# Automated Order Picking Systems and the Links between Design and Performance: A Systematic Literature Review



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# Automated order picking systems and the links between design and performance: a systematic literature review

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**ABSTRACT**

With new market developments and e-commerce, there is an increased use of and interest in automation for order picking. This paper presents a systematic review and content analysis of the literature. It has the purpose of understanding the relevant performance aspects for automated, or partly automated, OPSs and identifying the studied links between design and performance, i.e. identifying which combinations of design aspects and performance aspects have been studied in previous research. For this purpose, 74 papers were selected and reviewed. From the review, it is clear that there has been an increased number of papers dealing with the performance of automated, or partly automated, OPSs in recent years. Moreover, there are differences between the different OPS types, but, overall, the performance categories of throughput, lead time, and operational efficiency have received the most attention in the literature. The paper identifies links between design and performance that have been studied, as well as links that appear to be under-researched. For academics, this paper synthesises the current knowledge on the performance of automation in OPSs and identifies opportunities for future research. For practitioners, the paper provides knowledge that can support the decision-making process of automation in OPSs.

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**KEYWORDS**
Order picking; automation; warehouse operations; logistics; materials handling

## 1. Introduction

New market developments, e-commerce, and increased customer expectations have raised the competition for warehouses and manufacturing facilities to handle more orders within tighter delivery times (Andriansyah et al. 2014; Marchet, Melacini, and Perotti 2015). Automation in order picking (OP) has been suggested to further cost reduction, shorter delivery response times, better picking accuracy, and space utilisation (Caputo and Pelagagge 2006; Marchet, Melacini, and Perotti 2015), which makes the performance of order picking systems (OPSs) a vital aspect of company competitiveness. Consequently, recent research has been increasingly focusing on new automated technologies with the potential to improve picking performance (Caputo and Pelagagge 2006; De Koster, Andrew, and Roy 2017).

For a company designing an OPS, whether it is establishing new operations or reviewing existing operations for improvement, it is difficult to make decisions about whether and how to apply automation. Various aspects affect OP performance (Taljanovic and Salihbegovic 2009), and different solutions are likely to affect the performance of the OPS differently. Moreover, it is difficult to assess the links between different OP problems (Gu, Goetschalckx, and McGinnis 2007).

Research has focused on assessing OPS performance for certain OPS types and selected issues in OPS (De Koster, Le-Duc, and Roodbergen 2007; Bauters et al. 2011). However, to the best of our knowledge, no review papers have focused specifically on automated, or partly automated, OPS performance and its relation to OPS design decisions. Therefore, this paper, which has been adapted from a conference paper (Jaghbeer, Hanson, and Johansson 2017), presents a systematic review and content analysis of the existing literature on automation in OPSs, focusing on links between design and performance that have been studied in previous research. A more precise research purpose is presented in subsection 2.4.

The organisation of the paper is as follows. Section 2 presents the frame of reference used in the literature analysis. Thereafter, Section 3 presents the methodology used to conduct the study. The literature review analysis is presented in Section 4, including descriptive and content analyses. Discussion and opportunities for future research are presented in Section 5, and, finally, the conclusion can be found in Section 6.

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## 2. Frame of reference

This section introduces a classification scheme used to categorise the reviewed papers. The first classifier is presented in subsection 2.1 and divides papers according to the studied OPS type. The second classifier in subsection 2.2 divides papers according to the studied performance aspects. Thereafter, subsection 2.3 presents the OPS design aspects used in presenting the links between design and performance in the reviewed literature. Finally, subsection 2.4 presents the purpose of the paper.

### 2.1. OPSs classification

This section presents an OPS classification used for the content analysis in Section 4.2. Based on the different OPS classifications presented by Van den Berg (1999), De Koster, Le-Duc, and Roodbergen (2007), Dallari, Marchet, and Melacini (2009), and Huang, Chen, and Pan (2015), an OPS classification is proposed in Figure 1. This classification distinguishes OPSs according to whether a human, robot, or no picker is used, with an example of each category. As shown in Figure 1, this paper focuses on parts-to-picker, robot-to-parts, parts-to-robot, and picker-less OPSs, which are shaded in grey. Papers dealing with picker-to-parts OPSs are excluded, as they are mainly manual systems that are outside this paper's scope.

Parts-to-picker systems are partly automated and include an automatic device bringing items from a storage area to a picking station, where human pickers complete the OP and possible packing (Huang, Chen, and Pan 2015; Lenoble, Frein, and Hammami 2016). OPSs with a robotic picker include robot-to-parts and parts-to-robot systems, where a robot is performing the actual picking. Robot-to-parts systems include mobile robots moving to storage areas and picking the items, and parts-to-robot systems include robots carrying out the picking and packing at a picking station (Huang, Chen, and Pan 2015). Picker-less OPSs are fully automated with no human or robot performing the actual picking.

### 2.2. Performance categories

In this review, previously published review papers are utilised to develop the performance categories for the literature classification. Rouwenhorst et al. (2000) focus on warehouse design and control, including OP. They present an established warehouse performance criterion to be maximum throughput at minimum costs and discuss the importance of environmental and ergonomic aspects (Rouwenhorst et al. 2000). Staudt et al. (2015) present a structured analysis of the literature on the warehouse activities performance evaluation, including OP. For OP, the study highlights time, quality, cost, and productivity as the main performance evaluation criteria (Staudt et al. 2015). They find the most-used time aspects to be lead time and picking time. Furthermore, they define quality as including order fill rate and picking accuracy; cost as inventory and order processing cost; and productivity as throughput, resource utilisation, and picking productivity (Staudt et al. 2015). In a later study, Van Gils et al. (2018) use the performance aspects developed by Staudt et al. (2015) to review and classify manual OPS literature. De Koster, Le-Duc, and Roodbergen (2007) highlight flexibility as an important aspect in OPSs to accommodate changes and uncertainties. Gu, Goetschalckx, and McGinnis (2010) find that warehouse design affects performance in terms of throughput, quality, costs, space, and machine utilisation. Grosse, Glock, and Neumann (2017) highlight human factors in OP as a major determinant of OPS performance.

Seven performance categories are derived from previous review papers to classify the literature. It should be emphasised here that OPS performances are overlapping to a certain extent, and it is difficult to draw a sharp line between different categories. Therefore, the derived categories should not be regarded as unique or mutually exclusive. The derived performance categories are throughput, lead time, human factors, quality, flexibility, operational efficiency, and costs.

