPSs examined in the literature are presented in Table 5.11. The literature on picker-less OPSs studies the performance categories of throughput, order lead time, human factors, quality, operational efficiency, and investment and operational costs, with no aspects identified in the flexibility category.

Table 5.11. Performance aspects of picker-less order picking systems identified in the literature

| Performance-related category | Studied performance aspects |
|----------------------------------|---|
| Throughput | Throughput (Liu et al., 2011; Pazour and Meller, 2011) |
| Order lead time | Picking time (Yigong, 2008; Jin et al., 2015) |
| Human factors | Safety (Franklin et al., 2008) Staff satisfaction (Franklin et al., 2008) |
| Quality | Picking error (Franklin et al., 2008) |
| Operational efficiency | Dispensing efficiency (Franklin et al., 2008; Jin et al., 2015) |
| Investment and operational costs | Operational costs (Caputo and Pelagagge, 2006; Liu et al., 2011) Replenishment and picking costs (Meller and Pazour, 2008) Total restock cost (Liu et al., 2008) Infrastructure investment (Meller and Pazour, 2008) |

The studied relationships between the performance and design of picker-less OPSs appear in Table 5.12. Picking time in picker-less OPSs has been shown to be affected by the order picking sequence (Yigong, 2008) and the storage policy (Jin et al., 2015). Moreover, the quality of picking in terms of picking error seems to relate to the dispenser type, which in turn affects dispensing efficiency, safety, and employee satisfaction (Franklin et al., 2008). The operational and investment costs have been found to be influenced by the storage assignment policy of SKUs (Meller and Pazour, 2008; Pazour and Meller, 2011), slotting policy (Liu et al., 2008; Liu et al., 2011), and the number of pickers (Caputo and Pelagagge, 2006).

Table 5.12. Relationships between the performance and design of picker-less order picking systems addressed in the literature

| | | Performance categories | | | | | |
|-------------------|-----------|---|---|--|---|---|---|
| | | Throughput | Order lead time | Human factors | Quality | Operational efficiency | Investment and operational costs |
| Design categories | Equipment | | | Dispenser type affects safety and employee satisfaction (Franklin et al., 2008). | Dispenser type affects picking error (Franklin et al., 2008). | Dispenser type affects efficiency (Franklin et al., 2008). | |
| | Policy | Slotting policy affects throughput (Liu et al., 2011; Pazour and Meller, 2011). | Order picking sequence affects picking time (Yigong, 2008), as does storage assignment policy (Jin et al., 2015). | | | Order of storage containers affects dispensing efficiency (Jin et al., 2015). | The number of pickers affects operational costs (Caputo and Pelagagge, 2006). Slotting policy affects restock cost (Liu et al., 2008). Stock keeping unit storage assignment policy affects replenishment and picking costs (Meller and Pazour, 2008), as well as investment costs (Pazour and Meller, 2011). Slotting policy affects operational costs (Liu et al., 2011). |

5.1.4 Summary of performance categories in the literature

An overview of the performance categories in parts-to-picker, robot-to-parts, parts-to-robots, and picker-less OPSs addressed in the literature appears in Figure 5.2. The boxes shaded in dark grey indicate that more than five papers were found on the performance category, whereas boxes shaded in light grey mean that the performance category has rarely been studied (i.e. in from one to five papers found in the reviewed literature). Last, boxes without shading indicate that no studies were found on these performance categories.

In parts-to-picker OPSs, the performance categories of throughput, order lead time, and operational efficiency received the most attention in the literature, whereas human factors, quality, and investment and operational costs received the least. Robot-to-parts and parts-to-robot OPSs have generally received little attention in the literature on

automated OPSs. For robot-to-parts systems, a few papers addressed order lead time, flexibility, and investment and operational costs, whereas for parts-to-robot OPSs, throughput, order lead time, flexibility, and operational efficiency have been treated in some of the literature. Last, in picker-less OPSs, most performance categories aside from flexibility have been addressed in the literature.

