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Performance Characteristics of Robotic Mobile Fulfilment Systems in Order Picking Applications

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Abstract: This paper addresses the application of automation in warehouse order picking. Specifically, the paper deals with Robotic Mobile Fulfilment Systems (RMFSs). Existing literature has indicated that RMFSs can bring benefits in several performance areas, but research that deals with these benefits in detail is scarce. The purpose of the paper is to identify the performance characteristics of RMFSs and the relations between these performance characteristics and the design of the RMFSs as well as the context in which they are applied. The paper includes a review of existing literature on RMFSs and presents a case study from an application of an RMFS in the order picking of consumer goods in an e-commerce setting.

Keywords: Order picking, warehousing, automated material handling, Robotic Mobile Fulfilment Systems

1. INTRODUCTION

Warehouse order picking is an activity with an important role in many supply and distribution settings, not least since the recent increase in e-commerce. However, order picking often requires large amounts of manual labour. Solutions for applying automation in order picking processes have been available for decades, but in industrial applications, manual order picking has been the most common approach (De Koster et al. 2007). It seems that despite the high labour cost associated with manual order picking, the industry in general has either not identified sufficient benefits of automation, or has not had the ability to realise them. In the experience of the authors, knowledge is often lacking within industry regarding when and how automation should be applied. There is a multitude of different options available for applying automation in order picking, including different levels of automation, e.g. semi-automation or full automation, and different types of solutions, e.g. crane-based systems or dispensers (De Koster et al. 2007; Marchet et al. 2014). However, the multitude of options available does not facilitate decision-making with regard to whether and how automation should be applied in order picking. To make decisions like these, a designer of an order picking system needs knowledge of how different solutions would perform, given the context in which they would be applied.

Order picking systems are often classified as either picker-to-parts systems or parts-to-picker systems, where the former are generally manually operated and the latter generally partly or fully automated (Dallari et al. 2009; De Koster et al. 2007). The type of automation applied in parts-to-picker systems are generally AS/RS systems based on cranes (De Koster et al. 2007), but in recent years, Robotic Mobile Fulfillment Systems (RMFSs) have been introduced, in which automated guided vehicles, here referred to as robots, move along the floor and fetch materials to the pickers. As described by Lamballais et al. (2017), the system comprises a storage area, a number of movable inventory pods (often shelf racks), a number of robots, and a number of picking stations. Each inventory pod often contains several stock keeping units (SKUs). When an order is to be picked, it is assigned to a picking station. Thereafter, robots move underneath the inventory pods containing the required SKUs and bring them to the picking station, where a picker picks the required items. When the picker has finished picking from an inventory pod, the robot transports it back to the storage area or to another picking station. Replenishment of the inventory pods may be performed at the picking stations or, as described by Enright and Wurman (2011) and Huang et al. (2015), at separate replenishment stations. The system is managed by a control software, which coordinates the storing, moving, and picking activities (Huang et al. 2015). Fig. 1. shows components of an RMFS and what an RMFS warehouse can look like.

RMFSs in order picking have been suggested to support productivity and a reduced need for manual labour, compared to a fully manual system, while at the same time being flexible enough to enable large volume adjustments (Huang et al. 2015). Moreover, an RMFS can be used to reduce order fulfillment time in warehouses (Yuan and Gong 2017). Still, however, little research has been directed towards the applicability of RMFSs, identifying how they perform in different contexts. Without understanding of this, the full benefits of applying RMFSs are not likely to be realized. Therefore, the current paper has the purpose of identifying the performance characteristics of RMFSs and the relations

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between these performance characteristics and the design of the RMFS as well as the context in which it is applied. While the paper focuses on RMFSs, it also brings insight into the broader area of automation in order picking systems.

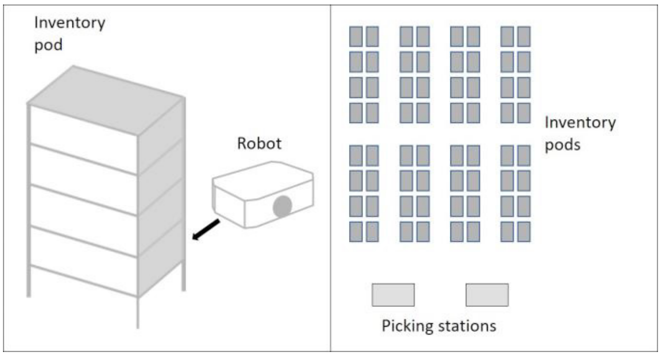

Fig. 1. An inventory pod (shelf rack) and a robot to the left and a layout sketch of a section of an RMFS warehouse to the right.

