Omni-Directional Conveyor Platform: A Review Paper from Automated Sorting System and Operation Research Perspective

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Abstract- **Global trends such as just-in-time, containerization, and e-commerce have led to an ever increasing freight volume to be transported under tight delivery schedules. Many supply chains, thus, apply fully-automated sorting systems as one basic component of their distribution processes. Examples range from baggage handling in airports, over parcels sorted by tilt tray conveyors in distribution centers of the postal service industry, up to batches of picking orders isolated in the warehouses of e-commerce retailers. This paper surveys the scientific literature on all kinds of fully-automated conveyor-based sorting systems from an operational research perspective. We describe the wide range of applications and their different sorting systems, define their joint decision problems to be solved when designing and operating a sorter, review the literature, and identify future research challenges.**

Index Terms- Automation; Sortation systems; Material handling; conveyor platform.

1. INTRODUCTION

Nowadays, automated sorting systems (ASS) have become an essential component in many supply chains, mainly because of four elementary characteristics:

ASS are fast: Next-day or even same-day deliveries are an elementary promise of many online retailers [4] and postal service providers [5]. When subtracting the transportation times this leaves only narrow time windows for all retrieval and sorting operations. Without automated sorting these targets seem barely realizable.

ASS handle a huge amount of shipments: For instance, the air hub in Cologne (Germany), which is one of world-wide three main hubs in postal service provider UPS' express logistics network, has a capacity for sorting up to 190,000 shipments per hour. ASS are reliable: The U.S. Department of Transportation [10], for instance, reports a range from 1.42 to 9.17 when ranking 19 U.S. airlines with regard to the mishandled baggage per 1.000 passengers. Clearly, any lost or delayed baggage causes loss in goodwill so that a reliable automated baggage handling became a critical success factor in the airline industry.

ASS handle heavy and bulky items: The aging societies in many industrialized countries suggest to automate activities causing high ergonomic stress for human workers. The repeated handling of heavy shipments is certainly among these activities so that ASS handling oversized shipments have a long tradition in postal distribution centers[6] and cross docks. Although the basic layout of an ASS is fairly simple – it mainly consists of one or multiple input stations for receiving, a network of conveyor segments, and multiple outbound stations for collecting the shipments sorted by addressee – quite a few decision problems need to be solved when designing and operating an ASS. This paper surveys ASS from an operational research (OR) perspective. We introduce the main fields of application for ASS and describe the basic strategic and operational decision problems. Furthermore, we survey the existing scientific literature and identify future research challenges.

For this purpose, the remainder of the paper is structured as follows. Section 2 defines the scope of this survey. Then, Sections 3 to 6 address the main fields of application for ASS. For each field, namely ASS in warehouses, cross docks, in the postal service industry and in airports, we describe the layout of their typical ASS, define the basic decision problems to be solved, and review the literature. Finally, the results, key findings, and future research needs are discussed in Section 7.

2 SCOPE OF SURVEY

An ASS is a fully-automated conveyor system where an intermixed sequence of inbound ship- ments, which enter the system via one or multiple inbound stations, is sorted into outbound stations assigned to different addressees. According to our definition an ASS consists of three basic elements: (i) inbound stations, (ii) the main conveyor, and (iii) outbound stations. To realize a specific ASS implementation these elements can be differentiated as follows:

(i)In its most basic form an ASS has only a single inbound station so that all shipments enter the system via the same access point. A typical inbound station consists of a conveyor belt, first, moving shipments towards a recognition system, where they are weighed and identified, e.g., by scanning a bar code attached to a piece of baggage [1], by identifying a handwritten address on a parcel by some optical character recognition (OCR) software [6] or by receiving information from an RFID chip [57]. Afterwards, a switch system successively loads the shipments onto the main conveyor and ensures an appropriate distance among each other. Alternatively, the main conveyor can also manually be loaded by human workers. Note that the succession of identification and loading can also be reverted. Larger ASS often have multiple inbound stations. For instance, the central airhub of postal service provider DHL in Leipzig (Germany) has four inbound stations [6]. Multiple access points increase the infeed capacity and avoid a bottleneck on the loading side. Properly spaced and alternatingly placed with outbound stations, multiple inbound stations allow for multiple loads of the same conveyor segment per cycle. Each occupied position on the main conveyor can be refilled at the successive inbound station, if the shipment reaches its dedicated outbound station beforehand.