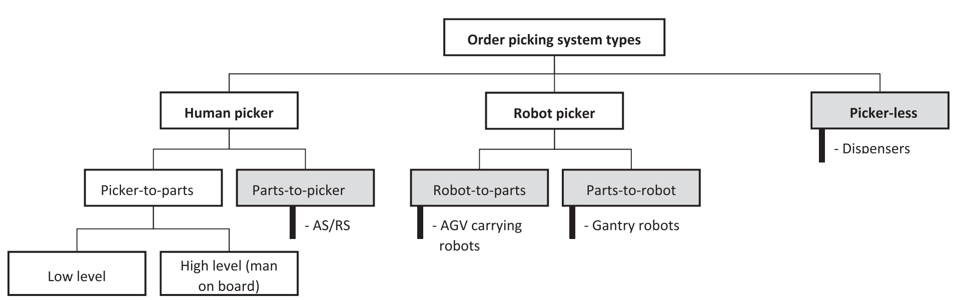


**Figure 1.** Classification of OPS types. The shaded OPSs are in focus in this paper. The figure also includes an example of each shaded type of OPS.

### 2.3. Design categories

Previous literature on the design of OPSs is used to formulate the design categories used in this paper. Matson and White (1982) present a literature review of automated OPSs and discuss equipment selection as essential in OPS design. Rouwenhorst et al. (2000) develop a framework for warehouse design and control. For OP, they consider the picking equipment, area layout, and picking policies. De Koster, Le-Duc, and Roodbergen (2007) focus on planning for efficient OPSs. Planning aspects frequently used in the literature are layout design, storage assignment, zoning, batching, and routing. Dallari, Marchet, and Melacini (2009) propose a procedure for designing OPSs, including equipment type and operational policies. Gu, Goetschalckx, and McGinnis (2010) study the design of warehouses including OP, where they consider layout, equipment selection, and operational strategies. Grosse, Glock, and Neumann (2017) consider OPS design to include layout, storage assignment, zoning, batching, routing, and equipment. Van Gils et al. (2018) present a literature review on the design of OPSs, taking into consideration material handling equipment and layout of the storage area, in addition to OP policies. OP policies include storage assignment and retrieval, routing, and batching policies (Chackelson et al. 2013; Van Gils et al. 2018). From the reviewed literature on OPS design, it appears that attention is directed towards three design categories: equipment, policy, and layout.

### 2.4. Research purpose

This paper has the purpose of understanding the relevant performance aspects for automated, or partly automated, OPSs and identifying the studied links between design and performance, i.e. identifying which combinations of design aspects and performance aspects have been studied in previous research. The paper presents a systematic literature review and content analysis that utilise a structure from the OPS classification, performance categories, and design categories that have been identified above in sub-sections 2.1–2.3.

## 3. Methodology

This section presents the research approach and methodology. The systematic literature review process proposed by Denyer and Tranfield (2009) was followed in this paper to ensure a scientific and transparent approach, in addition to an increase in reliability and validity. Systematic literature reviews increase the probability of an unbiased and comprehensive account of literature compared to a traditional literature review and are characterised by objectivity, systematicness, transparency, and replicability. The following steps developed by Denyer and Tranfield were utilised in this study: (1) location of studies, (2) study selection, (3) analysis, and (4) results reporting.

A research protocol was developed prior to the systematic literature review, including a detailed description of how the review should be conducted (Denyer and Tranfield 2009). The protocol included coding all reviewed papers according to their purpose, author, year, and frame of reference to minimise bias in the review process.

### 3.1. Locating studies

The first step includes identifying research papers relevant to the study's scope (Denyer and Tranfield 2009). Scopus database was chosen for the search to ensure wide coverage and good quality of publications, as it is the largest abstract and citation database of peer-reviewed articles and conference papers. Moreover, it covers the majority of scientific journal articles and conference papers in the area of automation in OP. The following keywords were used in the search engine, reflecting this paper's focus on automation in OPSs:

- 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 fulfillment'
- Robo* AND 'order fulfilment' OR 'order fulfillment'

The keywords were selected to appear in the abstract, title, or article keywords, which would direct the search results towards research with a focus on automation in OP, rather than studies that briefly mention it.

### 3.2. Study selection

In the second step, selection criteria (SC) were formulated for the inclusion and exclusion of papers. These criteria reflect aspects of the formulated RQs with a primary focus on the papers' content (Denyer and Tranfield 2009). The following three selection criteria were applied when reviewing the paper title, abstract, and, if needed, the full paper:

SC1: Conference and journal articles in the English language were included for any year of publication in the database until 2019.

SC2: Duplicate papers were excluded.