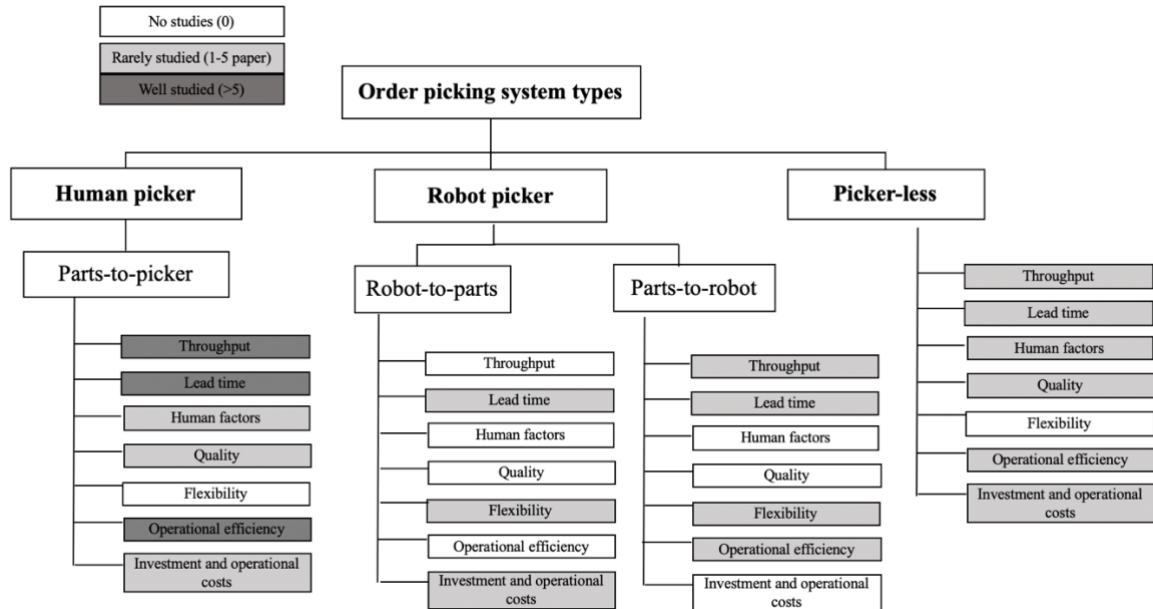


Figure 5.2. Overview of performance-related categories in the literature by type of order picking system

5.2 Research Question 2

Research Question 2 addressed the performance characteristics of RCSRSs and the impact of the system’s design on its performance:

What are the performance characteristics of robot-based compact storage and retrieval system, and how does the design of such a system affect its performance?

The results were divided into two areas: the performance characteristics of RCSRSs and the relationships between the design and performance of RCSRSs. Study 2 was performed utilising a multiple-case study which included two case companies.

The framework developed and used to perform the analysis in Study 2 appears in Figure 5.3. The performance categories of throughput, lead time, human factors, quality, flexibility, operational efficiency, and investment and operational costs were used to analyse the performance characteristics of the RCSRSs. Meanwhile, both the design and performance categories were used to analyse how the design of RCSRSs affect their performance.

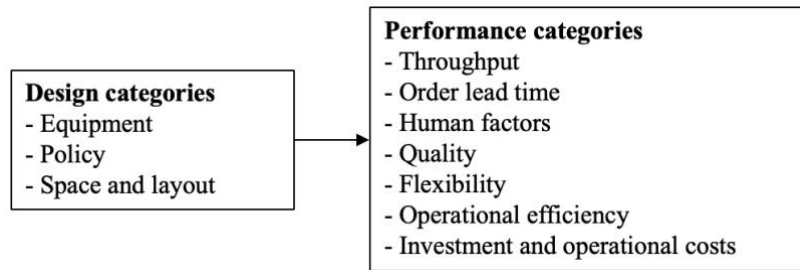


Figure 5.3. The framework used in Study 2 to analyse the cases and literature

The performance characteristics of the RCSRSs identified through the cases are described in Table 5.13, presented according to the seven performance categories from the framework in Figure 5.3.