Next, in section 2, the paper presents a review of existing literature on RMFSs. Thereafter, section 3 presents the method applied in the study. Section 4 presents the case description and analysis. In section 5, the results of the paper are presented. The paper concludes with a discussion and conclusions, presented in section 6.

2. LITERATURE REVIEW

The current section presents a review of literature published on the topic on RMFSs. In particular, the section presents the focus of the reviewed publication and the performance areas brought up.

Huang et al. (2015) present an overview of recent industrial development and discuss their implications for e-commerce logistics facilities. They mention several performance areas where RMFSs are beneficial: they can reduce manual labour, offer a high flexibility for handling a wide variety and variability of orders and for managing fluctuating volumes. Moreover, Huang et al. (2015) point out that RMFSs can be associated with high levels of OEE, as the different robots are independent of each other, so that if one robot breaks down or is taken out for maintenance, this does not affect the rest of the system.

Enright and Wurman (2011) present a general description of the RMFS provided by Kiva Systems and focus particularly on the control of the system and on the associated allocation problems. They point out that by eliminating the walking of the pickers, required in traditional warehouses, a RMFS increases the productivity of the pickers.

Lamballais et al. (2017) develop analytical queueing network models to estimate performance of RMFSs. They focus on the performance areas of order throughput, average order cycle time, robot utilisation, and workstation utilisation. In addition, they state that general benefits of RMFSs are that they are flexible, so that both layout and capacity of the systems can easily be adapted. The capacity can be adapted both in terms of the number of robots and the number of workstations. The system can also be configured so that the most popular products are located close to the picking stations. Moreover, Lamballais et al. (2017) state that the storage area of RMFSs is often compact, containing only a few days of inventory.

Yuan and Gong (2017) develop models and perform simulations to determine the optimal number and velocity of robots to minimise throughput time in an RMFS, considering congestion of the system.

Zou et al. (2017) build a semi-open queueing network and use it to study assignment rules and shelf block size affect throughput time of an RMFS.

Boysen et al. (2017) discuss that the introduction of an RMFS heavily influences the planning and sequencing of picking orders. Compared to simple rule-based approaches, often used in warehouses, an optimised order processing procedure suggested indicates a substantial reduction of the required number of robots. Moreover, Boysen et al. (2017) argue that storing of different SKUs in the same pod will further reduce the required number of robots. Thus RMFSs are especially suitable in warehouses storing small sized items.

Altogether, while research efforts have been directed towards the performance of RMFSs, these efforts seem to have largely disregarded any relations between performance and the contexts in which the RMFSs are operating. In the systems theory, contextual influence is highlighted to have a potentially significant impact on system performance.

3. METHOD

The paper is based on a case study of the implementation and operation of a RMFS in a distribution warehouse, where the RMFS was applied in the picking of consumer goods in an e-commerce setting. The warehouse in which the RMFS was applied was operated by a major, globally operating third-party logistics provider (3PL). The case was selected as it featured a full-scale implementation and operation of an RMFS in an order picking operation, which was found to support the fulfilment of the paper's aim. Moreover, through a joint research project with the third-party logistics provider, and through well-established relations also with the supplier of the RMFS in question, the researchers were given access to information. In the remainder of the paper, the provider of the RMFS will be referred to as the RMFS provider and the 3PL company applying the RMFS will be referred to as the RMFS operator.

The data were collected approximately two years after the RMFS had been implemented and put into service, at which time it was possible to learn about both the implementation and the operational performance of the RMFS. Interviews were conducted face-to-face with the personnel at the RMFS operator who were responsible for the introduction and initial operation of the RMFS, as well as with a representative from the RMFS provider. The interviews were semi-structured and each was conducted by two researchers. The researchers' notes from the interviews were sent to the respective interviewees for verification.