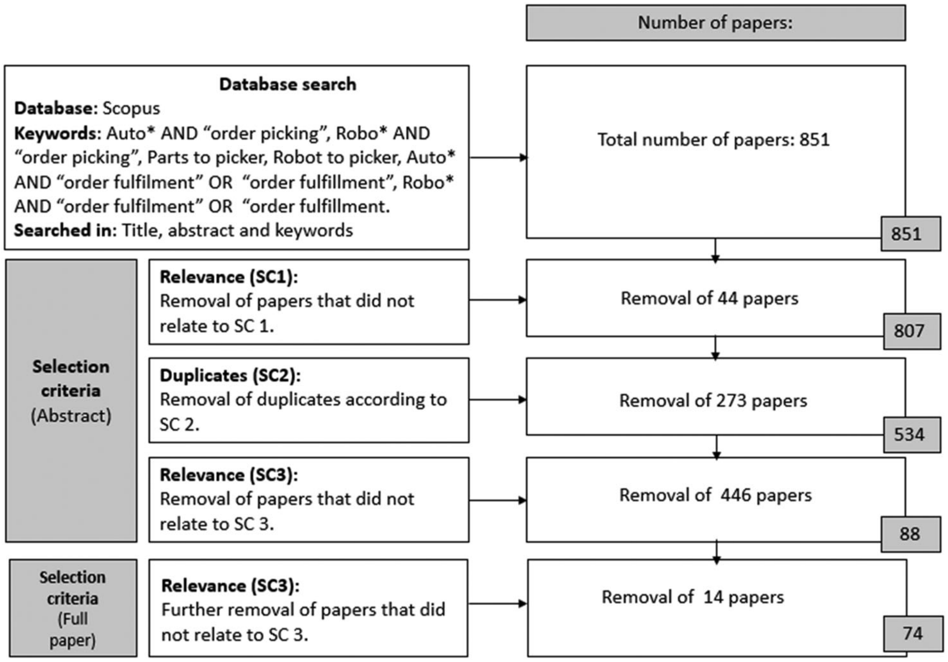


**Figure 2.** Data collection and selection summary.

SC3: Only relevant publications were included. When checking titles and abstracts, research publications should have dealt with a certain type of automated, or partly automated, OPS in accordance with Figure 1. To correspond to the present paper's purpose of studying the performance of order picking, publications should have studied one or more performance aspects of an OPS. This criterion led to excluding the following research papers: (a) papers not dealing with a certain automation type of OPSs and (b) papers with no performance aspect identified. This includes papers focusing only on the design of a particular material handling part or reporting a new technology in equipment (e.g. designing carousels, racks, cranes, and shelves in automated storage and retrieval systems (AS/RSs), or sensor types in robots). Some papers were removed after full review according to SC3.

The data collection and selection criteria are summarised in Figure 2. The total number of hits for all the search strings was 851. After SC1, a total of 807 journal and conference papers were considered. The removal of duplicate papers according to SC2 gave a result of 534 papers to be further examined for selection. After SC3, 88 papers were considered for full review after reading their abstracts. After examining the full papers according to SC3, 14 additional papers were removed, as they were found irrelevant to this paper's scope, leaving 74 papers to be reviewed.

### 3.3. Analysis and synthesis

The third step was to break down individual publications into their constituent parts and describe how they relate to one another (Denyer and Tranfield 2009). Literature findings were grouped according to Tranfield, Denyer, and Smart (2003) by presenting review findings in two steps summarised in Figure 3:

1. Descriptive analysis of findings: Papers were first categorised according to their year and type of publication.

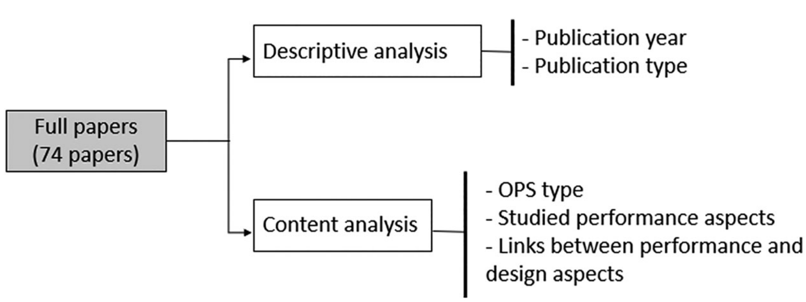


**Figure 3.** Literature analysis process.

2. Thematic content analysis based on literature synthesis: The papers were analysed in terms of the studied performance aspects identified in Section 2.2 and their links to design aspects identified in Section 2.3. Analyses were presented for each OPS type according to the classification in Figure 1.

## 4. Literature analysis

The results of the analyses are presented in this section. First, a descriptive analysis of the number of published papers per year and publication type is presented in Section 4.1. Second, a presentation of the literature with a focus on the performance categories and studied links to design is outlined in Section 4.2.

### 4.1. Descriptive analysis

The 74 papers identified in the systematic literature review were analysed according to the number of papers per year and publication type. As Figure 4 illustrates, all papers were published between 1979 and 2019. A relatively low number of research papers were found between 1990 and 2000, with a value of one or two papers per year. An increased number of papers on automation in OP were published afterwards, with six papers in 2016, five papers in 2017, and seven papers in both 2018 and 2019. Based on the evidence of this analysis, the research interest and use of automation in OPSs are continuously increasing.

The analysis of papers by publication type is presented in Table 1. This analysis shows that the majority of the reviewed papers, accounting for 47 papers, are journal articles, and the remaining 27 are conference papers. The papers are published in 22 different journals. The three journals with the highest number of publications are: International Journal of Production Research, IIE Transactions, and European Journal of Operational Research.

**Table 1.** Number of papers by publication type.

| | Number of publications |
|---|---|
| Journal papers | 47 |
| International Journal of Production Research | 10 |
| IIE Transactions | 6 |
| European Journal of Operational Research | 5 |
| Chinese Journal of Mechanical Engineering | 3 |
| International Journal of Advanced Manufacturing Technology | 2 |
| International Journal of Control and Automation | 2 |
| Journal of Applied Probability | 2 |
| Journal of the Chinese Institute of Engineers | 2 |
| Industrial Management & Data Systems | 2 |
| Journal of the Operational Research Society | 1 |
| Processes | 1 |
| International Journal of Simulation Modelling | 1 |
| Journal of Simulation | 1 |
| International Journal of Information and Management Sciences | 1 |
| Assembly Automation | 1 |
| Industrial Robot: An International Journal | 1 |
| IEEE Transactions on Engineering Management | 1 |
| Computers in Industry | 1 |
| International Journal of Wireless and Mobile Computing | 1 |
| Simulation | 1 |
| Transportation Research Part E: Logistics and Transportation Review | 1 |
| International Journal of Pharmacy Practice | 1 |
| Conference papers | 27 |
| Total | 74 |

### 4.2. Content analysis focusing on performance aspects

This section presents the reviewed academic literature. The analysis is presented according to the frame of reference in Section 2. Each subsection presents papers addressing a specific type of OPS in accordance with Figure 1. Furthermore, for each OPS type, the literature is themed according to the performance categories in subsection 2.2 and links to design aspects in subsection 2.3. Note that the performance categories are not mutually exclusive, as studies can include several performance categories.

