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A Simulation Analysis of Part Feeding to Assembly Stations with Vertical Robotic Storage and Retrieval Systems

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Abstract. The evolution of customer requirements has led companies to pursue mass customization and personalization strategies, increasing the complexity of part feeding operations in assembly systems. At the same time, emerging technologies, based on mobile robots, promise to support material handling activities in an efficient yet flexible manner. This paper studies part feeding to assembly stations with Vertical Robotic Storage and Retrieval Systems (VRSRS), a new technology that allows automating both the storage and the internal transportation activities with the same fleet of mobile robots. We develop a Discrete Event Simulation model of a system made of a Central Warehouse replenishing supermarkets which, in turn, supply mixed-model assembly stations. Through this model, we carry out experiments showing a clear trade-off between the number of robots, which affects the overall investment in the system, and the supermarkets size, which affects space occupation in the shop floor, where space is a critical resource. We also estimate the replenishment lead time and the downtime of assembly stations, showing that this system performs best when small production orders are issued and could therefore be a suitable solution to support part feeding activities in a mass customization context.

Keywords: Parts Feeding, Factory Logistics, Mobile Robots, Supermarket Warehouses, Discrete Event Simulation.

1 Introduction

The evolution of customer requirements has led companies to pursue mass customization and personalization strategies. Although beneficial from a sales perspective, the implementation of such strategies may increase the complexity of operations within assembly plants [1]. In fact, it calls for a sharp rise in the number of part variants and it entails assembling goods in small batches, so as to offer a wide product range without overly increasing inventories [2]. In this context, companies are adopting mixed-model assembly lines, where a single line is able to assemble several product variants or models [3]. To cope with these challenges, and since the available space at the border of the

lines is normally scarce [4], part feeding systems are shifting towards frequent deliveries of small quantities of parts, like boxes or totes, to assembly stations [5, 6]. This part feeding policy is often supported by the use of supermarkets, i.e. decentralized warehouses located in the shop floor allowing to reduce delivery lead times [7, 8]. The related academic literature is mainly focused on supermarkets design (e.g. [9, 10]) and on the scheduling, loading, and routing of tugger trains for parts delivery to assembly stations (e.g. [11, 12]). Some research gaps still need to be addressed. In particular, while emerging technologies, based on mobile robots, promise to support material handling activities in an efficient yet flexible manner, there is a gap about the application of such technologies in part feeding systems. Among these technologies, Vertical Robotic Storage and Retrieval Systems (VRSRS) are extremely interesting in this context because they allow automating both the storage and the internal transportation activities with the same fleet of mobile robots, thus seamlessly integrating the two activities. This is possible since the robots, carrying totes, can both roam the shop floor and navigate inside the storage racks, moving horizontally and vertically (Figure 1). This system has been studied in literature in relation with distribution centers only by [13]: they develop a queuing network-based model of VRSRS, but they neglect the possibility for robots to navigate outside the racks. Only one contribution has addressed the deployment of VRSRS in a factory environment [14], but it models the replenishment of supermarkets from the central warehouse, without considering the transportation of totes to assembly stations.

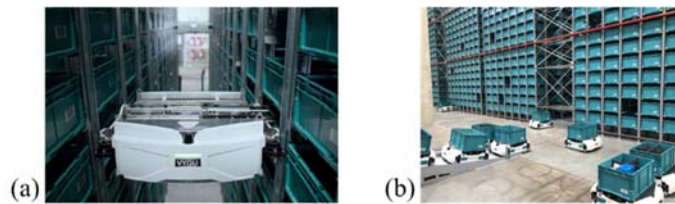


Fig. 1. Mobile robots inside (a) and outside (b) the storage racks (source: Exotec Solutions)

This research aims to assess the performance of a part feeding system to assembly stations based on VRSRS. We study the system through Discrete Event Simulation (DES), and we measure its performances in terms of replenishment lead time and downtime of assembly stations due to lack of materials.

The remainder of this paper is organised as follows. Section 2 gives an overview of the system under analysis, while Section 3 describes the developed simulation model. Section 4 reports the results of our analysis: we test alternative configurations of the part feeding system, differing among each other due to the supermarkets size, and we evaluate the impact of production order size (i.e. number of assembled products per order) on system performance. Finally, Section 5 includes conclusions and directions for future research.

2 System Description

Figure 2 shows the layout of the system considered in this paper. It consists of a central warehouse (CW) replenishing supermarkets which, in turn, supply mixed-model assembly stations. Each type of stations can make multiple product models. We assume that there are two stations of each type, facing away from each other (e.g. station “A” and station “B” in the figure), and they share the same stock. The product models made by one type of stations cannot be assembled by stations of a different type.