During the interviews, the researchers noted that the representatives of the RMFS operator and the representative of the RMFS provider were well aligned in their views and experience of the RMFS.

In a coming step of the case study, the existing literature will be reviewed further and a model will be developed that supports further analysis of the case data. Moreover, the case data will be complemented both with interview data from the company that was served by the RMFS, i.e. the customer of the RMFS provider, and with record data from the RMFS operator. This will give a more detailed insight into how the RMFS performed.

The record data that will be extracted reflects the performance of the RMFS in terms of resource consumption, measured through the number of operator as well as the amount of equipment applied, in relation to system output, measured through the number of order lines picked.

4. CASE DESCRIPTION AND ANALYSIS

The installation of the RMFS took place in 2015. The RMFS operator, i.e. the company that purchased and applied the system, was a third-party logistics provider (3PL). The initial application of the RMFS was in an order picking operation dedicated to one of the customers of the RMFS operator, selling consumer goods via e-commerce. The warehouse facility in which the RMFS was applied was rented by the RMFS operator with a 10-year contract. The facility had a ceiling height of 11,7 metres. Approximately 30,000 stock keeping units (SKUs) were handled in the RMFS, which included 65 robots and 1550 inventory pods. The inventory pods had different configurations, to enable them 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.

In the interviews, several performance areas were brought up, where an RMFS is likely to differ from alternative solutions for order picking. Below, the information from the interviews is presented under six different performance areas.

4.1 Productivity

Compared to fully manual order picking systems, an RMFS reduces the amount of manual labour in the order picking operations. Here, the interviewees pointed out that these benefits are greater if there are large numbers of SKUs handled. This is because with large numbers of SKUs, a fully manual order picking system would be associated with considerable time for travelling between the many picking locations, especially if the consumption rates were relatively evenly distributed between the different SKUs. The representative of the RMFS provider further pointed out that it would be possible to let the robots in an RMFS serve an automated picking station, instead of a human picker, which could then increase productivity further.

One aspect that affected the productivity in the system was the "hit rate", as the interviewees termed the number of successive picks that could be from one inventory pod at one picking station, before the pod was shifted. Different aspects affected the average hit rate, including the demand for the different SKUs and the number of customer orders that were picked at the same time.

4.2 Uptime

If one robot malfunctions or needs maintenance, it is easy to take it out of the system, without much interference with the rest of the system. Moreover, if the robot batteries are charged through induction while running, the overall uptime and utilisation could in theory be very high. In the studied case, however, the system was run during only one shift per day, apart from during demand peaks.

The robots in the studied case navigated by use of QR-codes on labels on the floor. A drawback of this navigation was that it was not entirely reliable. The representative of the RMFS provider admitted that with the current configuration and exactness of the equipment, a robot could miss a label, which would then make it stop. Since the RMFS applied in the studied case did not include stop sensors on the robots, which would make them stop in case an operator stepped in front of them, the entire system would have to be shut down for a few minutes, in order for an operator to put the robot back on track. During the interviews, it was pointed out that there exist other RMFSs with stop sensors. Moreover, the navigation could be developed to achieve a higher reliability.

4.3 Flexibility

The inventory pods used in an RMFS can be flexible, so that the compartments of the pods can be adapted in size, in turn enabling different types of goods to fit into them. For example, the inventory pods can be adapted to handle goods in boxes as well as goods hanging on racks. As one interviewee pointed out, this is attractive especially for third-party logistics providers, who may face situations where customers come and go, and where the types of goods handled hence may change. Moreover, as observed in the case, different types of inventory pods can be included in the same system at the same time, to enable a wide range of different types of goods in the system.

An RMFS can be said to be based on modules: robots, inventory pods, and picking stations. By adding or removing modules, it is easy to adapt the volume capacity of the system. The interviewees agreed that the system was easy to implement and did not require much other prerequisites than an even floor that was kept relatively clean. Because the robots in the case navigated by use of QR-codes on labels on the floor, it was important to keep the labels readable. In the case, the RMFS operator used large filters in the warehouse ventilation systems and while this was a solution that was applied also in many manually operated warehouses, it was found to be more or less a necessity in a warehouse where an RMFS should operate.