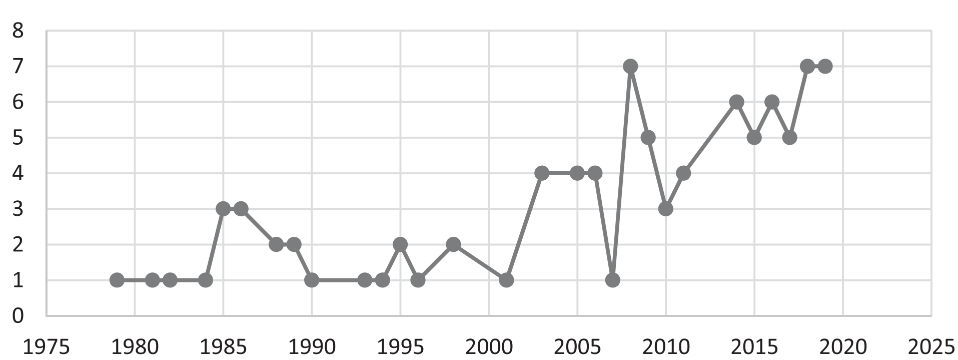


**Figure 4.** Time distribution of reviewed papers.

#### 4.2.1. Parts-to-picker

This section presents the performance aspects studied in the parts-to-picker OPS literature and the links between parts-to-picker OPS design and performance. The studied performance aspects are summarised in Table 2 for the various parts-to-picker OPSs. Tables 3–7 present the studied links between the design and performance of the parts-to-picker OPS literature.

**Table 2.** Performance aspects studied.

| Performance category | Studied performance aspects |
|---|---|
| Parts-to-picker systems with automated storage and retrieval systems (AS/RSs) | |
| Throughput | Throughput (Mahajan, Rao, and Peters 1998; Park, Foley, and Frazelle 2006; Manzini, Gamberi, and Regattieri 2006; Andriansyah et al. 2011; Güller and Hegmanns 2014; Ramtin and Pazour 2015) |
| Lead time | Order retrieval time (Khojasteh and Son 2008), order flow time (Andriansyah, Etman, and Rooda 2010) |
| Operational efficiency | Weighted tardiness (Kusiak, Hawaleshka, and Cormier 1985), operator and machine utilisation (Medeiros, Enscore, and Smith 1986; Bozer and White 1996), machine travel time (Hwang, Baek, and Lee 1988; Chiang et al. 1994; Su 1995; Su et al. 2009; Ramtin and Pazour 2014; Khojasteh and Jae-Dong 2016), picker and machine idle time (Wu and Mulgund 1998) |
| Parts-to-picker systems with vertical lift modules (VLMs) | |
| Throughput | Throughput (Bauters et al. 2011; Battini et al. 2015; Lenoble, Frein, and Hammami 2016; Sgarbossa, Calzavara, and Persona 2019) |
| Lead time | Order picking time (Lenoble, Frein, and Hammami 2018) |
| Human factors | Ergonomics (Dukic et al. 2018) |
| Operational efficiency | Space utilisation (Dukic et al. 2018) |
| Parts-to-picker systems with conveyors | |
| Throughput | Throughput (Andriansyah et al. 2014) |
| Lead time | Order processing time (Armstrong, Cook, and Saipe 1979), order flow time (Andriansyah, Etman, and Rooda 2009), order fulfilment time (Wu et al. 2017) |
| Operational efficiency | Picking efficiency (Wu and Wu 2014; Liu et al. 2015) |
| Parts-to-picker systems with carousels | |
| Throughput | Throughput (Park, Park, and Foley 2003; Park and Rhee 2005) |
| Lead time | Job sojourn time (Park and Rhee 2005), order picking time (Yanyan, Shandong, and Changpeng 2014; Lenoble, Frein, and Hammami 2017), retrieval time (Chang, Wen, and Lin 1993) |
| Operational efficiency | Machine travel time (Litvak and Adan 2001), picker utilisation (B. Park, Park, and Foley 2003) |
| Costs | Picking cost (Lee and Kuo 2008) |
| Robotic parts-to-picker OPSs | |
| Throughput | Throughput (Bauters et al. 2016; Lamballais, Roy, and De Koster 2017; Lamballais Tessensohn, Roy, and De Koster 2020; Roy et al. 2019) |
| Lead time | Average order cycle time (Ekren and Heragu 2010; Lamballais, Roy, and De Koster 2017), throughput time (Yuan and Gong 2017; Roy et al. 2019), picking time (Xue, Dong, and Qi 2018; Zou, Xu, and De Koster 2018) |
| Human factors | Ergonomics (Lee, Chang, and Choe 2017; Hanson, Medbo, and Johansson 2018), operator training (Hanson, Medbo, and Johansson 2018) |
| Quality | Picking accuracy (Hanson, Medbo, and Johansson 2018) |
| Flexibility | Flexibility (Hanson, Medbo, and Johansson 2018) |
| Operational efficiency | Robot utilisation (Lamballais, Roy, and De Koster 2017), uptime (Hanson, Medbo, and Johansson 2018), collision-free paths (Kumar and Kumar 2018), waiting times for vehicles (Ekren and Heragu 2010), average utilisation of vehicles and lifts (Ekren and Heragu 2010), effeciency (Zhao et al. 2019), picker and robot utilisation (Wang, Chen, and Wang 2019), robot travel time (Wang, Yang, and Li 2019). |
| Costs | Costs (Boysen, Briskorn, and Emde 2017), costs (Li et al. 2017) |
| Robot-to-parts OPSs | |
| Lead time | Picking time (Zhu et al. 2016), picking cycle time (Boudella, Sahin, and Dallery 2018) |
| Flexibility | Easily adjusted to changes in product quantity (Kimura et al. 2015) |
| Costs | Investment costs and payback period (Bonini, Urru, and Echelmeyer 2016) |
| Parts-to-robot OPSs | |
| Throughput | Throughput (Derby 2008) |
| Lead time | Cycle time (Kim et al. 2003a), picking time (Khachatryan and McGinnis 2005) |
| Flexibility | Adapt robot to pick new items (Dieter Schraft and Ledermann 2003) |
| Operational efficiency | Robot travel time (Kim et al. 2003b), robot utilisation (Li and Bozer 2010) |
| Picker-less OPSs with dispensers | |
| Throughput | Throughput (Liu et al. 2011) |
| Lead time | Picking time (Yigong 2008) |
| Human factors | Safety (Franklin et al. 2008)Staff satisfaction (Franklin et al. 2008) |
| Quality | Picking error (Franklin et al. 2008) |
| Operational efficiency | Efficiency (Franklin et al. 2008) |
| Costs | Operational costs (Caputo and Pelagagge 2006; Liu et al. 2011) |
| Picker-less OPSs with A-frames | |
| Throughput | Throughput (Pazour and Meller 2011) |
| Lead time | Picking time (Jin, Yun, and Gao 2015) |
| Operational efficiency | Dispensing efficiency (Jin, Yun, and Gao 2015)Picker utilisation (Boywitz, Schwerdfeger, and Boysen 2019) |
| Costs | Total restock cost (Liu et al. 2008)Replenishment and picking costs (Meller and Pazour 2008)Infrastructure investment (Meller and Pazour 2008) |

**Table 3.** Links between performance and design identified in the literature on parts-to-picker OPSs with automated storage and retrieval systems (AS/RSs).