All warehouses are VRSRS made of one aisle (supermarkets) or multiple aisles (CW), with two single-deep storage racks per aisle. Each rack is divided into storage columns and storage levels. Totes are stored randomly within the warehouses, i.e. the probability of accessing any column or level is based on the uniform distribution. Each CW aisle has an input/output (i/o) point for robots, while each supermarket has an input point, facing the CW, and an output point, facing assembly stations.

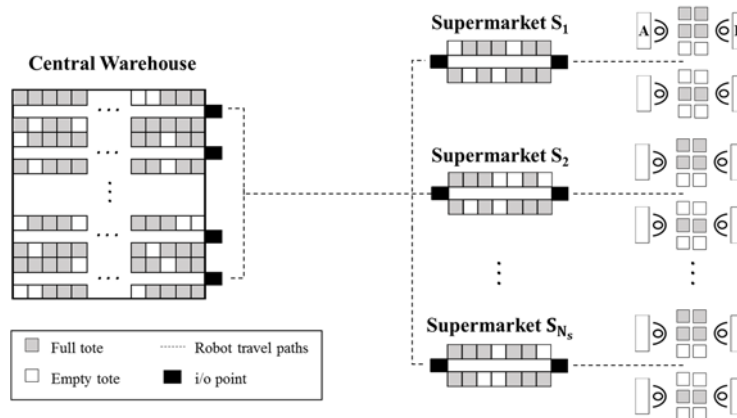


Fig. 2. Part feeding system layout

Robots handle mono-item totes, denoted as “full totes”, and perform single-command cycles inside storage racks: they enter the storage aisle input point, travel horizontally to reach the storage column, climb the rack up to the storage level where they retrieve or store the tote, and then travel vertically and horizontally towards the output point. To avoid deadlocks, one robot at a time can access a supermarket or a CW aisle.

Robots can also travel outside the racks, following the bi-directional paths shown in Figure 2, so as to replenish supermarkets and to feed assembly stations with full totes. Supermarket replenishment works according to the kanban system, as in previous studies (e.g. [5]): whenever a tote is retrieved from the supermarket, its replenishment from the CW is triggered. Similarly, part feeding to assembly stations is controlled through a two-bin inventory system [15]: two totes per each part type are stored between each couple of stations of the same type and, whenever a tote is empty, its replenishment from the supermarket is triggered. Each supermarket supplies four assembly stations.

Finally, we assume that the management of empty totes at the assembly stations is out of scope. For instance, empty totes could be stacked on pallets next to each assembly station and forklift trucks could be used to periodically collect them.

3 Simulation Model

The DES model of the system was implemented in MATLAB-Simulink, using the SimEvents library. As shown in Figure 3, it is made of four main parts. The first part, highlighted in green, models the generation of robots at the start of the simulation and their travel inside the CW. Robots are modelled as entities of the system: after they are generated, they queue up before the CW in a First In First Out (FIFO) robot queue, waiting to be matched with tote replenishment orders. An order can be issued by either an assembly station or a supermarket. In the former case, if the robot queue in front of the supermarket supplying the assembly station is empty, a robot travels from the CW robot queue to that supermarket, in order to replenish the station as explained further in this section. In the latter case, instead, the robot travels from the CW robot queue to the input point of the CW aisle where the tote required by the supermarket is stored. This travel is modelled as an infinite server, assuming that there are no interferences among robots outside the racks. The same assumption is made for all the other robot movements outside the racks. Thus, the robot travel time from the queue to the CW aisle only depends on the selected aisle and on the robot speed. As in [13], a fixed speed equal to 1 m/s is assumed. Then, to simulate the robot movement inside the racks, each of the 7 CW aisles is modelled as a single server, so as to allow its access to one entity at a time. The CW maximum height is set equal to 10 m. To compute the number of storage levels and all the dimensions of the CW, the assumptions made by [13] about storage locations size are taken into account.

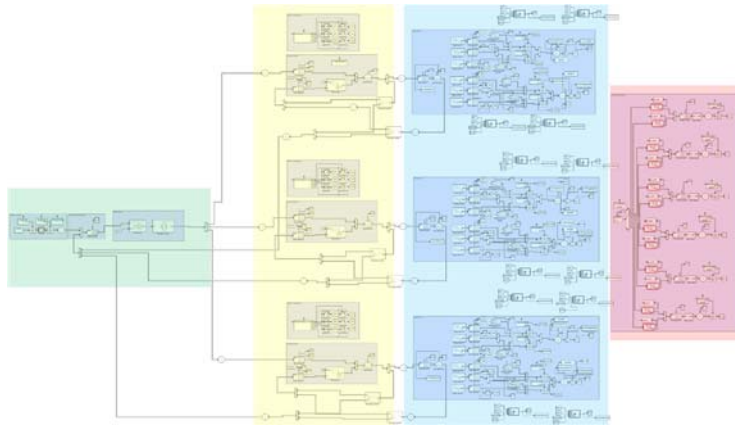


Fig. 3. DES model of the robot-based part feeding system, implemented in Simulink