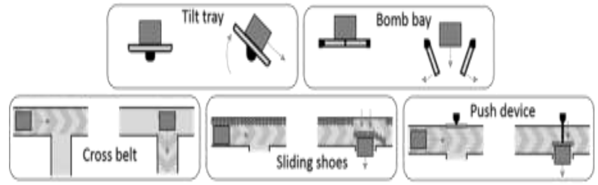


Figure 1: Alternative sorter technologies

(ii)The main conveyor steadily moves loaded shipments along a fixed pathway, while passing junctions towards outbound stations. A typical velocity for such a conveyor is about 2.5 m/s [6]. There are different technical solutions of how a shipment is redirected into its outbound station (see Figure 1). A wide-spread solution are tilt tray conveyors consisting of distinct trays each of which to be loaded with a single shipment. Each tray is tiltable to one or both sides so that a shipment can slide into its dedicated outbound station. Other solutions are bomb bay sorters, where the floor plate is opened and the shipment falls into a large bag or container, and cross belt sorters, where each conveyor segment is a small conveyor by itself operating at right angles towards the direction of the main conveyor. Finally, also some form of sliding shoes or other push mechanism can be applied. From an OR perspective, the technical realization of the sort mechanism is less of an issue. It is rather the structure of the pathway, which influences the operational processes. In its most basic form the pathway is just a line. A line requires that undelivered shipments, e.g., due to a tailback at an outbound station, are collected at the end, transported back to the access point, and reinserted into the system from time to time. This additional effort can be avoided if the pathway is a closed loop (resp. recirculation conveyor, loop sorter). Then, undelivered shipments can cycle on the loop until congestion is eliminated. However, there also exist bi-directional systems consisting of multiple loops arranged above each other [7]. These systems allow to direct shipments into both directions so that the shorter path towards the respective outbound station can be selected. Finally, the pathway may consist of a complex network of conveyors. For instance, Jarrah et al. [11] report on a distribution center of a postal service provider applying a hierarchical system, i.e., consisting of pre-sorter plus final sorters. In this way, a decomposition into smaller subsystems is enabled. We like to emphasize here that normally it is sufficient to capture the structure of the pathway (e.g., loop) rather than the exact shape (e.g., circle).

(iii)Each outbound station can be assigned a specific addressee to receive all dedicated shipments. The appearance of an outbound station heavily depends on the field of application as well as the size and weight of the shipments. Wide-spread solutions are dead-end conveyor segments, e.g., piers for collecting all baggage for a specific flight [7] or telescope conveyors to be pulled directly into a truck trailer [6]. On the other hand, bomb-bays or chutes can also direct a shipment directly into a large bag or small transport container. Again, from an OR perspective the technical realization does, typically, not influence the decision problems. An important issue, however, is the durability of the destination assignments. If outbound destinations are served again and again, e.g., by multiple trucks each day, then fixed destination assignments are typically applied. This allows the workers to learn the topology of the terminal. Fixed destinations are often applied in the postal service industry, where they are altered just once every couple of months [8]. Online retailers supply a huge variety of customers so that under these circumstances variable destination assignments need to be applied. Here, an outbound station is only briefly assigned to a specific order until all items are collected. Then, the station is reassigned to receive the next order.

By combining these characteristics of our three basic system elements different ASS can be realized. The schematic layout of a multi-inbound, loop-based tilt tray system, which is, for instance, often applied in the postal service industry, is depicted in the left part of Figure 2. In the following, we briefly sketch the main fields of application where ASS are applied (see the right part of Figure 2). We systemize these applications by the source of its inbound stream, which may either stem from a warehouse or has just been delivered in a hub environment, and the dedicated means of transportation, i.e., truck or aircraft.