Table 5.13. Performance characteristics of robot-based compact storage and retrieval systems (RCSRSs)

| Performance category | Performance characteristics in the case studies |
|----------------------------------|--|
| Throughput | <ul style="list-style-type: none"> - Set by the RCSRS'S supplier: 120 to 350 bins per hour at each operator port. - The case companies have throughput between 65 and 178 bins per hour at each operator port. |
| Quality | <ul style="list-style-type: none"> - Order picking quality is high, with an error rate in the order lines of less than 0.09%. |
| Flexibility | <ul style="list-style-type: none"> - Different sizes of bins allow different product sizes to be stored in the system. - The physical expansion of the system and the addition of robots takes a relatively short time. - Several picking policies (e.g. batching and urgent order handling) are available. - Changes in demand are accommodated by increasing or decreasing the number of active operator ports. |
| Order lead time | <ul style="list-style-type: none"> - Throughput time is less than 24 hours. |
| Human factors | <ul style="list-style-type: none"> - Unexperienced operators can work with an RCSRS with appropriate training in a relatively short time. - Repetitive tasks at operator ports can be managed by introducing a rotation system for the operators. |
| Operational efficiency | <ul style="list-style-type: none"> - RCSRSs can allow up to 80% more space utilisation than manual systems, because of their increased capacity to store more items per square meter. - RCSRSs usually boost efficiency in manning hours by at least 50% compared to a manual system, as it allows an increased pick-per-hour rate and eliminates operators' transportation in the storage area. - The RCSRSs have no single point of failure which decreases downtime, where downtime is reported to be less than 1% for the systems. - RCSRSs are more energy-efficient than manual systems, taking into account the lightning reduction in RCSRSs, and the energy efficient robots. |
| Investment and operational costs | <ul style="list-style-type: none"> - The investment costs for RCSRSs are higher than those of mini-load systems, whereas their expansion costs are less, in terms of the needed infrastructure and equipment. - Annual maintenance and licencing costs are high. |

A literature review on robotic parts-to-picker OPSs revealed several relationships between the design and performance of OPSs, all of which appear in boxes without shading in the matrix in Table 5.14. Additional relationships between robotic parts-to-picker OPSs performance and design were identified during the case studies and are shaded in light grey in the matrix, while the few relationships identified from both the literature and the case studies are shaded in dark grey.

The relationships in the boxes shaded in dark grey are discussed here, for they represent the relationships identified from both the case studies and the literature. Throughput has been found to be affected by the placement of workstations (Lamballais et al., 2017), which the case studies confirmed, as the placement of workstations affects the distances travelled by the robots in the RCSRS which in turn affects throughput. Another relationship identified by the case studies is that an RCSRS's flexibility with regards to accommodating to demand changes could be achieved through adding or removing robots and operator ports, which confirm earlier literature results on the impact of adding robots to meet changes in the demand (Heragu et al., 2011; Cai et al., 2014; Malmborg, 2003). The results from the case studies show that a mixed storage policy increases throughput compared to a single product storage policy. The impact of mixed storage policy is investigated by Beckschäfer et al. (2017) and Zou et al. (2016). Amongst the other results, throughput is found to be affected by the retrieval policy by Beckschäfer et al. (2017). In the case companies, an empty bin retrieval policy is found to increase throughput compared to a first in, first out retrieval policy. An empty bin retrieval policy prioritises and selects the bins with lowest number of items or the completely empty bins. This policy allows for the product to be distributed in multiple bins across the grid, which makes them more easily accessible by the robots, as it is less likely that they are stored deep down the grid. Because the bins are more widely distributed in the grid when using an empty retrieval policy compared to a first in, first out policy, they are probably located near to the workstations which are also distributed in the grid, which in turn increases throughput. Moreover, an empty bin retrieval policy allows for faster replenishment of the system, as it allows the empty bins to be presented at the workstations (i.e. replenishment workstations) quicker than in the first in, first out policy.

The relationships identified in the case studies and shaded in light grey in Table 5.14 are discussed here as well. First, in terms of their flexibility, the RCSRSs allow for two bin sizes to be stored in the systems, which increases the systems' flexibility in storing a greater variety of products. Second, their flexibility is decreased by the fact that the company operating the RCSRS's has a limited ability to perform changes to the system, as any changes to the system's interface with the order picker has to be done by the RCSRS's supplier. Third, mixing the storage space for different customers increases storage flexibility for it allows the storage space to be shared by multiple customers, however, this implies that the administrative tasks increase as the operator has to login each time an order has to be picked to choose the customer which the order belongs to. The operational efficiency of RCSRSs in terms of energy consumption increases according to the weight of bins, and the downtime of robots is affected by the replenishment policy, for filling the bins completely can increase the robot stops as they get stuck over the completely filled bins, thus, it is recommended to not fill the bins with their maximum volume. Last, the licencing and maintenance costs are found to be dependent on the installed equipment.