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

**Table 4.** Links between performance and design identified in the literature on parts-to-picker OPSs with vertical lift modules (VLMs).

| | | Performance categories | |
|---|---|---|---|
| | | Throughput | Lead time |
| Design categories | Policy | Storage policy affects throughput (Battini et al. 2015; Sgarbossa, Calzavara, and Persona 2019).<br>Batching increases throughput (Lenoble, Frein, and Hammami 2016). | Order batching policy affects order picking time (Lenoble, Frein, and Hammami 2018). |

*4.2.1.1. Automated storage and retrieval systems (AS/RSs).* **Throughput** is studied by many researchers. Medeiros, Enscore, and Smith (1986) develop a model to predict the performance of a mini-load through analysing throughput by changing storage policies, crane speed, and aisle layout. Mahajan, Rao, and Peters (1998) study the retrieval sequencing in an AS/RS and its effect on throughput. Park, Foley, and Frazelle (2006) analyse high and low storage turnover zone effects on AS/RS throughput. Manzini, Gamberi, and Regattieri (2006)

**Table 5.** Links between performance and design identified in the literature on parts-to-picker OPSs with conveyors.

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

**Table 6.** Links between performance and design identified in the literature on parts-to-picker OPSs with carousels.

| | | Performance categories | | | |
|---|---|---|---|---|---|
| | | Throughput | Lead time | Operational efficiency | Costs |
| Design categories | Policy | Dwell-point policy affects throughput (Park and Rhee 2005). | Picking policy affects retrieval time (Chang, Wen, and Lin 1993).Dwell-point policy affects job sojourn time (Park and Rhee 2005).Batching policy affects order picking time (Lenoble, Frein, and Hammami 2017). | Retrieval policy affects carousel travelling time (Litvak and Adan 2001). | Picking policy affects picking costs (Lee and Kuo 2008). |

**Table 7.** Links between performance and design identified in the literature on parts-to-picker OPSs with robotic parts-to-picker systems.

| | | Performance categories | | | | |
|---|---|---|---|---|---|---|
| | | Throughput | Lead time | Flexibility | Operational efficiency | Costs |
| Design categories | Equipment | Number of robots affects throughput (Bauters et al. 2016). | | Sensor type affects flexibility (Hanson, Medbo, and Johansson 2018). | | Order batching and sequencing affect used robot numbers (Boysen, Briskorn, and Emde 2017). |
| | Policy | Storage and replenishment policies affect throughput (Lamballais Tessensohn, Roy, and De Koster 2020). Robot assignment strategies affect throughput (Roy et al. 2019). | Robot-sharing policy affects throughput time (Yuan and Gong 2017), picking policy affects picking time (Xue, Dong, and Qi 2018). Battery management policy affects throughput time (Zou, Xu, and De Koster 2018). Robot assignment strategies affect throughput time (Roy et al. 2019). | Battery management policy affects flexibility (Hanson, Medbo, and Johansson 2018). | Battery management policy affects robot uptime (Hanson, Medbo, and Johansson 2018). Robot routing policy affects collision rate (Kumar and Kumar 2018). Order sequencing affects efficiency Zhao et al. (2019). Routing strategy affects picker and robot utilisation (Wang, Chen, and Wang 2019). | Order batching and sequencing affect robot maintenance and charging costs (Boysen, Briskorn, and Emde 2017). Shelves' moving time affects costs (Li et al. 2017). |
| | Layout | Location of workstations affects throughput (Lamballais, Roy, and De Koster 2017). Ratio of picking stations to replenishment stations (Lamballais Tessensohn, Roy, and De Koster 2020). | Warehouse height and footprint affects average cycle time (Ekren and Heragu 2010). | | Warehouse height and footprint affect vehicle and lift waiting times and average utilisation (Ekren and Heragu 2010). Picking area layout affects robot travel time (Wang, Yang, and Li 2019). | |

study how throughput is affected by storage assignment and fulfilment policies, order consolidation, and routing and sequencing policies. Andriansyah et al. (2011) propose a simulation model for a mini-load OPS and study how retrieval strategy and number of mini-load machines affect throughput. Güller and Hegmanns (2014) study the effect of the number of order lines per order on the throughput of AS/RSs. Ramtin and Pazour (2015) investigate how throughput is affected by optimal stock keeping unit (SKU) assignments for pick positions in AS/RSs.

**Lead time**-related aspects have been studied by several researchers. Khojasteh and Son (2008) modelled an AS/RS in different warehouse settings and saw the effect on order retrieval time. The considered design parameters were number of aisles, warehouse density and configuration of rack (Khojasteh and Son 2008). Andriansyah, Etman, and Rooda (2010) present a model to predict order flow time performance for an AS/RS that reflects warehouse reliability in meeting customer due dates. The model analyses the system performance in different settings of product interarrival rates, order release strategies, and order length distribution, which is the number of SKUs to be picked in an order (Andriansyah, Etman, and Rooda 2010).

**Operational efficiency** for AS/RSs is investigated by examining various aspects. Kusiak, Hawaleshka, and Cormier (1985) study the effect of picking density on weighted tardiness. They find that tardiness is reduced for a high number of locations and low machine tour numbers. Medeiros, Enscore, and Smith (1986) study the effect of storage policies, crane speed, and aisle layout on operator and machine utilisation. Hwang, Baek, and Lee (1988) present heuristic algorithms for order batching, which leads to decreasing AS/RS machine travel times. Chiang et al. (1994) study the effect of several design aspects: rack shape, number of picking locations, and picking area layout, on machine travel time in AS/RSs. In addition, Bozer and White (1996) estimate picker and machine utilisation in an AS/RS and how it is affected by retrieval and storage policies. Wu and Mulgund (1998) develop a model to minimise picker and machine idle time by balancing the work between them. Su (1995) reduces AS/RS machine travel time by optimising OP sequencing and routing. In a later study, Su et al. (2009) study the effect of machine routing on the distance travelled by the machine. Ramtin and Pazour (2014) compare different storage policies in an AS/RS and investigate their effect on machine travel time. Khojasteh and Jae-Dong (2016) develop a heuristic to minimise machine travel time in an AS/RS. A summary of the studied performance aspects of parts-to-picker AS/RSs is presented in Table 2. The links identified between performance aspects and relevant design aspects in parts-to-picker OPSs with AS/RSs are presented in Table 3.