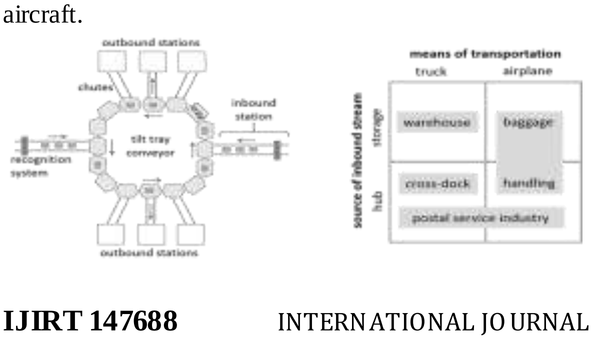


Figure 2: Schematic ASS layout (left) and fields of application (right)

The typical applications of ASS in Warehouses, i.e., facilities to intermediately store goods in between two successive stages of a supply chain (see [51]), are twofold. First, ASS play a crucial role if a batching and/or zoning policy is applied (see [12]). Batching means that multiple customer orders (i.e., a batch) are jointly collected from the shelves by a picker so that more efficient picker tours through the warehouse are enabled. Under a zoning policy, the warehouse is subdivided into multiple areas from which order pickers pick the part of the order that is in his/her assigned zone. In both cases, an ASS can be applied to split the collected items and to accumulate the customer orders. Once each picking order is readily packed into a dedicated shipment, ASS can also be applied to sort these packages bytheir dedicated shipping ways. The outbound stations of these ASS are often telescope conveyors to directly transport the parcels into the truck trailers of different transport providers.

Cross docks are special distribution terminals without long-term storage dedicated to a consolidation of smaller shipments to full truckloads (see [24, 111, 34]). These terminals often apply closed-loop sub-surface chain conveyors (also denoted as draglines, see [15]). In these systems, hand pallet trucks carrying pallets of goods can be coupled with the chain, which pulls them through the terminal. This way, pallets pass by their dedicated trailers so that logistic workers can release the respective pallet truck and can directly move the pallet into the trailer. Alternatively, the literature also reports on less-than truckload logistics providers applying belt-based ASS to consolidate shipments (see [8]).

In the postal service industry, sorting mail and parcels is barely thinkable without ASS. Postal service providers, such as UPS and DHL, apply huge systems consisting of complex conveyor networks, and bi-directional loops with multiple inbound stations as described in [6]. They exist for both truck-based continental transports [6] and airborne intercontinental services.

Baggage handling is among the most elementary services in any airport. Inbound bag- gage, i.e., newly arriving with passengers from the air- or landside or early check-in baggage from a storage area, needs to be delivered towards baggage sorting stations each assigned with an outgoing flight and terminating baggage of arriving flights needs to be transported towards baggage claims [13]. The huge amount of baggage to be handled in modern airports and the tight schedules make ASS an important facility inany airport.

Note that a more detailed description of the ASS applied in each field is given in Sections 3 to 6 each dedicated to one of these fields of application. Our (positive) definition of the paper's scope is now amended by a (negative) demarcation from related fields. We restrict our survey on conveyor-based systems where the path of a shipment is fixed for a given pair of inbound and outbound station. On this path, shipments do not move individually; that is at each moment all shipments on the conveyor move with the same speed.

Obviously, sorting can also be achieved by moving the shipments more individually, for exam- ple by placing each shipment on separate vehicles, which can either individually travel along a shared pathway or can reach their dedicated outbound stations on facultative paths. In this case, however, the routing aspect, i.e., the position of shipments over time, often is pre- dominant. Corresponding optimization problems, therefore, are rather close to vehicle routing problems and pick-up and delivery problems, which are very well covered by literature surveys, e.g., [69] and [16]. Our restriction excludes the following (related) sorting and transportation systems.

In container ports, automated guided vehicles (AGVs) transport containers between quay cranes servicing vessels and yard cranes of multiple container blocks [113]. AGVs can travel on individual paths (on a possibly restricted network) and are, thus, excluded. AGVs are also applied in warehouses to preposition items, e.g., in the KIVA system, see [20]. These systems are also excluded.