The second part of the model, highlighted in yellow in Figure 3, simulates the travel of the robot from the i/o point of a CW aisle to the input point of a supermarket and inside the supermarket. The travel from the CW to the supermarket is modelled as an infinite server, whose service time depends on the robot speed and on the distance along the path shown in Figure 2 (120 m for the cross-aisle connecting the CW with the supermarket area, plus the distance from the CW aisle i/o point to this cross-aisle and from this cross-aisle to the supermarket input point). Three supermarkets, evenly distributed along the shop floor, are considered in the model. Supermarkets are modelled as single

servers, whose service times depend on the same assumptions made for the CW aisles. After storing the tote and exiting the supermarket from its output point, robots queue up in front of the supermarket, waiting for a replenishment order. When a replenishment order is received from an assembly station, as soon as the supermarket is idle and the required tote is available, the robot enters the supermarket, picks up the tote and exits the supermarket. A signal is sent to the CW to trigger the tote replenishment. The maximum supermarket height is set equal to 5 m, accounting for the real industrial applications. Based on the supermarket storage capacity, the number of storage columns is determined. We assume that the supermarket is full at the start of the simulation.

The model section highlighted in blue in Figure 3 simulates the travel of the robot between the supermarket output point and the assembly station, the assembly activity and the ensuing consumption of parts. The distance between a supermarket and a station is assumed to be fixed (15 m). After delivering the full tote to the assembly station, the robot either returns to the queue in front of the supermarket, if this queue is empty, or travels to the queue in front of the CW. After a tote is delivered to the assembly station, new entities are generated, corresponding to the parts stored in that tote, that queue up before the station. As regards the assembly activity, we assume that each type of assembly station can make four different product models and each model is made of two parts replenished through the robot-based feeding system: a first part specific of that model and a second one shared with another model assembled at the same station. The assembly of a product may start when three conditions have been verified through a gate: a signal has been received to start the assembly (as explained later in this section) and the two parts are available at the station. These parts are subtracted from the total stock available at the station through an entity terminator, so as to model parts consumption: when all the parts in a tote have been used up, the replenishment from the supermarket is triggered. The number of parts stored in a tote is assumed to be equal to 10, for part types specific of one product model, and to 20, for part types shared by two models. Each couple of stations of the same type is modelled as a dual server, meaning that one product at a time can be assembled at each station. Service times of the assembly stations are exponentially distributed, as in previous simulation analyses of production systems (e.g. [16]), with an average of 30 seconds.

The model part highlighted in pink in Figure 3 simulates the arrival of production orders (i.e. the demand). An entity generator creates orders with exponentially distributed inter-arrival times. An order is assigned to one of the product models through an entity output switch, according to a uniform distribution. Then, an entity replicator generates a number of entities corresponding to the production order size, i.e. the number of assembled products per order. The order size is fixed for all the orders during a simulation. Based on the product model, the entities of an order are assigned to an assembly station and wait in a FIFO queue before a single server. When the first entity enters this server, a signal is sent to the assembly station (model section highlighted in blue) to trigger assembly activities. After they exit the single server, entities are terminated.

Each run of the model simulates an 8-hours shift. The model was verified and then validated by comparing its output, in terms of assembled products per shift, with the theoretical output, i.e. the overall demand per shift. This comparison was made considering a number of robots high enough to avoid that robots were the bottleneck in the system. It was found that the difference between the simulation output and the theoretical one is always below 5%, thus mostly due to the stochasticity of the assembly time.

4 Results Discussion

4.1 Relationship between Supermarkets Size and Number of Robots

The main design variables of this system are the supermarkets size, S_s , i.e. the number of totes that can be stored in each supermarket, and the number of robots, N_R , needed to fulfill all the replenishment orders. Once fixed the number of supermarkets, S_s determines space occupation in the shop floor, where space is a critical resource, while robots are the main component of the investment in this system [14]. Thus, the first experiments are aimed at studying the relationship between these two variables.