Table 5.14. Matrix of relationships between the design and performance of robot-based compact storage and retrieval systems from case studies (shaded in light grey), literature and case studies (shaded in dark grey), and literature (no shading)

| | | Design-related categories | | |
|------------------------|----------------------------------|---|--|--|
| | | Equipment | Policy | Space and layout |
| Performance categories | Throughput | Throughput increases for medium-speed robots. | Throughput is affected by the robot assignment policy. | Throughput is affected by the location of workstations. |
| | | | A mixed storage policy affects throughput. | |
| | | | Retrieval policy affects throughput and replenishment rate. | |
| | Flexibility | Different bin sizes allow for product variety. | A system supplier's authority to make changes decreases flexibility. | |
| | | Accommodating to changes in the demand depends on the number of robots and operator ports. | Mixing the storage space for different customers increases storage flexibility. | |
| | Order lead time | Throughput time is affected by the robots' velocity. Cycle time can be reduced by using long racks at a high robot utilisation rate. | Throughput time is affected by the robots' assignment strategy, the ratio of pickers to robots, and the storage policy. Storage and retrieval cycle times could be shortened depending on the dwell-point policy. | Cycle time can be optimised with a tier depth-to-width ratio of 2:1. |
| | Operational efficiency | A high robot utilisation rate can be reached by using long racks. | Robot travel time is affected by the storage and retrieval policy. Robot and lift utilisation rate is affected by the picking policy (i.e. number of zones and a zone or no-zone policy). | |
| | | Energy consumption increases as the weight of bins increases. | Replenishment policy affects downtime. | |
| | Investment and operational costs | Licencing and maintenance costs depend on the equipment installed. | | |

5.3 Research Question 3

Research Question 3 concerned the impact of an RMFS context on the system's performance:

How does the context of a robotic mobile fulfilment system affect its performance?

A single case study was used in Study 3, and a framework of contextual aspects in OPSs was developed with reference to literature and structured in light of three contextual categories also used in Study 3 to analyse the data:

- System profile aspects: these are long-term factors relating to the number of customers and suppliers, number of SKUs stored in the system, and the operators safety.
- Demand profile aspects: these are aspects related to the demand and the picking order itself, which directly influence the OPS and include aspects related to the order frequency, order volume, number of lines per order, and quantity per order line; and
- Item profile aspects: these relate to the characteristics of the items to be picked, which affects the selection of an OPS and the type of equipment used.

The performance categories (Section 2.4) addressed in Study 3 were throughput, lead time, human factors, quality, flexibility, operational efficiency, and investment and operational costs. Based on the data from the case company, relationships were identified between the RMFS's contextual aspects and the performance categories. Table 5.15 describes the identified relationships and presents them according to the system, demand,

Table 5.15. Description of the relationships between the context and performance of robotic mobile fulfilment systems (RMFSs)

| Relationship No. | Relationship description |
|-----------------------|--|
| System profile | |
| 1 | If several customers are served by the same system, it could be possible to increase overall efficiency, assuming demand variations between customers can even out overall demand (supplier). Similar results would be achieved if robot pooling is possible, where the volume flexibility is increased as robots and inventory pods can then be added or subtracted (supplier). |
| 2 | When there is a large number of SKUs the relative efficiency of the RMFS compared to manual OP increases as an increasing number of SKUs increases the travel distances in a manual system (supplier and operator). |
| 3 | When the building is low the RMFS is more competitive as the space efficiency is then higher than in a high building (supplier and operator). |
| 4 | When RMFS needs to be reconfigured, it takes some time to move or expand the safety fences around the system and that this could restrict the speed with which the RMFS could be reconfigured (operator). |
| Demand profile | |
| 5 | With varying demand in the RMFS it is easy to add robots and inventory pods to thereby increase capacity. This relates to flexibility (supplier and operator). |
| 6 | The more skewed the distribution of demand for the different SKUs, the average robot travel time becomes shorter and thereby the RMFS has a greater throughput capacity and can achieve shorter lead time in relation to the number of robots (operator). |
| 7 | With an increasing number of customers the RMFS has a high flexibility to adapt as it is easy to add robots and inventory pods (supplier and operator). |
| 8 | With low demand for each SKU the relative efficiency of the RMFS increases as it is designed to carry only small quantities per SKU (operator). |
| 9 | With medium-to-high volumes, the productivity/investment ratio of an RMFS is increased, but with very high volumes it is more attractive to invest in other systems that require larger investments but are faster (supplier and operator). |
| Item profile | |
| 10 | With varying item size the RMFS has a high flexibility to manage this because of the different compartment sizes in the inventory pods (supplier and operator). |

and item profiles. For each explained relationship, information is provided in brackets regarding whether the relationship was identified by the supplier or operator of the system or both. Each relationship is given a number in Table 5.15 to indicate its relationship with the performance categories in the matrix in Table 5.16.