Individual vehicles moving along ever changing paths are also applied in an innovative sorting system based on autonomous robots (see [92, 104]). Each robot of a large fleet is loaded with an item and moves along a grid of squares on the shop floor towards one of many scuttles dedicated to the item's destination. Here, the robot tilts its tray so that the items on top slides into the scuttle where items are collected.

For baggage handling, there exist systems where each piece of baggage is placed on an individual destination-coded vehicle (see [13]). These unmanned carts propelled by linear induction motors are mounted on tracks, but can travel with varying velocity and distance among each other. Similar systems are also applied for supplying parts in production environments (see [70]).

Loop-based automated handling systems are applied in production environments to de- liver workpieces towards assembly stations. Nazzal and El-Nashar [88], for instance, survey these systems in wafer production systems; other hoist-based systems are applied in the electronics industry.. However, these systems typically have to successively visit multiple stations for assembly operations, such that no direct relation to sorting exists.

Recent prototypes try to apply the basic logic of ASS for even larger shipments such as containers. They are, for instance, applied in railway yards where gantry cranes consoli- date containers among different freight trains (see [27]). To relieve the cranes from long horizontal travel along the yard (and the crane interference such a movement would in- duce) modern yards apply rail-bound shuttle cars, which move containers between crane areas (see [8]). These shuttles, however, move individually along the tracks so that these systems are excluded.

Another sorting system in the rail context are traditional shunting yards. Here, inbound waggons are uncoupled, moved over a shunting hill, and – when rolling down – directed onto outbound tracks via switches. This way, intermixed inbound trains are assembled (sorted) to outbound trains heading towards their respective destination. A recent survey on shunting yards is provided by Boysen et al. [2]. However, the movement downwards the shunting hill can facultatively be retarded with the help of break shoes so that no steady movement arises.

Our survey is not dedicated to technical aspects, such as the applied hardware, but rather takes the OR perspective. We, thus, focus the main decision problems to be solved when planning and designing a new ASS (or altering an existing one) and when operating an ASS. Ordered with regard to their planning horizon, we structure the multitude of decision problems into the following four areas:

Layout problems need to be solved if a new system is designed or an existing one is to be altered. In these cases, layout alternatives need to be evaluated according to the basic trade-off between performance and investment costs. Specifically, the decision problems of this phase have to decide on all structural aspects, such as the number and locations of inbound stations, structure and length of the main conveyor (e.g., single-loop vs. bi-directional system), and the number and locations of outbound stations.

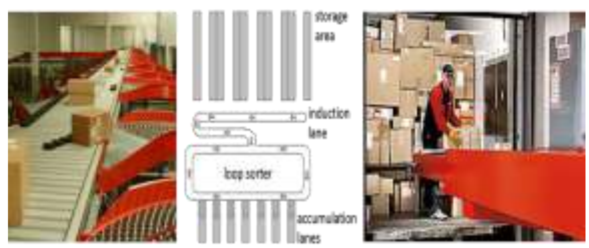
On the inbound side, the way of the shipments into an ASS has to be structured. This includes the choice of the inbound station for each shipment and the feeding sequence per station. In many terminals of the postal service industry, for instance, inbound trucks can be unloaded at different sides of the terminal so that alternative inbound stations are applied. This way, an appropriate assignment of unloading docks to trucks can influence the sortation performance (see [23]).

On the outbound side, destinations (addressees) have to be assigned to outbound sta- tions during ASS operations. In the literature, this problem is also denoted as the destination assignment problem [8]. The structure of this problem is mainly affected depending on whether a fixed (e.g., valid for several months) or a variable assignment that continuously alters is sought. Other decision problems on the outbound side are related to the staffing of the packing operations, which are required once shipments have reached their outbound stations.

Finally, short-term (or even real-time) scheduling decisions have to be made. They are, for instance, related to the point in time a shipment should be loaded onto the main conveyor. If alternatives are available, the specific path (in the network of conveyors) for each shipment has to be determined (see [7]).