In the studied case, the robots in the RMFS did not include sensors that stopped them in case anything, or anyone, came in their way. Therefore, the system operated within safety fences. The representatives of the RMFS operator stated that it took some time to move or expand the safety fences and that this could restrict the speed with which the RMFS could be reconfigured. A similar phenomenon was linked to the use of inductive charging of the robots while they were running. This approach was optional and had been chosen by the case company in order to reduce the need to stop the system. A drawback was that the charging system, which was built into the floor, made the whole RMFS more complicated to move or to reconfigure in terms of floor space.

The relative volume flexibility of an RMFS depends on what it is compared to. In many respects, manual order picking systems can be said to have a high volume flexibility, but in practice, it can be difficult to quickly increase the capacity of a manual order picking system, especially if only for a short period of time. The RMFS operator of the studied case chose to apply an RMFS because of their previous experience of manual order picking systems, which were found insufficient when it came to handling demand peaks around "Black Friday" and Christmas. The problems with the manual systems were foremost that it was difficult to gather enough staff for such short periods of time and that the temporary staff did not have sufficient experience to achieve satisfactory levels of productivity. In addition, the manual order picking systems had been found to get congested when too many pickers operated at the same time.

While the RMFS enabled the RMFS operator to meet peak demand, it was in practice difficult for the company to adapt capacity to follow the demand fluctuations. In terms of staffing, additional shifts were added around the peaks, which meant that the number of operators was relatively well adapted to the demand variations. However, the number of robots was more or less constant over the entire year, which in practice meant that most of the year, the robots did not have a very high utilisation rate over a full day, but were mostly run during only one shift. The interviewees stated that if there had existed other RMFSs, with which robots and inventory pods could be pooled, these problems could have mitigated, assuming the demand patterns of these other systems were different, but this was not the case.

A further measure that was used to adapt capacity to match variations in demand was to alternate between a "pick-and-pack" approach, which was the approach used most of the time, and a "pick-and-pass" approach, which was used during demand peaks. In the "pick-and-pack" approach, the same operator performed both picking and packing of orders, whereas in the "pick-and-pass" approach, the picking was performed by one operator and the packing by another, which meant that the capacity in the system was increased.

4.4 Picking accuracy and operator training

One interviewee, representing the RMFS operator, stated that picking accuracy could be supported by use of RMFSs, compared to manual order picking systems. By using stationary picking stations, as opposed to having the pickers moving around the warehouse and picking at different locations, it was easier to install picking support systems. In the studied case, picking accuracy was supported by a light beam that indicated the correct picking location, and by a place-to-light system, with lights indicating the correct placement locations. This was also related to the time required for training new operators, which was found to be shorter with an RMFS than in manual order picking.

4.5 Space utilisation

Compared to manual picking from shelves, an RMFS was by the interviewees stated to offer a higher space utilisation, as the aisles required for the robots to extract the inventory pods is narrower than the aisles required for manual picking. In contrast, compared to other types of automation, such as crane- or shuttle-based systems, the space utilisation of the RMFS is often poor, as the RMFS cannot utilise the space of higher buildings. Hence, as pointed out by the representative of the RMFS provider, RMFSs are competitive foremost when applied in relatively low buildings. However, in the studied case, the ceiling height of the facility in which the RMFS was applied would have been sufficient for a crane- or shuttle-based system, but the RMFS operator still preferred the RMFS over crane- or shuttle-based systems, mainly due to flexibility requirements.

4.6 Investment cost

The representatives of the RMFS operator and the representative of the RMFS provider agreed that the use of an RMFS is associated with a relatively low investment cost in relation to other types of automation in order picking. Alternatives such as crane- or shuttle-based systems are generally considerably more expensive. However, the interviewees agreed that the suitability of RMFSs relates to the volumes handled. An RMFS was found to be best applied in environments with moderate to high volumes: with low volumes, a fully manual system would generally be more suitable, and with very high volumes, crane- or shuttle-based systems would generally be more suitable.