Table 5.16. Matrix of relationships between the context and performance of robotic mobile fulfilment systems

| | System profile | Demand profile | Item profile |
|----------------------------------|----------------|----------------|--------------|
| Throughput | | 5, 6 | |
| Order lead time | | 6 | |
| Flexibility | 1, 4 | 5, 7 | 10 |
| Operational efficiency | 1, 2, 3 | 8 | |
| Investment and operational costs | | 9 | |

6. Discussion and further research

This chapter discusses the results of the thesis, presented in Chapter 5, which provide answers to the three research questions. Section 6.1 provides a discussion of the results concerning each research question in relation to the thesis's purpose and its contribution. Thereafter, in Section 6.2, the discussion shifts attention to potential directions for further research.

6.1 Contributions of the thesis

In response to the research's purpose to expand knowledge about the performance of robotic parts-to-picker OPSs and how the design and context of such systems influence their performance, the thesis provides knowledge on the performance of robotic parts-to-picker OPSs which is useful in relation to selection and design of OPSs as well as the redesign of existing OPSs in order to maximise the benefits of automation in order picking. As can be acknowledged by reviewing the research's purpose and research questions, each research question adheres to the same logic; two questions seek answers about how an OPS's design influences its performance, whereas the other seeks an answer about how the system's context influences its performance.

The answer to Research Question 1 illuminates current understandings about the performance aspects of automated OPSs, namely parts-to-picker systems (e.g. robotic parts-to-picker OPSs), robot-to-parts, parts-to-robot, and picker-less systems. The identification of relationships studied between the design and performance of automated OPSs contributes to research by providing a structured overview of how the design of an automated OPS influences its performance. This provides an overview of how the different design options have been found to affect the performance of OPSs in previous studies conducted on the matter, which can assist the selection and design of OPSs or redesign of existing OPSs. Moreover, the results of Study 1 revealed the performance categories that have received the most and least attention in research on the topic to date. The less studied performance categories, presented in Figure 5.2, could be addressed in future research. Furthermore, the tables in Section 5.1 that present the relationships between the design and performance of automated OPSs provide indications about which relationships could benefit from further research.

Taking into consideration the multitude of aspects affecting an OPS's performance, as highlighted by Taljanovic and Salihbegovic (2009), as well as the complexity of relationships between an OPS's design and performance, as identified by Gu et al. (2007), and the fragmented knowledge about the performance of automated OPSs in relation to their design, an overview of how an OPS's design affects its performance has become important. Against that background, the tables presented in Section 5.1 provide an overview of the performance aspects for parts-to-picker, robot-to-parts, parts-to-robot, and picker-less systems and which design categories influence the performance of those systems. Taken together, the tables offer a framework to help practitioners when selecting and designing OPSs or redesigning current OPSs, for they provide insights into which design aspects affect the system's performance, particularly in terms of the equipment used in the OPS, the policies implemented (e.g. storage policies), and the layout of the

order picking area (e.g. aisles layout). However, considering that the answer to Research Question 1 was derived from reviewing and synthesizing literature, the contribution from answering it is not the revelation of new knowledge but an overview of knowledge available on the topic, an outline of the relationships between an automated OPS's performance and its design, and exploration of avenues for future research. With that overview at hand, decision makers in industry can recognise the performance aspects of different automated OPSs and which design aspects relate to changes in the performance of those systems. For example, using different picking and storage policies will affect the throughput of the OPS in different ways.