The multitude of ASS applications make it anything but astounding that already some related survey papers exist. For instance, there are the surveys of De Koster et al. [12] on warehousing, of To˘sić[13], Ashford et al. [8] on airport operations, and of Boysen and Fliedner[8], Van Belle et al. [111], Buijs et al. [34], Ladier and Alpan [68] on cross docks. They all mention ASS as one aspect in a much broader context. Only the survey paper of Muth and White [86] is explicitly dealing with sorting systems. On the one hand, this paper is already quite old so that plenty additional papers have accumulated in the meantime. Moreover, the focus of theirsurvey is on analytical methods specifically dedicated to layout aspects. Thus, an up-to-date survey paper on ASS seems well justified.

Finally, we briefly specify our database search for retrieving the papers to be reviewed (see, e.g., Hochrein and Glock[14]] for a general description of how to set up a systematic literature retrieval). As keywords specifying our domain we apply “sorter”, “sorting system”, “sortation system”, “sortation conveyor”, “automated sorting”, and “order accumulation system”. Fur- thermore, a second group of keywords, i.e., “warehousing”, “warehouse”, “cross dock”, “cross docking”, “postal service” and “baggage handling” is applied to specify the field of application. Any combination of keywords from first and second group has been applied as a query in two scholarly databases, namely Business Source Premier and Scopus. All English-language papers published in peer-reviewed journals that have been retrieved and those cited in their reference lists (snowball approach) were checked for relevance by analyzing their abstracts. Additionally, some selected working papers and conference proceedings have been integrated, if (according to the authors’ subjective assessment) they considerably contribute to the surveyed field.



3.1 Layout planning

During the design phase, the physical layout of an ASS has to be determined. The main system elements that need to be selected during this phase and whose specification can be supported by OR methods are the following:

- selection of either line and loop sorter,
- capacity (length) of the sorter,
- velocity of the sorter, and
- number and capacity of accumulation lanes.

To quickly evaluate the trade-off between investment costs and operational performance of different elements and layouts, mainly fast methods such as analytical methods and simulation studies are suggested by the existing literature.

The items may then leave the system through one of multiple accumulation lanes. Items that do not leave the sorter circulate on a single recirculation conveyor. Finally, items leaving the system through the accumulation lanes are handled by a worker, who removes items from the lanes with a deterministic rate. In a slightly alternative setting, which is also simulated, the sorter does not allow recirculations at all, while the remaining setup remains identical. In that case, items are held at the end of the induction lane, if none of the suitable accumulation lanes is free. To account for stochasticity of the picking process, the authors assume that items entering the induction lane follow a Poisson distribution, while the destinations of the items are uniformly distributed. Service rates of operations on all lanes are deterministic, the system's total input capacity equals its total output capacity, and recirculation is only applied if an accumulation lane is full, i.e., failures like reading label errors are not considered. The simulation results show that in a system without recirculation the throughput ratio of the system decreases if the number of accumulation lanes increases. The throughput of a system with recirculation depends on the number of accumulation lanes, if those are uncapacitated. However, if the accumulation lanes are capacitated, the throughput capacity increases with the number of accumulation lanes and the capacity of the induction lane.

Summary and future research needs

The detailed breakdown of all 70 reviewed papers and how they fit into our framework is presented in the appendix. As a summary, we present the stacked bar chart of Figure 7 where we see the number of papers published in our four areas of ASS application over time. Except for warehousing, where ASS have a long lasting tradition and the number of published papers remains rather stable, the other three areas of application gain increasing attention over the years. In spite of the tremendous scientific work that already exists on ASS, we see a wide range of future research challenges which we elaborate in the following. We structure these challenges according to our framework which differentiates four areas of application and four decision areas.