4.7 Ergonomics

One of the interviewees, representing the RMFS operator, stated that the benefits of an RMFS, compared to fully manually operated warehouses, included improved working conditions and ergonomics of the pickers. Instead of constantly having to move around the warehouse, the pickers in an RMFS perform picking at stationary picking stations, under controlled and predictable conditions. Linked to this, the interviewee stated that it was easier to recruit pickers to an RMFS than to a fully manual picking system. Moreover, the interviewee anticipated it would be easier for older pickers to operate an RMFS than a manual system.

5. RESULTS

The results of the paper, derived from the case description and analysis presented in section 4, are presented in Tables 1, 2, and 3. Table 1 presents general performance characteristics of an RMFS, i.e. performance characteristics that do not seem to be closely linked to any particular aspects of the design or of the context. Table 2 instead presents relations that between the design and the performance of an RMFS. Similarly, Table 3 presents relations between the context and the performance of an RMFS.

Table 1. General performance characteristics

General performance characteristics
Uptime: An RMFS can display a high overall uptime as maintenance and repairs can be performed of one robot or workstation at a time, without stopping the whole system.
Flexibility: The compartments of the inventory pods can be adapted to fit different types and sizes of goods.
Flexibility: An RMFS is based on modules (robots, inventory pods, and picking stations) and can be easily implemented and adapted to changing volumes.
Flexibility: An RMFS can be applied either with a "pick-and-pack" or with a "pick-and-pass" approach. This way, capacity adjustment can be made through the number of operators in the system, without changing the number of robots or picking stations.
Picking accuracy and operator training: The operator may be better supported in the stationary picking of the RMFS, compared to a fully manual system. This can support picking accuracy and reduce the need for operator training.
Ergonomics: The stationary picking associated with an RMFS may support ergonomics, compared to a fully manual order picking system.

Table 2. Relations between RMFS design and performance

Design aspect	Performance impact
No. of orders picked at the same time	*Productivity*: With many orders picked at the same time, overall time for shifting inventory pods at the picking stations is reduced and productivity increased.
Induction charging during operations	*Uptime*: If the robot batteries are charged during operations, the maximum potential uptime of the system increases.
Induction charging during operations	*Flexibility*: If the robot batteries are charged during operations, the system for induction charging may restrict
Robot sensors	*Uptime*: If the robots do not have stop sensors, the entire system needs to be temporarily stopped in order for an operator to enter the area where the robots operate.
Robot sensors	*Flexibility*: If the robots do not have stop sensors, the safety fences needed around the system makes it more difficult to move the RMFS or to adjust the area where it operates.

Table 3. Relations between RMFS context and performance

Contextual aspect	Performance impact
Number of SKUs	*Productivity*: With a large number of SKUs, the advantages of a RMFS compared to a manual system are increased.
Possibility to pool resources	*Flexibility*: If pooling of robots can be achieved with other RMFSs, flexibility to efficiently handle volume fluctuations can be increased. Otherwise, overcapacity may be required to handle volume peaks.
Ceiling height of building	*Space utilisation*: An RMFS does not utilise the full height of a high building.
Volumes picked	*Investment cost*: Compared to fully manual systems and other automated systems, the productivity in relation to the investment cost favours RMFSs when volumes are medium to high.

6. DISCUSSION AND CONCLUSIONS

This paper has presented preliminary findings from an ongoing study. From the paper, it is clear that several performance areas can be affected by the application of an RMFS, compared to fully manual systems or other types of automation. Based on a case study of the application of an RMFS, the paper has provided insights into the performance of RMFSs and how this performance relates to the design as well as the context of the RMFS.

The paper is based on a single case study, which is something that could limit the generalisability of the findings. However, through the case study and the interviews it entailed, insight was given also regarding the applicability of RMFSs in contexts other than that of the studied case. The case study included interviews with representatives from both the provider and the operator of the RMFS, i.e. two parties with different perspectives of the system. The fact that these two parties were well aligned in terms of their statements strengthen the validity of the paper’s findings.

In a coming step, the case study will be developed further, based on additional data as well as on a more refined analysis approach, utilising a model derived from existing literature.

So far, the application of RMFSs is relatively limited and research on the topic is scarce. Several areas could be addressed in future research. It seems that RMFSs are mainly applied in settings of distribution to consumer. It could be interesting to consider potential applications in settings of distribution to business customers or in materials supply to manufacturing.

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