#### *4.2.1.2. Vertical lift modules (VLMs).*

**Throughput** of VLMs has been studied by Bauters et al. (2011), who presented general guidelines to select between three parts-to-picker OPSs: VLMs, AS/RSs, and carousels. The comparison includes throughput, needed floor space, and number of operators, with the paper further highlighting some contextual constraints associated with item characteristics (Bauters et al. 2011). In addition, Battini et al. (2015) compare three storage assignment strategies in a VLM and develop a model to study their effects on throughput. Lenoble, Frein, and Hammami (2016) found that batching increases throughput in VLMs, and Sgarbossa, Calzavara, and Persona (2019) found that class-based storage policies also increase throughput in VLMs.

**Lead time** has been studied by Lenoble, Frein, and Hammami (2018) for different order batching strategies and their effects on OP time. **Human factors and operational efficiency** have been studied by Dukic et al. (2018), who presented a comparison between VLMs and traditional manual picking systems in terms of ergonomics, space utilisation, and time. They find VLMs to be more ergonomic than manual OPSs (Dukic et al. 2018). A summary of the studied performance aspects of VLMs is found in Table 2. The links identified between performance aspects and relevant design aspects in parts-to-picker OPSs with VLMs are presented in Table 4.

#### *4.2.1.3. Conveyors.*

**Throughput** has been studied by Andriansyah et al. (2014), who investigated the effects of picking policies on throughput in a conveyor-based OPS and found that dynamic picking results in higher throughput rates. Furthermore, Liu et al. (2015) developed an algorithm in a conveyor-based OPS and found that throughput and conveyor waiting times are affected by the OP strategy.

**Lead time** in OP is studied in three papers. Armstrong, Cook, and Saipe (1979) study how batching affects order processing time in a conveyor system. Andriansyah, Etman, and Rooda (2009) propose a simulation model for a conveyor-based OPS to predict the mean and variability of order flow times and the effect of order size distribution on flow time prediction. Wu et al. (2017) develop a heuristic to minimise order fulfilment time by reducing idle time and open space in conveyor- and dispenser-based OPSs.

**Operational efficiency** has been addressed by Wu and Wu (2014), who developed a heuristic algorithm to improve picking efficiency in conveyor- and dispenser-based OPSs by reducing idle time. They find that idle time affects order fulfilment time (Wu and Wu 2014). A summary of the studied performance aspects of conveyor-based OPSs is found in Table 2. The links identified between performance aspects and relevant design aspects in parts-to-picker OPSs with conveyors are presented in Table 5.

*4.2.1.4. Carousels.* **Throughput** of carousels is studied by Park, Park, and Foley (2003); the researchers examine throughput under two different pick-time distributions, depending on whether the picker is a person or a robot. In addition, Park and Rhee (2005) measure the throughput of a carousel and how it is affected by a floating or fixed dwell-point strategy.

**Lead time**, specifically retrieval time, is studied by Chang, Wen, and Lin (1993), who study the effect of different picking strategies on retrieval time. Job sojourn time is investigated by Park and Rhee (2005) in relation to two dwell-point strategies. Lenoble, Frein, and Hammami (2017) provide a model of batching strategies in the case of single and multiple carousels, with the objective of minimising OP time. Furthermore, Yanyan, Shandong, and Changpeng (2014) present a method to select suitable OPSs between a conveyor or a carousel based on the density and quantity of customer orders, from the standpoint of OP time.

**Operational efficiency** is investigated by Litvak and Adan (2001), who develop a heuristic to minimise carousel travel time under different retrieval strategies. Park, Park, and Foley (2003) studied picker utilisation in carousels.

**Costs** are studied by Lee and Kuo (2008), who investigate the effect of different picking strategies and item density on picking cost in a carousel conveyor system. Table 2 summarises the performance aspects of carousel-based OPSs studied in the reviewed literature. The links identified between performance aspects and relevant design aspects in parts-to-picker OPSs with carousels are presented in Table 6.

*4.2.1.5. Robotic parts-to-picker OPSs.* Recently, attention has been brought to robotic parts-to-picker OPSs. **Throughput** is studied by Bauters et al. (2016), who analyse the performance of robotic mobile fulfilment systems (RMFSs) capable of lifting and moving inventory pods and compare them with AS/RSs performance. They find that the throughput of RMFSs is higher than that of AS/RSs and is affected by the number of automated guided vehicles (AGVs) and SKUs per rack (Bauters et al. 2016). Lamballais, Roy, and De Koster (2017) build models to estimate throughput in an RMFS. They find that the maximum throughput is affected by the location of workstations (Lamballais, Roy, and De Koster 2017). Furthermore, Lamballais Tessensohn, Roy, and De Koster (2020) also find that throughput increases when spreading inventory across multiple pods in RMFSs, when there is an optimal ratio between the number of pick and replenishment stations and when the pod is replenished before it is empty. Roy et al. (2019) analyse the effect of robot assignment strategies on throughput in RMFSs.

**Lead time** has been studied in several papers. Ekren and Heragu (2010) model the performance of an autonomous vehicle storage and retrieval system (AVS/RS). They investigate the effect of warehouse height and footprint on average cycle time. Lamballais, Roy, and De Koster (2017) build models to estimate average order cycle time in RMFS. Yuan and Gong (2017) evaluate the throughput time of an RMFS by comparing two robot-sharing policies and studying their effect on throughput time. Xue, Dong, and Qi (2018) provide a comparative analysis of three picking strategies in an RMFS and their effect on picking time and distance travelled by robots. Zou, Xu, and De Koster (2018) evaluate the effect of battery management strategy on throughput time in an RMFS, where they compare robots' battery swapping and charging strategies. Roy et al. (2019) find that the robot assignment strategies affect throughput in an RMFS.