Warehousing: One major problem of ASS in warehouses applied to sort customer orders picked under a batching and/or zoning policy is, that they are hardly scalable. Many warehouses face workloads that extraordinarily vary both during the week (i.e., most online retailers have their peak load after the weekend) and over the year (e.g., due to cyber monday or end of season sales). Moreover, many online retailers have to adopt their order fulfillment capacities to their growth rates so that they aim to flexibly adapt their sortation capacity. ASS, however, require plenty fixedly installed hardware, which is hardly adaptable over a shorter period of time. Due to this drawback, many online retailers apply manual sortation processes where they apply so-called put walls (see [30]). A put wall is a simple reach-trough rack separated into multiple shelves each temporarily dedicated to a specific customer order. On the other side of the wall reside packing workers, who empty shelves and pack completed orders into cardboard boxes. By adapting the workforce either to put items into the shelves or to pack them on the other side, sortation capacity can flexibly be altered. Future research should integrate the scalability aspect when evaluating the basic trade-off between the higher investment costs for ASS and higher personnel costs of manual sorting processes. Also, ideas how to make ASS better scalable seem very welcome.

Cross docks: Many cross docking terminals do not apply a sorter at all. Goods are moved with forklifts or pallet jacks inside the terminal instead. Future research should investigate the general trade-off between higher investment costs if an ASS is installed and larger personnel costs if goods are sorted manually in more detail. Decision support under which circumstances either solution is preferable seems highly welcome.

Postal service industry: Two general ASS layouts dominate within the postal service industry. Terminals either consist of two-stage sorting systems where a pre-sorter feeds multiple main sorters [11] or they provide a single loop (or a bi-directional system where conveyors are erected on top of each other) [43, 33]. The former provides redundancy and the system can still process even if one of the main sorters suffers a breakdown or is maintained. The reduced structure of the latter layout eases control and avoids schedul- ing and workforce decisions with regard to equalizing the workload among multiple main sorters. Systematic decision support with regard to which layout is best suited for whatspecific situation, however, is yet missing.

Airport: Baggage handling systems (BHS) in airports consist of complex conveyor net- works, whose structure is strongly influenced by the terminal layout. Therefore, exist- ing research mainly treats isolated case studies, whose results are barely generalizable. A valid general research question, however, is the comparison between the conveyor-based ASS surveyed in this paper and destination-coded vehicles (DCVs). The latter are shuttle-based system transferring bags individually (see [13]) so that they promise more flexibility and, thus, a higher throughput. However, quantifying the potential gains of DCV in dependency of different structural properties of the BHS (and comparing these gains with the higher investment costs) would be valuable decision support for airport managers having to decide on the proper type of BHS.

Layout: Scalability is promised by an alternative sorting system, which is not based on fixed pathways. In this system (see Section 2), individual autonomous robots move along a grid of squares on the shop floor towards one of many scuttles dedicated to the shipments's destination. A first application of such a grid-based sorting system consisting of a fleet of Hikvision robots is reported for a large warehouse in Hangzhou (China) [92, 104]). Each robot having the size of an autonomous vacuum cleaner is able to tilt its tray so that the item on top slides into the scuttle where items are collected for a specific destination. Such a system is easily scalable by adding or removing robots. However, the layout and operational decision problems to be solved for such a problem are completely different to those of traditional ASS. Another novel system applied in warehouses, e.g., the Zalando distribution center in Mönchengladbach (Germany) [15], is a bag sorter. They adapt the basic principle of hanging goods handling and move items in small bags hanging from trolley conveyors. After picking, individual items are filled each in a hanging bag, which are automatically moved into an intermediate storage area. Upon request, bags are moved out of their storage lanes, automatically sorted into the right sequence via a systemof switches and conveyed to packing stations. Here, items arrive in the right sequence so that one order after the other can be packed into its dedicated cardboard box. The big advantage of a bag sorter is that multiple orders can queue in front of their destination so that gridlocks due to unavailable packing can only occur if all queues are full. Scientific research on these systems is (to the best of the authors' knowledge) yet not available.