Research Questions 2 and 3 were narrower in scope than Research Question 1. Whereas Research Question 1 addressed several automated OPSs, Research Questions 2 and 3 specifically addressed robotic parts-to-picker OPSs. Accordingly, the answers to Research Question 2 and 3 provide results that are more in-depth. Those two questions were designed to guide investigations into the performance of RCSRSs and RMFSs, respectively, about which little knowledge is available in the literature. The corresponding studies—that is, Study 1 and Study 2—involved conducting empirical research on the performance of OPSs, as recommended by Marchet et al. (2015).

The answer to Research Question 2 improves current understandings of the performance of RCSRSs by first clarifying how RCSRSs perform in terms of throughput, order lead time, human factors, quality, operational efficiency, and investment and operational costs, as shown in Table 5.13, which can facilitate the process of selecting a proper OPS type for warehouses. Second, the results contribute by showing how the design of an RCSRS affects the system's performance, as detailed in Table 5.14, which can aid the design of new RCSRSs or the redesign of existing RCSRSs. For example, the results reveal that if a company seeks to enhance its system's throughput, then a designer could alter the speed of robots, the robots' assignment policy, the storage policy or even the retrieval policy. For another example, to increase the system's flexibility, changes to the bin sizes allow storing different product varieties, while changes to the number of robots and operator ports can be performed to accommodate seasons of low and high demand. Furthermore, system designers should pay attention to the selected replenishment policy, which can increase downtime in RCSRSs.

The results from the case studies used to answer Research Question 2 reveal that RCSRSs are flexible in meeting changes in order demand, which corroborates the findings of previous research (e.g. Heragu et al., 2011; Cai et al., 2014). Study 2 demonstrated that the retrieval policy in an RCSRS affects its throughput and replenishment rate. In detail, adopting an empty bin retrieval policy RCSRSs can increase throughput compared to a first in, first out retrieval policy, which expands upon the findings of Beckschäfer et al. (2017), who observed that an empty bin retrieval policy yielded higher throughput and faster replenishment than an adding retrieval policy. Another useful finding, especially for companies seeking to increase their RCSRS throughput or in the process of changing their storage policy, is that examining the effects of the storage policy on throughput is important. Although the results of the case studies indicate a relationship between using a mixed storage policy and increased throughput, the impact of adopting a mixed storage policy in an RCSRS on throughput contradicts previous findings. In particular, Beckschäfer et al. (2017), who examined the impacts of using a mixed storage policy, found that doing so does not increase throughput. At the same time, Zou et al. (2016) observed that a single product storage policy reduced throughput time compared to a

mixed storage policy. In that regard, the impact of implementing a mixed storage policy on an RCSRS's throughput provides fertile ground for further studies.

Apart from a few studies focusing on RCSRSs' throughput (e.g. Beckschäfer et al., 2017), order lead time, and space utilisation (e.g. Zou et al., 2016), research on the performance of RCSRSs remains scarce, and the need for more research on the topic has been recognised by both Beckschäfer et al. (2017) and Zou et al. (2017). In response, the results of Study 2 contribute a general perspective on the performance of RCSRSs by highlighting several performance categories that are deemed important in literature on order picking (i.e. throughput, order lead time, human factors, quality, flexibility, operational efficiency, and investment and operational costs). Moreover, the results identify several relationships between RCSRSs' performance and design not addressed in previous research on RCSRSs but that are nevertheless important to efficiently designing a RCSRS. For one, the findings clarify how an RCSRS's flexibility is affected by a mixed storage policy and the limited authority of the warehouse operating an RCSRS on making changes to the system. For another, they reveal that the energy consumption can be attributed to the weight of bins. Because the application of RCSRSs is expanding in industry (Azadeh et al., 2017), the findings of Study 2 are relevant to practice when selecting or designing an RCSRS.

The answer to Research Question 3 showcases new avenues for understanding the context of RMFSs. Whereas earlier research on RMFSs has focused on investigating the relationships between an RMFS's design and performance (e.g. Bauters et al., 2016; Lamballais et al., 2017; Zou et al., 2017; Roy et al., 2019). Research Question 3 was designed to pinpoint contextual aspects of RMFSs, namely in their system, demand, and item profiles, and their impact on the performance of the RMFSs.