**Human factors** are evaluated by Lee, Chang, and Choe (2017) with a focus on ergonomics in RMFSs and AS/RSs; they find that AS/RSs have lower risk factors for human workers than RMFSs. In addition, Hanson, Medbo, and Johansson (2018) study the performance characteristics of RMFSs and the links between their performance and design, taking ergonomics and operator training into consideration.

**Quality and flexibility** are studied by Hanson, Medbo, and Johansson (2018); they elaborate on RMFS picking accuracy and find that robot design with regard to sensors and battery management strategy, in specific induction charging, affects RMFS flexibility.

**Operational efficiency** is addressed by Ekren and Heragu (2010), who study the effect of warehouse height and footprint on the waiting times for vehicles and the average utilisation of vehicles and lifts in an AVS/RS. Lamballais, Roy, and De Koster (2017) estimate robot utilisation in RMFS. Hanson, Medbo, and Johansson (2018) find a correlation between the uptime of robot sensors and battery management strategy as well as between robot sensors and operational efficiency. Kumar and Kumar (2018) developed a robot routing algorithm that results in a collision-free path for RMFSs. Zhao et al. (2019) found that order sequencing affects efficiency in AVS/RSs. Wang, Chen, and Wang (2019) find that the routing strategy in RMFSs affects picker and robot utilisation. Wang, Yang, and Li (2019) find that different RMFS layouts affect robot travel time. Table 2 summarises the performance aspects of robotic parts-to-picker OPSs studied in reviewed literature. The links identified between performance aspects and relevant design aspects in parts-to-picker OPSs with robotic parts-to-picker systems are presented in Table 7.

#### 4.2.2. Robot-to-parts

Kimura et al. (2015) study the **flexibility** of an OPS consisting of a mobile dual arm robot performing the actual picking, mounted on an AGV for transportation. The system can be easily adjusted to changes in product quantity by changing the system design, specifically the number of AGVs used, the use of a dual or single arm robot, and a change in the number of grippers (Kimura et al. 2015).

**Costs** are studied by Bonini, Urru, and Echelmeyer (2016), specifically investment costs and the payback period for a robot mounted on an AGV.

**Lead time**, in specific picking time, has been studied by Zhu et al. (2016); they examine different picking strategies for a robot performing the actual picking of items for e-commerce and the effects of picking strategy on reachability, collision, picking success rate, and picking time. Boudella, Sahin, and Dallery (2018) develop a mathematical model for the assignment of SKUs in a robot-to-parts OPS.

Table 2 summarises the performance aspects of robot-to-parts OPSs studied in the reviewed literature. Furthermore, the links between performance aspects and relevant design aspects in robot-to-parts OPSs are presented in Table 8.

#### 4.2.3. Parts-to-robot

Derby (2008) studies a multi-arm robot designed for pick-and-place operations where **throughput** is found to be dependent on robot speed and acceleration.

**Lead time** is studied by Kim et al. (2003a), who develop a replenishment process logic for gantry picking to shorten cycle time. Khachatryan and McGinnis (2005) study a gantry pick-and-place robot in a puffer picking station and find that the greater the number of buffers, the shorter the picking time.

**The flexibility** of robots in terms of adaption to picking new items is studied by Dieter Schraft and Ledermann (2003), who study a robot for picking chaotically stored objects in a bin. To adapt the robot for new items, they consider the items' sizes and geometry, bin geometry, positioning of items, and the area's layout (Dieter Schraft and Ledermann 2003).

**Operational efficiency** is investigated by Kim et al. (2003b), who develop a heuristic to minimise travelling time of a gantry robot. In addition, Li and Bozer (2010) develop a simulation model to analyse four retrieval strategies in a carousel-based OPS, with robots performing the picking activity; they study the effect of retrieval strategies on robot utilisation (Li and Bozer 2010).

Table 2 presents a summary of the studied performance aspects of parts-to-robot OPSs. The links between

**Table 8.** Links between performance and design identified in robot-to-parts OPS literature.

| | | Performance categories | |
|---|---|---|---|
| | | 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 affect 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).<br>The storage assignment of stock keeping units affects picking cycle time (Boudella, Sahin, and Dallery 2018). | |

**Table 9.** Links between performance and design identified in parts-to-robot OPS literature.

| | | Performance categories | | |
|---|---|---|---|---|
| | | Throughput | 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).<br>Number of buffers affects picking time (Khachatryan and McGinnis 2005). | Retrieval policy affects robot utilisation (Li and Bozer 2010). |

**Table 10.** Links between performance and design identified in picker-less OPS literature.

| Design categories | | Performance categories: Throughput | Lead time | Human factors | Quality | Operational efficiency | Costs |
|---|---|---|---|---|---|---|---|
| | 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, Yun, and Gao 2015). | | | Order of storage containers affects dispensing efficiency (Jin, Yun, and Gao 2015). Order sequencing affects picker utilisation (Boywitz, Schwerdfeger, and Boysen 2019). | The number of pickers affects operational costs (Caputo and Pelagagge 2006).Slotting policy affects restock costs (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). |

performance aspects and relevant design aspects in parts-to-robot OPSs are presented in Table 9.

### 4.2.4. Picker-less

The performance of dispensers and A-frames is studied by many researchers. Liu et al. (2011) conclude that for a multi-dispenser OPS, the slotting strategy influences **throughput**. **Lead time** aspects are studied by Yigong (2008), who finds that OP sequence in dispensers affects picking time. Jin, Yun, and Gao (2015) find that a dispenser picking time is affected by storage container assignment. **Human factors** are studied by Franklin et al. (2008), who investigated the effect of two dispenser types on safety and staff satisfaction. **Quality** is studied by Franklin et al. (2008), where they study the effect of two dispenser types on picking error.

**Operational efficiency** is studied by Franklin et al. (2008), who evaluate the impact of dispensers on efficiency. In addition, Jin, Yun, and Gao (2015) develop a simulation model of a dispenser route and find that dispensing efficiency is affected by the order of storage containers. Boywitz, Schwerdfeger, and Boysen (2019) find that the order sequencing affects pickers' utilisation of A-frames.

**Cost**-related aspects are covered by many researchers. Caputo and Pelagagge (2006) develop a decision support system for operating a dispenser OPS. In this study, the operational costs of OP are linked to the number of pickers and demand contextual aspects (Caputo and Pelagagge 2006). Liu et al. (2008) present an optimal slotting solution for an A-frame, focusing on minimising total restock costs. In a later study, Liu et al. (2011) find that the slotting strategy influences operational costs. Meller and Pazour (2008) develop a heuristic for an A-frame dispenser addressing SKU assignment and allocation with consideration of replenishment and picking costs. Pazour and Meller (2011) determine the amount of A-frame infrastructure investment, considering the assignment and allocation of SKUs to meet the throughput requirement.