Inbound side: Existing research mainly focuses the assignment of incoming shipments to inbound stations (if multiple alternatives exist). In some applications, however, either a manual pre-sorting process or an intermediate transfer into and out off some automated storage and retrieval system (e.g., a crane-operated high-bay rack, see [29]) also allows for a manipulation of the sequence of incoming items. The first paper investigating the impact of the inbound sequence on sortation performance is the one of Briskorn et al. [7]. More research into this direction seems valuable.

Outbound side: An operational problem on the outbound side, which (to the best of the authors' knowledge) has not received any attention in the literature yet, is staffing and workforce scheduling in the outbound area. In warehouses, for instance, the accumulation lanes of an ASS are, typically, equipped with beacons that indicate completed orders. The packers filling these orders into cardboard boxes can either be assigned a fixed number of (typically consecutive) lanes or can freely roam through the packing area. The former is inflexible and may lead to additional idle time of packers, but has the advantage thaterrors can definitely be assigned to its culprit. Comparing both assignment policies and deriving suited scheduling procedures for both of them has not yet been considered in the literature. This is especially unsatisfying, because inefficient packing processes may lead to blocked outbound stations, which in the worst case may lead to gridlocks (see Section 3.2) on the main conveyor. Analogously, the staffing and workforce scheduling problems in cross docking terminals and facilities of the postal service industry have not yet been considered. Here, the workforce loading sorted shipments into the trailers needs to be scheduled. Each outbound station can be assigned its separate logistics worker. This rules out congested outbound stations and, thus, gridlocks, but comes for the price of high personnel costs. Instead, most terminals assign each worker multiple outbound stations. Decision support how many stations each worker should support is yet missing. This, also, holds true for the question when each worker should switch among stations in his/her area. A decision rule for this task has to consider the distributions of parcel arrivals, the fill levels of lanes (and the remaining time up to a congestion), and the worker's walking times among lanes.

Scheduling: Especially in the fixed-path ASS surveyed in this paper, there is often not much flexibility when feeding shipments onto the main sorter and channeling them to- wards outbound stations. Therefore, short-term scheduling may not be the foremost lever for increasing system performance. However, there are still quite a few interesting short-term scheduling problems whose impact on system performance should be evalu- ated. For instance, the application of in-floor chain conveyors in cross docking terminals gives rise to a novel scheduling problem. If a single logistics worker is assigned the task to load a trailer with the dedicated pallets circulating on a dragline at given positions, this problem resembles single machine scheduling where moving a pallet into a trailer con- stitutes a job. The main peculiarity, however, is that the processing times for a job and the sequence-dependent setup times among jobs (i.e., walking back from the trailer to the current position of the next pallet) vary with the circulation of the conveyor. Time- dependent processing times are a well researched topic in machine scheduling (e.g., see the survey paper of Cheng et al. [38]), but circulating items constitute a specific metric for the processing times, which has not been considered yet.Generally, it can be stated that there is a need for holistic models that consider the mutual interdependence between inbound processes, main conveyor, and outbound processes in more detail. Without shipments arriving from the inbound side, the main sorter runs idle. On the other hand, if the throughput of the main sorter increases, more shipments can be loaded. Analogously, congestion in outbound stations impacts the throughput of the main sorter. The feedback links between all three basic elements should be modeled in more detail so that additional knowledge on the dynamics of ASS can be gained.

Finally, transferring the knowledge gained for ASS to related settings and vice versa seems promising. For instance, AGVs transferring containers between quay cranes processing con- tainer vessels and gantry cranes servicing container yards can be interpreted as some kind of ASS (see Section 2). Recall that these systems have been excluded from our survey, because AGVs travel individually along their paths (and not in a steady flow). However, transferring the knowledge between both fields may help to derive future port systems that rather resemble a traditional ASS or more flexible ASS based on individual flows may be possible. Analogously, knowledge transfers with individual destination-coded vehicles for baggage sorting and con- tainer shuttles in rail-rail transshipment yards (see [4]) seem desirable. The same holds truefor a knowledge transfer among the four applications surveyed in this paper and their specific ASS implementations.

In light of these manifold future research tasks it can be projected that ASS will remain a fruitful field of research in the foreseeable future.

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