Although research on order picking has recognised the importance of contextual aspects in the design of OPSs (e.g. Sharp et al., 1991; Baker and Canessa, 2009), knowledge on the impact of contextual aspects on an RMFS's performance remains unavailable in the literature. For example, in the case of needing to serve several customers with an RMFS, the overall efficiency of the system could be increased to accommodate variations in demand between customers. Furthermore, safety requirements in terms of having fences surrounding the system could affect the RMFS's flexibility, particularly the expansion time of the system. In that regard, the findings of Study 3 contribute to research by pinpointing the contextual aspects in RMFSs and by generating knowledge on how the context of RMFSs affect their performance. From another angle, because knowledge about when and how an RMFS should be applied is often lacking in industry, a designer of an RMFS, to make decisions about whether and how such a system should be applied, needs knowledge about how the system will perform given the context in which it could be applied.

The answers to the three research questions indicate how the design and context of robotic parts-to-picker OPSs affect its performance in terms of throughput, order lead time, human factors, quality, flexibility, operational efficiency, and investment and operational costs. In turn, such knowledge can improve understandings of the expected performance of the systems given a certain design or context, which can guide the selection and design of robotic parts-to-picker OPSs. For example, the replenishment policy in an RCSRS was found to affect the system's downtime, because robots stops increases when they fill the bins with the maximum number of items. Another finding concerns the volumes handled

in an RMFS and their impact on the productivity-to-investment ratio. In particular, that ratio increases with medium to high volumes in an RMFS, whereas very high volumes could make other OPSs more attractive. In that light, considering the different performance categories in the thesis helped to provide a multifaceted view on the performance of robotic parts-to-picker OPSs.

Regarding the generalisability of Studies 2 and 3, the main approach for generalisation in case research is analytic generalisation to theory by means of propositions (Yin, 2017). In this thesis, theory was used to derive propositions that prompted the results and, in turn, related back to theory. Ultimately, the results can be deemed valid as long as the propositions are applicable. Although the case research conducted in the thesis is bounded by the case characteristics, described in Chapter 3, the findings from the research are applicable to other environments in which RCSRSs and RMFSs are applied, considering their similar preconditions. Moreover, the case descriptions provided are detailed enough to support the judgement of whether or not the results are valid in certain companies.

6.2 Further research

This thesis provides an understanding on the performance characteristics of automated OPSs, especially robotic parts-to-picker OPSs, and the impact of the design and context of OPSs on their performance. Such knowledge affords a new perspective on the relationships between a certain design and context and the expected outcome in terms of performance. The identification of design, performance, and context categories in order picking provides a structure for future research on the topic, because those categories can be used to pinpoint relationships between the design and context in terms of how they affect the performance of types of OPSs other than RCSRSs and RMFSs considered in the thesis and even other automated OPSs beyond robotic parts-to-picker OPSs.

Concerning the performance categories of automated OPSs, the results of Study 1 show that the performance categories of human factors, flexibility, and quality in parts-to-picker OPSs have rarely been studied. However, considering the importance of those categories in assessing the performance of automated OPSs, the literature could benefit from more research on those categories. Moreover, some automated OPSs with robot pickers (i.e. robot-to-parts and parts-to-robot systems) could also be further examined in terms of their performance, design, and how their design affects their performance.

Concerning the performance of RCSRSs (Study 2), the thesis provides insights into the characteristics of that performance. However, no relationships between an RCSRS's design and picking quality could be identified from reviewed literature on robotic parts-to-picker OPSs or from the case studies performed. Nevertheless, the absence of identified relationships between an RCSRS's design and its picking quality does not mean that no impact exists but simply that, within the scope of Study 2, no relationships could be identified. In the light of the importance of picking quality in warehouses, the literature would benefit from an investigation into how an RCSRS's design affects the picking quality. At the same time, no relationships were found concerning the effect of the order picking area's space and layout on the RCSRS's flexibility and investment and operational costs. Accordingly, taking into consideration the importance of increasing the flexibility of RCSRSs and the goal of companies to reduce the associated investment and operational costs of such systems, researchers should set out to examine those relationships. Last, as discussed in Section 6.1, the impact of the storage policy on

throughput in RCSRSs remains controversial, for the findings of the thesis concerning the effect of a mixed storage policy on throughput contradicts the results of earlier research, which underscores the need for further research on the topic.

Regarding the performance of RMFSs and how it is influenced by the context of the systems (Study 3), the results highlight the need for more studies that address the contextual aspects of robotic parts-to-picker OPSs. Although this thesis identifies several relationships between an RMFS's context and its performance with reference to the case study, no other research that has addressed those contextual aspects and their influence on an OPS's performance was found.