Table 2 presents a summary of the studied performance aspects of picker-less OPSs. Furthermore, the links between performance aspects and relevant design aspects in picker-less OPSs are summarised in Table 10.

## 5. Discussion and opportunities for future research

The descriptive analysis indicates an increased research interest in the area of automation in OPSs in recent years, which may be due to its importance, technological advancements and the increased use of automation in practice.

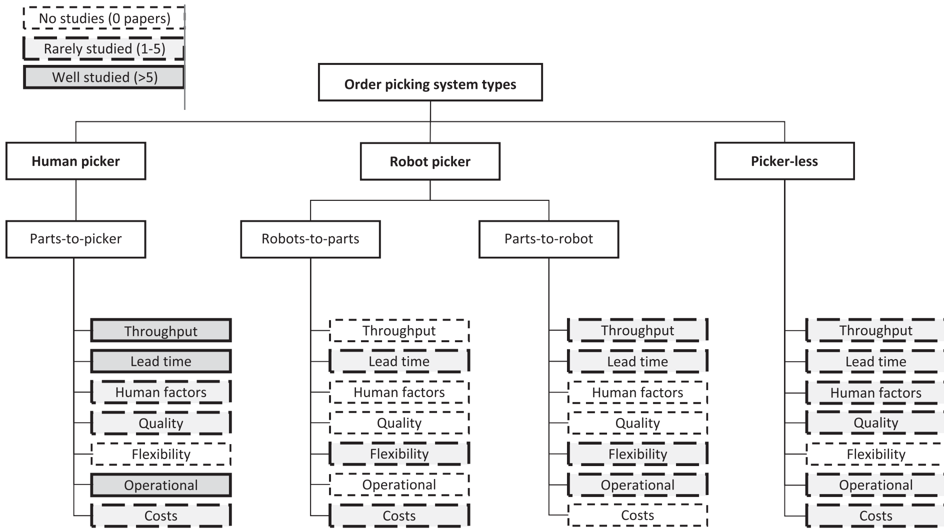


**Figure 5.** Summary of studied performance aspects per OPS type.

Figure 5 presents a summary of the studied performance categories in the reviewed papers for each OPS type, indicating the number of studies for each performance category. Accordingly, throughput, lead time, and operational efficiency were the most-studied performances in parts-to-picker OPSs. Few papers focus on human factors, quality, and costs. In robot-to-parts OPSs, few papers study lead time, flexibility, and costs. In parts-to-robot OPSs, throughput, lead time, flexibility and operational efficiency are investigated only in few papers. In picker-less OPSs, studies cover most performance categories except flexibility. More research could be directed towards the flexibility of parts-to-picker systems to adequately compare them with other OPSs, including OPSs with robot pickers. Despite their importance, human factors are poorly studied in automated, or partly automated, OPSs; therefore, more research is deemed necessary to cover these factors. Quality and operational efficiency of OPSs with a robot picker could also benefit from more research, considering the technological developments in the area and their increased use in the industry.

Maximising throughput is the goal of most warehouses and companies operating a parts-to-picker OPS with an AS/RS. The reviewed literature highlights that the storage, retrieval and routing policies affect throughput (e.g. Medeiros, Enscore, and Smith 1986; Manzini, Gamberi, and Regattieri 2006). This is mainly because different policies impact the distance travelled by the storage and retrieval machine differently, in addition to the different effects the policies have on machine and operator utilisation. All of these contribute to the throughput of the OPS. In OPSs with VLMs, order batching is found to positively impact throughput in studies by Lenoble, Frein, and Hammami (2016; 2018). The researchers found batching to result in time savings by reducing the number of times a tray is called for picking, which allows orders to be picked simultaneously (Lenoble, Frein, and Hammami 2016; Lenoble, Frein, and Hammami 2018). In robotic parts-to-picker OPSs, batching is also found to affect the number of robots used (Boysen, Briskorn, and Emde 2017), as batching requires fewer robots to supply the picking station in a timely manner. Moreover, the battery management policy in robotic parts-to-picker OPSs is found to affect throughput time (Zou, Xu, and De Koster 2018), as the charging time of robots differs depending on whether it is a high- or low-demand period. In low demand, the robots are working one shift and charging at night, while more charging time is needed when the robots are working for more than one shift, which affects the number of available robots and throughput time.

Decision support for selection and design of automated, or partly automated, OPSs is still lacking in the literature. In this regard, further research would be recommended to, first, adequately address the support for decision-making regarding automation in OP systems and, second, perform comparative analysis of the different OPSs with regard to their installation, performance categories, and strengths and limitations. Furthermore, layout design aspects appear to be less studied than picking policies, which could be the result of a lack of appropriate tools and metrics. Thus, these could be interesting areas for further research. In addition, contextual aspects, which are factors outside the control of the system designer, were not considered in this study, although they could affect the OPS performance, as indicated by several authors (e.g. Caputo and Pelagagge 2006; Yanyan, Shandong, and Changpeng 2014). Therefore, this area would be important to investigate in future research. Finally, the scarcity of empirical research has been recognised, which is also emphasised by Marchet, Melacini, and Perotti (2015). The majority of papers use analytical and simulation models, with a limited number of papers having empirical data. Therefore, there is rationale for conducting further empirical research and performing case studies on automated OPSs to understand their performances.

## 6. Conclusion

This paper has presented a systematic literature review of papers in the field of automation in OPSs. In total, 74 papers were selected, reviewed, categorised, and analysed to understand the performance aspects for each automated, or partly automated, OPS and the studied links between their design and performance. The study identified the decision-making process of automation in OPS to be a complex area that would benefit from more academic research, particularly in the links between the different performance and design aspects.

The study has both academic and practical implications. For academics, this paper synthesises the current knowledge and accomplished work in automation in OPSs and identifies opportunities for future research. For practitioners, the paper offers a better understanding and overview of the performance and design aspects of various OPSs and the links existing between them. These links need to be considered to enhance and support the decision-making process of automation in OPSs.

## Disclosure statement

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

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