Figure 4 shows the results when the average demand is 960 orders per shift and the order size is 10 products per order. The colored areas inside the chart represent the difference between the system output, i.e. assembled products per shift, and the required output, i.e. overall demand. In particular, the dark blue area corresponds to the combinations of S_s and N_R for which the system is able to fulfill demand (difference below 5%, that can be ascribed to the stochasticity of demand). Results show a trade-off between S_s and N_R : by increasing N_R , a lower S_s is needed to fulfill demand because the throughput capacity of the system increases; vice versa, the higher S_s the lower the needed N_R , since more totes are stored in the shop floor and thus a lower speed of supermarket replenishment activities has a lesser impact on overall system performances.

Results also show that, given an adequate investment in the robot fleet, the system can fulfill demand with extremely small supermarkets (in the scenario of Figure 4, even less than 50 totes per supermarket, corresponding to less than 5 m² per supermarket).

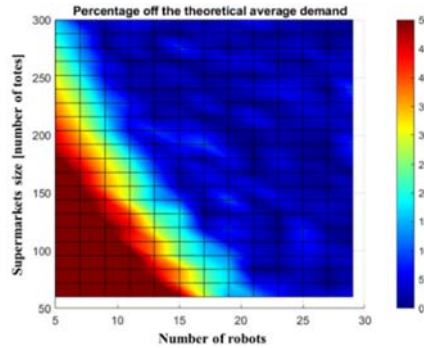


Fig. 4. Relationship between supermarkets size and number of robots

4.2 Relationship between Order Size and System Performance

One of the effects of mass customization is a smaller size of production orders. Therefore, with the second group of experiments we study how system performances change when varying the number of assembled products per order and the number of robots. Performance measures encompass the average replenishment lead time (LT) and the average downtime of the assembly stations due to lack of parts (DT). LT is defined as the average time elapsed between a request for tote replenishment by an assembly station and the tote delivery to the station. DT is defined as the percentage of the 8-hours shift during which assembly stations are not working due to lack of materials.

In order to plot results and make them comparable, the overall demand in terms of assembled products per shift was fixed for all the scenarios and the number of orders per shift was varied accordingly. For instance, Figure 5 shows results for a demand equal to 9,600 products per shift and S_S equal to 150 totes: LT and DT improve when decreasing the production order size, going from the red areas (where LT can be as high as 100 seconds and DT can reach 15% of the 8-hours shift) to the dark blue ones (LT close to 30 seconds and DT close to 0%). Therefore, results show that this system performs better with a lower order size. This is due to the nature of the system itself, which is designed to handle small quantities of several part types: big production orders would overly stress the system since they would require a high quantity of one or few part types, exceeding the quantity stored at the border of the stations and possibly even the quantity stored in the supermarkets.

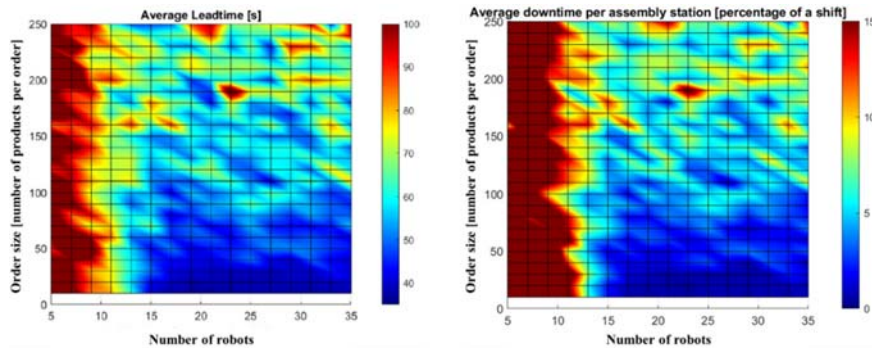


Fig. 5. Relationship between order size and LT (on the left), DT (on the right)

5 Conclusion

New material handling technologies, based on mobile robots, promise to improve the efficiency of part feeding activities in the context of mass customization and personalization. This paper is the first to study a part feeding system to assembly stations based on VRSRS. We develop a DES model of a system made of a CW replenishing supermarkets that, in turn, supply mixed-model assembly stations.

Through the experiments we conduct, we show the trade-off between the number of robots and the supermarkets size, concluding that, if an adequate investment in the robot fleet is made, this system is able to effectively supply assembly stations even with extremely small supermarkets, thus saving space in the shop floor. Furthermore, we show that this system performs best, in terms of replenishment lead time and downtime of assembly stations, with small production orders, and therefore may be suitable to support part feeding activities in a mass-customized system.

The main limitations of this study are related to the assumptions made in the model development; future research could enlarge the experiments performing sensitivity analyses to understand how our results change when varying parameters. Moreover, future developments could include cost analyses or model extensions to test different layouts of the system, considering a different number of supermarkets or even direct deliveries of totes from the CW to assembly stations.

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