In this thesis, one research question focused on how an RCSRS's design affects its performance. In turn, that question raises another one concerning the potential impact of the contextual aspects of an RCSRS on its performance. Along similar lines, another research question focused on identifying the impact of an RMFS's context on the system's performance; however, the relationships between the RMFS's design and performance remain to be probed in future research. Last, case study research offers the opportunity to obtain snapshots of operations and to collect historical data. In this thesis, however, limitations were faced in collecting data about order lead time in RCSRSs due to the lack of historical data in the case companies and the difficulty of collecting such data, which requires proximity to the case companies over an extended period.

7. Conclusions

This thesis sheds light on the performance of automated OPSs, especially robotic parts-to-picker OPSs, and its relationships with the systems' design and performance. The seven categories of performance considered in the thesis are throughput, order lead time, human factors, quality, flexibility, operational efficiency, and investment and operational costs. The importance of understanding the performance of robotic parts-to-picker systems and its relationships to the design and context stems from the increased application of these systems in practice, where experience and guidelines for how these systems perform are limited. From a theoretical standpoint, the performance of robotic parts-to-picker OPSs is understudied, especially in terms of how it is affected by their design and context.

The research for this thesis began with existing knowledge on the performance of automated OPSs. In parallel, the thesis research observed the problems highlighted by the companies involved in the research project of which the author is part of, and through recommendations from previous research. The state of science and the needs of industry guided the research towards focusing on the performance of robotic parts-to-picker OPSs, particularly how their design and context influence their performance.

In line with the thesis's purpose, three research questions were respectively addressed in three studies focusing on the performance of automated OPSs (Study 1), the performance of RCSRSs (Study 2), and the performance of an RMFS (Study 3). Study 1 was designed as a systematic literature review study aimed at pinpointing the performance aspects of automated OPSs and how they are influenced by the design of the systems. Study 1 revealed an increase in the number of studies on robotic parts-to-picker OPSs in recent years. Accordingly, Studies 2 and 3 were designed after conducting the preliminary analysis of Study 1 as well as during discussions with the industrial partners in the project. In particular, Study 2 was designed as a multiple-case study to identify the performance characteristics of RCSRSs and the impact of the design of RCSRSs on their performance. Study 3 was designed as a single-case study to investigate the impact of the context of an RMFS on its performance.

The systematic literature review study was designed to provide an overview on which types of automated OPSs are addressed in literature, their performance aspects, and the relationships between their design and performance. Selection criteria were created and followed to assemble relevant literature, and a detailed identification of the performance aspects reported therein was performed. As a result, a matrix of relationships between each automated OPS's performance and its design was developed. The results furnish knowledge about the performance aspects of the different automated OPSs and how their performance relates to changes in the design of the systems.

The performance of RCSRSs was examined in two case studies in order to improve current understandings about the performance characteristics of RCSRSs and how the design of those systems can affect their performance. A matrix of relationships between the system's performance and design was developed with reference to literature on robotic parts-to-picker OPSs, specifically RCSRSs, RMFSs, and AVS/RSs. The matrix

acted as a guide for developing a more detailed understanding of the relationships using empirical data from the case studies. Altogether, the results of the RCSRSs study provide knowledge useful to designing an RCSRS—for example, that the policies and equipment used will influence the RCSRS's performance.

The performance of RMFSs was scrutinised in a single-case study designed to expand understandings about how the context of an RMFS affects its performance. To that end, relevant contextual aspects were derived from literature on order picking and categorised as belonging to system, demand, or item profiles. Results from the study offer knowledge about the relationships between an RMFS's performance (i.e. throughput, order lead time, human factors, quality, flexibility, operational efficiency, and investment and operational costs) and its contextual aspects. For example, if increasing the number of customers served by an RMFS is necessary, then the system has a high flexibility that allows easily adapting the number of robots and inventory pods.

The thesis contributes to practice by providing guidance to decision makers within industry in terms of the performance to expect of robotic parts-to-picker OPSs depending on their design and context. In turn, such knowledge can facilitate the selection and design of an OPS or else the redesign of a current system. At the same time, the thesis contributes to theory by providing a synthesis of literature addressing the performance of automated OPSs and by outlining the relationships between their design and performance.

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